Ecological Indicators 153 (2023) 110382

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Impact of wetland change on ecosystem services in different urbanization stages: A case study in the Hang-Jia-Hu region, China

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ARTICLE INFO

Keywords:
Urbanization process
Ecosystem service
Wetland restoration
Dynamic change
Hang-Jia-Hu region

ABSTRACT

Urbanization has had a profound impact on wetlands, and wetland conservation and restoration have attracted much attention. However, the detailed impacts of different urbanization and wetland changing processes on ecosystem services (ESs) are not well understood. Based on long-time series of remote sensing data (1990–2020), flood mitigation (FM), water purification (WP), carbon sequestration (CS), and biodiversity conservation (BC) were quantified in the Hang-Jia-Hu (HJH) region, China. According to the changing trend of urban land, the study period was divided into three urbanization stages: slow urbanization (1990–1998), rapid urbanization (1998–2013), and moderate urbanization (2013–2020). Regression analysis was used to explore the quantitative relationship between urbanization/wetland changes and ESs. The results showed that the urban land expansion rates in the slow urbanization, rapid urbanization, and moderate urbanization stages were 46.51 km^2/yr, 100.62 km^2/yr, and 70.87 km^2/yr, respectively, and the corresponding wetland changing rates were 5.14 km^2/yr, 19.54 km^2/yr and -20.88 km^2/yr, respectively. FM decreased in the slow and moderate urbanization stages and increased in the rapid urbanization stage, and WP increased in the slow and rapid urbanization stages and decreased in the moderate urbanization stage. Urbanization led to a decrease in FM, CS, and BC. Wetland restoration improved these ESs, while wetland loss caused a decline in multiple ESs in the slow and rapid urbanization stages. Wetland restoration partially offsets the negative effects of urbanization and wetland loss on ESs in the rapid urbanization stage. Urbanization and wetland changes have linear and nonlinear effects on ESs in different urbanization stages. Wetland restoration is an effective way to improve ESs in urbanization regions. This study can make an important contribution to sustainable wetland ecosystem development in urbanization regions.

1. Introduction

Wetlands are special ecosystems with interactions between land and water that provide important ecosystem services (ESs), including flood mitigation (FM), water purification (WP), carbon sequestration (CS), and biodiversity conservation (BC) (Ma et al., 2021a; Xue et al., 2018). However, due to the combined impacts of human activities and climate change, wetlands are becoming fragmented and shrinking, especially in urbanization regions (Nsenga Kumwimba et al., 2021; Murray et al., 2014). The land is required for urban expansion, and wetlands are often the priority areas for urbanization (Mao et al., 2018; Wu et al., 2022). With the acceleration of urbanization, the contradiction between wetland protection and utilization has attracted widespread attention (Yang et al., 2022). Thus, assessing the impacts of urbanization on wetland changes is of great significance for balancing wetland conservation and economic development.

Continuous urbanization has a profound impact on wetlands, leading to the loss of ESs, and serious environmental problems such as flood disasters and water pollution, which seriously restrict the sustainable development of urbanization (Seto et al., 2012; Xu et al., 2019). The lack of information on wetland loss and its relationship with urban expansion poses a great challenge to wetland conservation (Rojas et al., 2019; Tian

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https://doi.org/10.1016/j.ecolind.2023.110382
Received 15 December 2022; Received in revised form 22 April 2023; Accepted 17 May 2023
Available online 25 May 2023

et al., 2015). Therefore, it is important to accurately understand the spatiotemporal patterns of wetlands in urbanization regions. At present, many scholars have used remote sensing data with different resolutions to monitor the changing characteristics of wetlands in different regions. Landmann et al. (2010) used MODIS (250 m) time-series data to map wetlands in semi-arid Africa. With the development of remote sensing technology, increasing attention has been given to wetland changes at finer resolutions. Athukorala et al. (2021) used Landsat (30 m) images at three-time points (1997, 2007, and 2017) to explore the impact of urbanization on wetland landscape patterns in Sri Lanka. However, analyzing only one or several short-term trends is not enough to accurately reflect the dynamic process of wetland change under urbanization (Yang et al., 2022). Mao et al. (2018) quantified wetland loss driven by urbanization in China based on Landsat (30 m) time-series images during 1990–2010. The impacts of wetland changes in recent years in urbanization regions need to be updated. Therefore, this study used long time series of remote sensing data (1990–2020) to explore the dynamic changing characteristics of wetlands and urbanization.

To reverse the loss of wetlands and improve ESs, the Chinese government has launched an ambitious National Wetland Conservation Program (NWCP) (Jiang and Xu, 2019; Xu et al., 2018). The NWCP has extensive coverage and is considered the largest wetland conservation program in the world (Wang et al., 2012). Unlike the widespread attention that afforestation and revegetation programs have attracted, the NWCP has had a limited impact (Lian et al., 2021; Liu et al., 2008; Xiang et al., 2020). Only a few studies have explored the effectiveness of the NWCP. Xiang et al. (2020) evaluated the impact of the NWCP on ESs in the Sanjiang Plain based on Landsat images before and after NWCP implementation and proved the important role of the NWCP in improving ESs. However, the above study failed to accurately characterize wetland dynamic changes. In addition, because the above study was conducted in an area rich in natural ecosystems, the impact of wetland restoration on ESs in urbanization regions is still unclear. The Chinese government has also set up an ecological redline policy to protect wetlands, which involves some urbanization regions (Bai et al., 2018). Therefore, assessing the impact of wetland restoration on ESs in urbanization regions has dual significance for the sustainable development of wetlands and urbanization. Existing studies have tended to focus on the short-term scale, while the urbanization process tends to show different trends on the long-term scale. Few scholars have divided urbanization into different stages to explore the similarities and differences in urbanization and wetland changing characteristics in the urbanization process. Thus, it is of great significance for realizing sustainable development to reveal the impacts of urbanization and wetland changes on ESs in different urbanization stages.

The Hang-Jia-Hu region (HJH) is an area with a developed economy and rich natural resources. HJH has several national wetland parks and provincial wetland parks, providing multiple ESs, which play an important role in realizing the harmony between people and nature. Rapid urbanization in the HJH has placed great pressure on wetlands. There are important trade-offs between wetland conservation and economic development, making wetland conservation and restoration extremely challenging. At present, the dynamically changing characteristics of wetlands under long-term urbanization in the HJH are not clear. Therefore, it is urgent to evaluate the impact of urbanization and wetland changes on ESs in different urbanization stages to ensure ecological security. In this study, the HJH was selected as the research area, and the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model was used to evaluate four important ESs (FM, CS, WP, and BC) in the HJH based on long-term remote sensing data (1990–2020). The objectives of this study were: (1) to analyze the dynamic changes in wetlands in different urbanization stages, (2) to explore the changes in ESs in different urbanization stages, and (3) to reveal the impact of urbanization and wetland changes on ESs in different urbanization stages.

2. Materials and methods

2.1. Study area

The HJH (29.47° N-31.19° N, 118.63° E-121.28° E) is located in northern Zhejiang Province, China, and has the largest plain in Zhejiang Province (Fig. 1). HJH consists of Hangzhou city, Jiaxing city, and Huzhou city in Zhejiang Province, covering an area of 27,613.40 km^2. The elevation is between 0 and 1771 m, showing a decreasing trend from the southwest to the northeast. HJH has a subtropical monsoon climate with four distinct seasons and abundant precipitation, but there is a large interannual difference (Xia et al., 2023). The average annual rainfall is between 1300 and 1400 mm, and the average annual temperature is between 15 and 20 ℃. There are various types of wetlands in the HJH, including river wetland, lake wetland, reservoir wetland, coastal wetland, swamp wetland, and marsh wetland, which is a typical area of the Yangtze River Delta (Mao et al., 2018). The gross domestic product of HJH in 2020 was 2,481.70 billion RMB (http://tjj.zj.gov.cn/). The permanent population of HJH was 20.75 million, and the urban population was 16.04 million in 2020 (http://tjj.zj.gov.cn/). In the past 30 years, the rapid urbanization process in HJH and intense and frequent human activities have led to great pressure on wetlands, which has led to a series of hydrological and water resource problems (Wang et al., 2021b; Xia et al., 2023). It is urgent to explore the impact of wetland changes on ESs under urbanization to provide theoretical support for wetland protection and management.

2.2. Framework and data sources

This study developed a framework to analyze the changes in wetlands and ESs in different urbanization stages (Fig. 2): (1) urbanization is divided into slow urbanization, moderate urbanization, and rapid urbanization according to the trend of urbanization; (2) preparing data required for ES evaluation; (3) evaluating the key ESs by using the InVEST model; (4) quantifying the impact of wetland changes on ESs in different urbanization stages.

The 30 m annual land use/cover (LULC) data from 1990 to 2020 came from China's Land-Use/Cover Datasets (CLUD) (https://zenodo.org/record/5816591). The CLUD was constructed using more than 300,000 Landsat images from the Google Earth Engine and achieved an overall accuracy of 79.31%. The 30 m digital elevation model (DEM) data came from the geospatial data cloud (http://www.gscloud.cn/). The 1 km precipitation and potential evapotranspiration (calculated by the Hargreaves method) from 1990 to 2020 came from the National Earth System Science Data Center (http://www.geodata.cn/, accessed on 14 January 2022) (Peng et al., 2019b; Peng et al., 2017). 1 km soil data in the Harmonized World Soil Database were derived from the National Tibetan Plateau Data Center (https://data.tpdc.ac.cn/). The spatial resolution of the data used in this study was unified to 30 m by bilinear interpolation.

2.3. Ecosystem service assessment

According to the needs of relevant stakeholders in the HJH region and data availability, four important ESs (FM, CS, WP, and BC) were selected for this study (Table 1). The InVEST model is derived from the Natural Capital Project and has become the most influential and widely used model for assessing ESs due to its accessible data requirements (Benra et al., 2021; Wang et al., 2022b). Each ES was evaluated using the corresponding model according to the InVEST User Guide. The purpose of this study is to explore the impact of wetland changes on ESs under urbanization; therefore, the average climate data from 1990 to 2020 were used in this study to eliminate the impact of climate change. We validated the evaluation results of the InVEST model using independent data from other studies involving the HJH region. Detailed processing and setting of model parameters can be found in the Supplementary

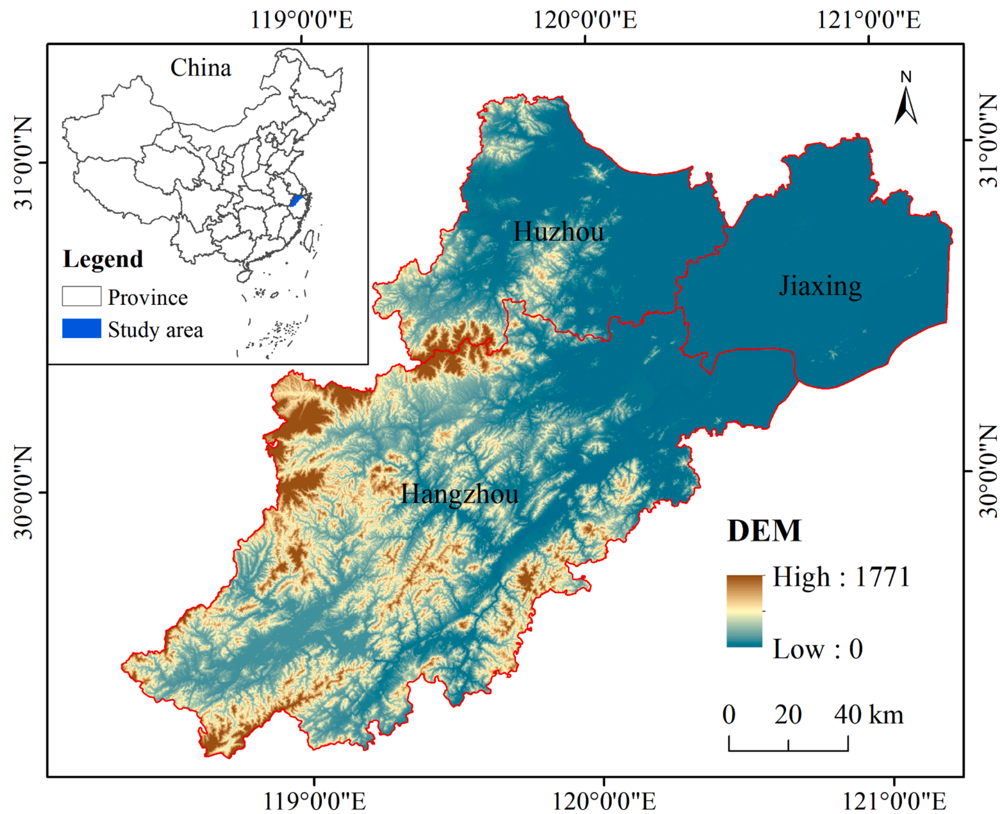

Fig. 1. General situation of the Hang-Jia-Hu region.

Materials. The data required by each model are shown in Table 2.

2.3.1. Flood mitigation

Due to abundant rainfall, HJH has rich water resources and is also at high risk of flooding. Therefore, FM is particularly important for HJH. The water yield (WY) model in the InVEST model was used to calculate WY based on the Budyko curve. This study used the reduction rate of WY to represent FM (Ma et al., 2022c; Zheng et al., 2019).

$$WY_x = (1 - \frac{AET_x}{P_x}) \times P_x \tag{1}$$

where WY_x, AET_x, and P_x are WY, actual evapotranspiration, and precipitation for pixel x, respectively. The higher the WY is, the lower the FM.

2.3.2. Carbon sequestration

CS is closely linked to climate change and is essential for China to achieve carbon neutrality. The carbon model in the InVEST model was used to map the carbon pool of each LULC (Ma et al., 2022d; Zhang et al., 2022c).

$$C_{total} = C_{above} + C_{below} + C_{soil} + C_{dead} \tag{2}$$

where C_{total}, C_{above}, C_{below}, C_{soil}, and C_{dead} are the total CS and CS of aboveground biomass, belowground biomass, soil, and dead biomass, respectively.

2.3.3. Water purification

Agricultural nonpoint source pollution and industrial pollution place great pressure on water quality in HJH. After investigation, nitrogen export (NE) was determined to be the main cause of water pollution in HJH. The nutrient delivery ratio model in the InVEST model was used to calculate NE (Ma et al., 2022c; Zheng et al., 2022). This study used the reduction rate of NE to represent WP.

$$ALV_x = HSS_x \times pol_x \tag{3}$$

where ALV_x, HSS_x, and pol_x are NE, hydrological sensitivity, and output coefficients of NE for pixel x, respectively. The higher the NE is, the lower the WP.

2.3.4. Biodiversity conservation

Due to the large proportion of forests and wetlands, HJH has great potential for BC. The habitat quality model in the InVEST model was used to measure BC (Ma et al., 2022d; Ren et al., 2022).

$$Q_{xj} = H_j(1 - (\frac{D_{xj}^z}{D_{xj}^z + k^z})) \tag{4}$$

where Q_{xj} is the BC for pixel x and LULC j, H_j is the habitat suitability of LULC j, D_{xj}^z is the threat level for pixel x and LULC j, and k is a half-saturation constant.

2.4. Trend analysis

This study used the urban land area as an urbanization indicator and used linear regression to detect the trend of urbanization.

$$y = a \times t + b + \varepsilon \tag{5}$$

where y represents the urbanization indicator, a represents the linear trend coefficient, t represents the time series, b represents the intercept, and ε represents a random error. Urbanization was divided into three stages according to the linear trend coefficient: slow urbanization, moderate urbanization, and rapid urbanization. We also used linear regression to detect the trend of change in wetlands and ESs.

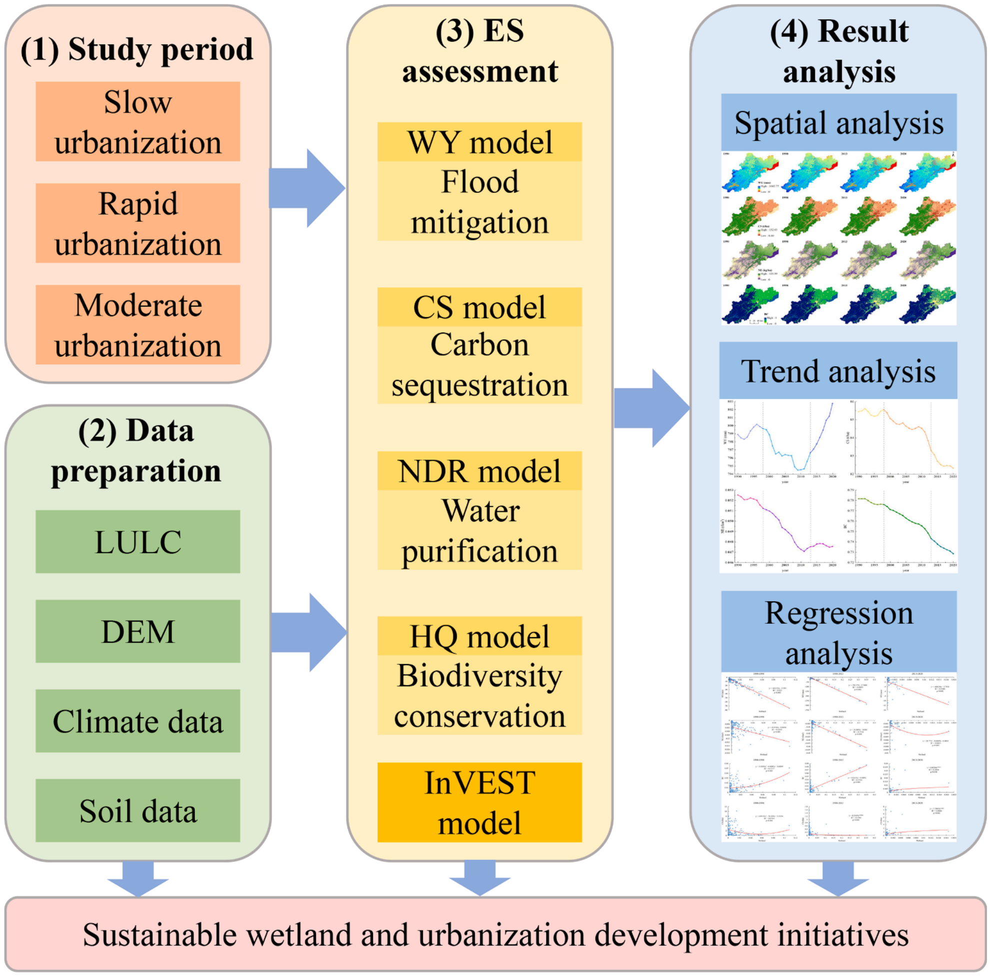

Fig. 2. Framework for sustainable wetland development under urbanization.

Table 1
Determination of ESs based on stakeholder analysis.

Stakeholder	Objective	Related ESs
Government	Protect the ecological environment and promote economic development	CS: Closely related to achieving carbon neutrality BC: Important indicator for ecological protection FM: Closely related to the life and property of the public WP: Closely related to the health of the public
Enterprise	Reduce carbon emissions and sewage emissions	WP: Closely related to the health of the public CS: Closely related to achieving carbon neutrality
Public	Clean drinking water and safety of life	FM: Closely related to the life and property of the public WP: Closely related to the health of the public

2.5. *Impacts of urbanization and wetland change on ESs*

We used the fishnet creation tool in ArcGIS software to divide the study area into 3 km × 3 km grids. We calculated the proportion of urban land and wetlands in each grid and subtracted the data from two years before and after each urbanization stage to obtain the change in urban land and wetlands in each grid. Similarly, we calculated the change in ESs for each grid. Finally, we used regression analysis based on grid data to reveal the quantitative relationship between urban land change and ES change as well as the quantitative relationship between wetland change and ES change.

Table 2
Data used in ecosystem service assessment.

Data	ESs
LULC	FM, CS, WP, BC
DEM	FM, WP
Precipitation	FM, WP
Potential evapotranspiration	FM
Soil data	FM

3. Results

3.1. *Spatial and temporal characteristics of urbanization and wetland change*

Spatially, the urban land was mainly distributed in northern Hangzhou city, and some occurred in eastern Huzhou city and western Jiaxing city. Wetlands were mainly distributed in southwestern and northeastern HJH (Fig. 3). According to the changing trend of urban land, we divided the period from 1990 to 2020 into three stages: slow urbanization (1990–1998), rapid urbanization (1998–2013), and moderate urbanization (2013–2020). The urban land expansion rates in the slow urbanization, rapid urbanization, and moderate urbanization

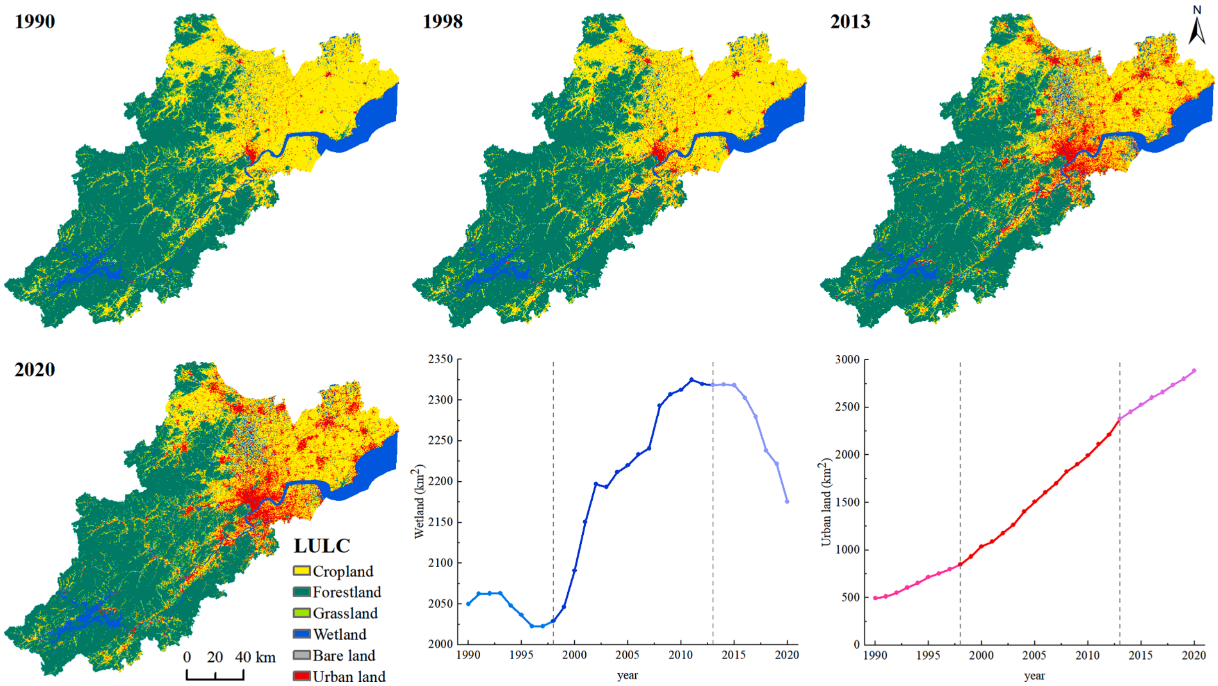

Fig. 3. Spatial pattern and changes in urbanization and wetlands from 1990 to 2020.

stages were 46.51 km^2/yr, 100.62 km^2/yr, and 70.87 km^2/yr, respectively, and the rates of wetland change in the slow urbanization, rapid urbanization, and moderate urbanization stages were −5.14 km^2/yr, 19.54 km^2/yr, and −20.88 km^2/yr, respectively. We found that the wetlands first increased and then decreased in the slow urbanization stage, the wetlands recovered in the rapid urbanization stage, and the wetlands declined in the moderate urbanization stage. Wetland restoration and urban expansion can coexist.

In the slow urbanization stage, urban land had a trend of slow expansion from a point outward. During this period, urban land expanded by 355.02 km^2, while wetlands did not change significantly. In the rapid urbanization stage, both urban land and wetlands showed an obvious expansion trend in northern HJH. During this period, urban land expanded nearly twice and wetlands by 14.24%. Especially in the Hangzhou Bay area, a large area of concentrated contiguous urban land was added. The newly added wetlands were mainly in northeastern Hangzhou city, eastern Huzhou city, and northern Jiaxing city. In the moderate urbanization stage, the outward expansion of urban land can

Table 3
LULC transition matrix during 1990–2020.

Area (km^2)		1998					
		Cropland	Forestland	Grassland	Wetland	Bare land	Urban land
1990	Cropland	9575.11	291.58	0.29	60.65	0.01	329.80
	Forestland	226.85	14572.54	0.09	0.22	0.00	7.87
	Grassland	0.92	0.87	2.21	0.08	0.02	0.69
	Wetland	54.36	10.55	0.00	1965.59	0.00	19.47
	Bare land	0.00	0.00	0.00	0.00	0.01	0.02
	Urban land	0.09	0.01	0.00	2.72	0.00	490.77
		2013					
		Cropland	Forestland	Grassland	Wetland	Bare land	Urban land
1998	Cropland	7805.11	242.71	1.26	395.99	0.24	1412.04
	Forestland	615.42	14155.08	1.27	9.10	0.02	94.66
	Grassland	0.28	0.86	0.76	0.10	0.02	0.58
	Wetland	79.00	12.48	0.01	1895.65	0.02	42.09
	Bare land	0.00	0.00	0.00	0.00	0.00	0.04
	Urban land	1.77	0.05	0.00	17.46	0.00	829.33
		2020					
		Cropland	Forestland	Grassland	Wetland	Bare land	Urban land
2013	Cropland	7809.94	166.91	0.42	57.84	0.01	466.48
	Forestland	359.12	14034.23	0.20	0.09	0.00	17.53
	Grassland	0.75	0.51	1.25	0.01	0.05	0.74
	Wetland	178.73	0.55	0.00	2112.21	0.16	26.64
	Bare land	0.01	0.00	0.00	0.00	0.14	0.15
	Urban land	0.87	0.01	0.00	5.04	0.00	2372.80

still be observed but is not as pronounced as that in the rapid urbanization stage. During this period, urban land increased by 505.62 km^2, while wetland decreased by 143.11 km^2. We found that some increased wetlands in the rapid urbanization stage were lost in the moderate urbanization stage.

There was a mutual conversion between urban land and wetlands (Table 3). In the slow rapid urbanization stage, 19.47 km^2 of wetland was encroached on by urban land. In the rapid urbanization stage, 42.09 km^2 of wetland was converted to urban land, while 17.46 km^2 of urban land was converted to wetland. In the moderate urbanization stage, 26.64 km^2 of wetland was occupied by urban land. Urbanization has indeed encroached on some wetlands during 1990–2020. The main source of increased urban land was cropland. In the slow, rapid, and moderate urbanization stages, 329.80 km^2, 1412.03 km^2, and 466.48 km^2 of cropland were transformed into urban land, respectively. In the rapid and moderate urbanization stages, urban land also encroached on 94.66 km^2 and 17.53 km^2 of forestland, respectively. The loss of wetland was mainly converted to cropland, which was 54.36 km^2, 79.00 km^2, and 178.73 km^2 in the slow, rapid, and moderate urbanization stages, respectively. In the rapid urbanization stage, the main source of wetland restoration was cropland (395.99 km^2). Although some cropland was converted to wetland in the slow and moderate urbanization stages, it was not enough to reverse wetland loss. In addition, we also found that there was a large area of conversion between cropland and forestland during 1990–2020. Wetland and forestland were under increasing pressure of degradation.

3.2. Spatial and temporal changes in ESs

WY showed a distribution pattern of high in the southwest and low in the northeast, which indicates that FM was high in the northeast and low in the southwest (Fig. 4). The regions of WY increased and decreased in the slow urbanization stage were scattered, while the spatial distribution of WY change in the rapid and moderate urbanization stages was similar, in central and northwestern HJH and decreasing in northern HJH. We found that WY increased in urbanized areas while WY decreased in wetland restoration areas; that is, FM decreased in urbanized areas and increased in wetland restoration areas. WY showed an inverted “N” shape change in the slow urbanization stage, reaching a minimum value in 1992 and a maximum value in 1996. In the rapid urbanization stage, WY first decreased and then increased, with the lowest value appearing in 2009. In the moderate urbanization stage, WY increased approximately linearly. The changing rates of WY in the slow, rapid, and moderate urbanization stages were 5.54 million m^3/yr, −7.78 million m^3/yr, and 23.99 million m^3/yr, respectively (Fig. 5). In general, FM decreased in the slow and moderate urbanization stages and increased in the rapid urbanization stage.

The spatial distribution patterns of CS and BC were similar, showing a trend of high in the southwest and low in the northeast. In the slow urbanization stage, the spatial changes in CS and BC were not obvious. CS and BC showed obvious spatial changes in the rapid and moderate urbanization stages, especially in the rapid urbanization stage, showing a trend of decreasing in the central and northwestern regions and

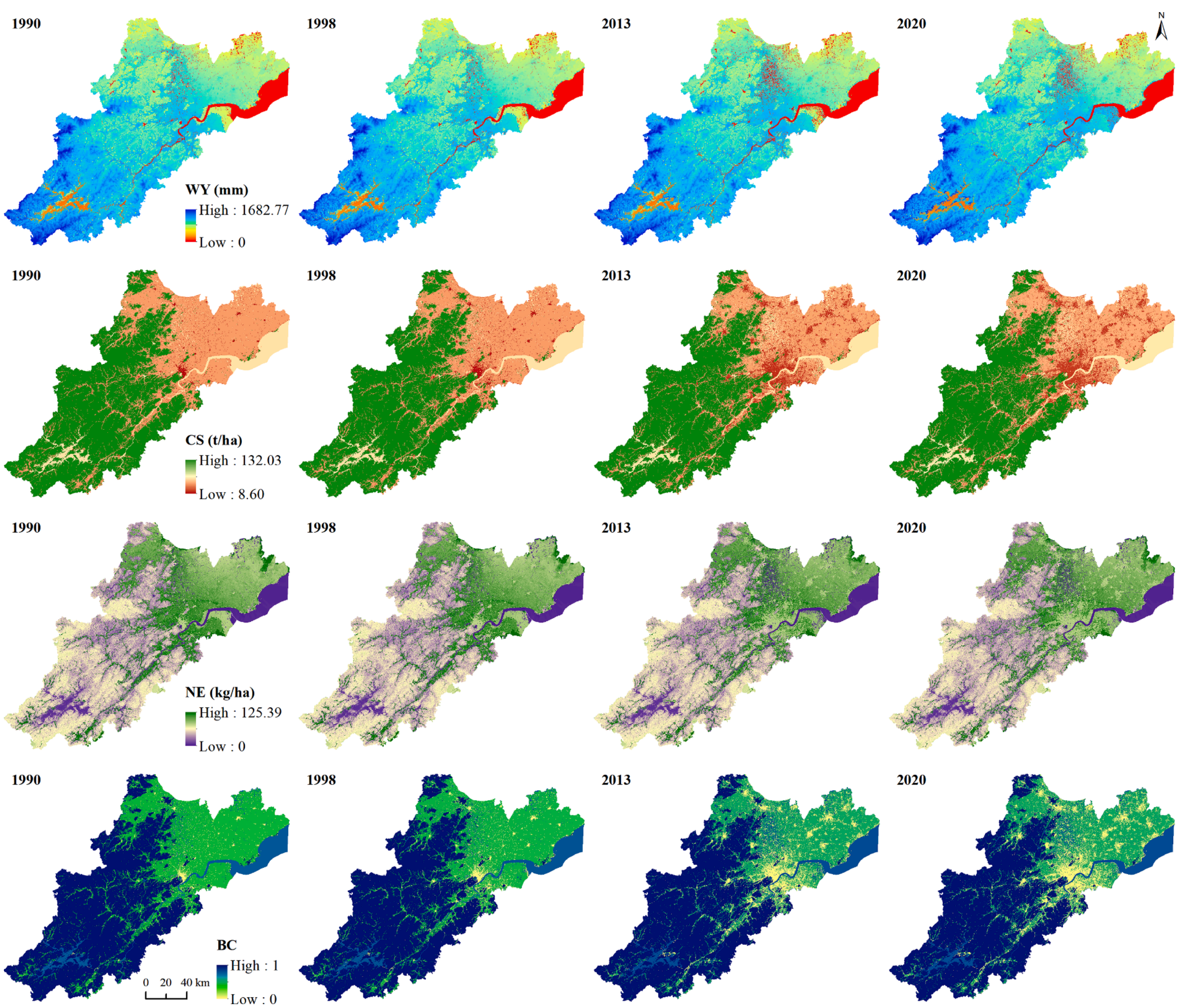

Fig. 4. Spatial pattern of ESs from 1990 to 2020.

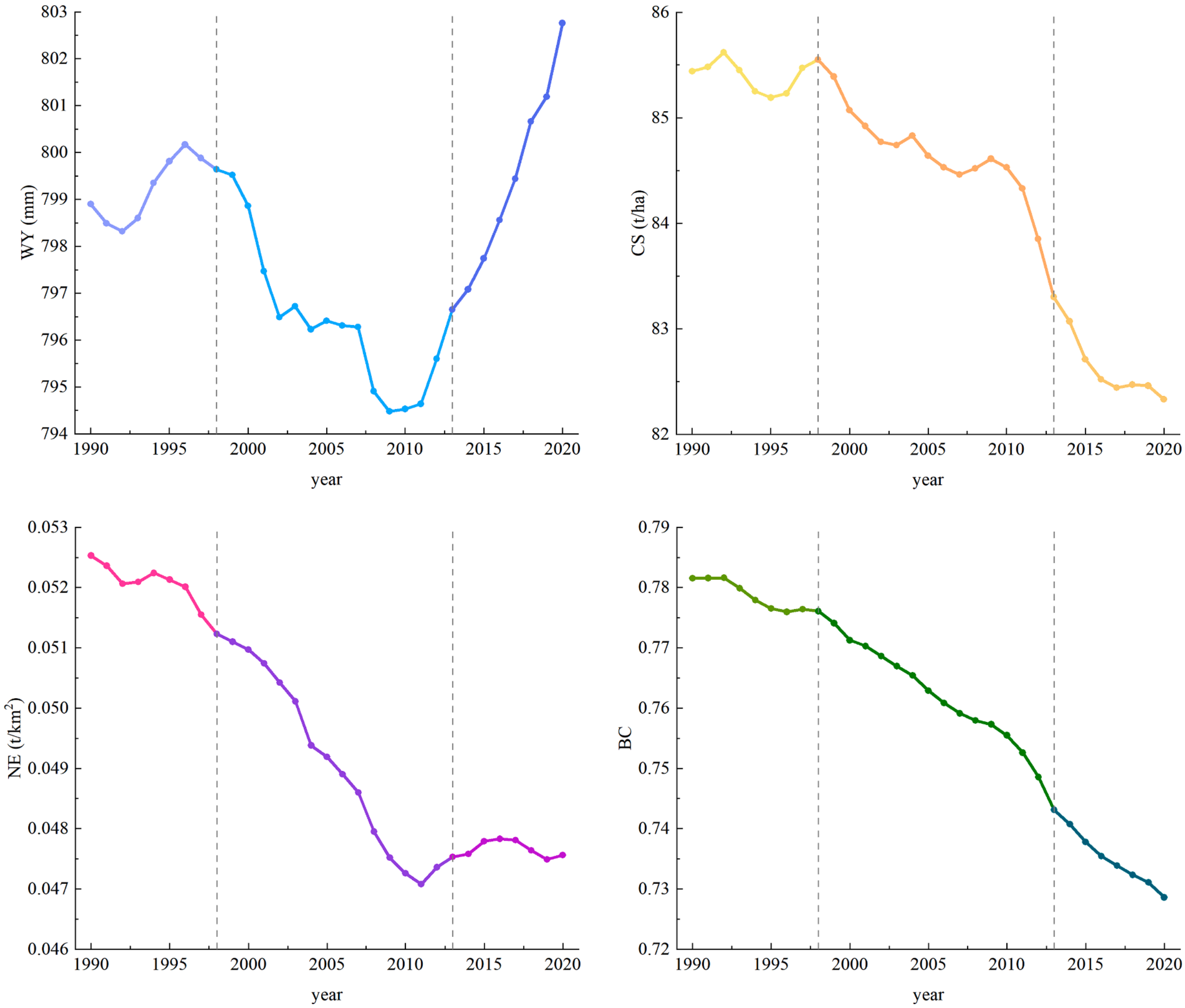

Fig. 5. Changes in ESs from 1990 to 2020.

slightly increasing in the northeast. The decrease in CS and BC was consistent with the urbanization area, while the increase in CS and BC was in the wetland restoration area. In the slow urbanization stage, CS showed an N-type change, and in the rapid urbanization stage, CS first decreased, then gently decreased, and then accelerated. CS first decreased and then remained relatively stable in the moderate urbanization stage. BC showed a downward trend in all urbanization stages, and the decline accelerated with time. The changing rates of CS in the slow, rapid, and moderate urbanization stages were −0.03 million t/yr, −0.28 million t/yr, and −0.35 million t/yr, respectively. The changing rates of BC in the slow, rapid, and moderate urbanization stages were −0.0090/yr, −0.0019/yr, and −0.0020/yr, respectively. In general, the loss rates of CS and BC in the moderate urbanization stage were higher than those in the rapid urbanization stage.

NE showed a distribution pattern of high in the northeast and low in the southwest, which indicates that WP was high in the southwest and low in the northeast. The decrease in NE in a large area, namely, the increase in WP, can be observed, mainly distributed in the central and northern regions in the rapid and moderate urbanization stages, and a few also appeared in the slow urbanization stage. NE showed an N-shaped change in the slow urbanization stage, first decreasing and then increasing in the rapid urbanization stage. The turning point appeared in 2011, and an inverted V-shaped change appeared in the moderate urbanization stage. The changing rates of NE in the slow and rapid and moderate urbanization stages were −2.76 t/yr, −8.28 t/yr, and 0.00 t/yr, respectively. In general, WP improved in the slow and fast urbanization stages, and the rate of increase accelerated, but there was no significant change in the moderate urbanization stage.

3.3. Impacts of wetland changes on ESs in different urbanization stages

We quantified the contribution of urbanization and wetland change to ESs according to LULC changes (Table 4). WY increased but CS, BC, and NE decreased in the urbanized regions, and the impact of urbanization in the rapid urbanization stage was the largest and that in the slow urbanization stage was the smallest. WY and NE increased while BC decreased in wetland loss areas. In other words, wetland loss resulted in a decrease in FM, WP, and BC, and the impact of wetland loss was the largest in the moderate urbanization stage and the lowest in the slow urbanization stage. Interestingly, the CS in the wetland loss area increased by 5856.43 t and 4372.21 t in the slow and rapid urbanization stages, respectively, but decreased by 6528.35 t in the moderate urbanization stage. In wetland restoration areas, WY and NE decreased, while BC and CS increased. That is, wetland restoration improved all ESs. The impact of wetland restoration on ESs was the largest in the rapid urbanization stage but the smallest in the moderate urbanization stage. At all stages of urbanization, the FM increase (WY decrease) from wetland restoration outweighed the FM decrease (WY increase) from urbanization. The FM decrease (WY increase) was contributed by wetland loss (61.88 million m^3 and 166.68 million m^3, respectively) in the slow and moderate urbanization stages but by urbanization in the rapid urbanization stage (120.39 million m^3). In particular, the positive

Table 4
Contribution of urbanization and wetland changes to ESs in different urbanization stages.

		WY (million m^3)	CS (t)	BC	NE (t)
Slow urbanization	urbanization	32.13	−41658.98	−0.007	−26.71
	wetland loss	61.88	5856.43	−0.001	8.03
	wetland restoration	−48.70	1441.21	0.001	−8.00
Rapid urbanization	urbanization	120.39	−234264.73	−0.030	−108.63
	wetland loss	101.31	4372.21	−0.002	12.71
	wetland restoration	−322.24	2569.37	0.005	−49.88
Medium urbanization	urbanization	46.78	−65179.55	−0.010	−34.17
	wetland loss	166.68	−6528.35	−0.003	23.59
	wetland restoration	−48.47	1761.11	0.001	−7.37

effects of wetland restoration on FM during the rapid urbanization phase outweighed the negative effects of urbanization and wetland loss. However, the impact of wetland restoration on other ESs was lower than that of urbanization. Surprisingly, the positive effects of wetland loss on CS (5856.43 t and 4372.21 t, respectively) in the slow and rapid urbanization stages outweighed the positive effects of wetland restoration on CS (1441.21 t and 2569.37 t, respectively). In the rapid urbanization stage, the positive impact of wetland restoration on BC and WP (0.005 and −49.88 t, respectively) was greater than the negative impact of wetland loss (−0.002 and 12.71 t, respectively), while the opposite was true during the other urbanization stages.

We further explored the impact of the urbanization process on ESs. The regression relationship between urbanization and ESs in different urbanization stages was generally similar but slightly different (Fig. 6). With the increase in urban land, NE and BC decreased almost linearly and significantly ($p < 0.01$), and the fitted R^2 values exceeded 0.67, except for the R^2 value of NE and urbanization in the moderate urbanization stage, which was 0.39. In other words, urbanization improved WP but reduced BC. In addition, there was no obvious difference in the impact of urbanization on WP and BC in different urbanization stages. WY increased significantly ($p < 0.01$) with urbanization in all different urbanization stages, which indicates that urbanization decreased FM. In the rapid and moderate urbanization stages, WY first accelerated and then slowly increased with urbanization; that is, the decreasing rate of FM decreased with urbanization. The R^2 value of the regression relationship between urbanization and CS was relatively low and changed in different urbanization stages. CS decreased significantly ($p < 0.01$) with urbanization in the slow and rapid urbanization stages. In the rapid

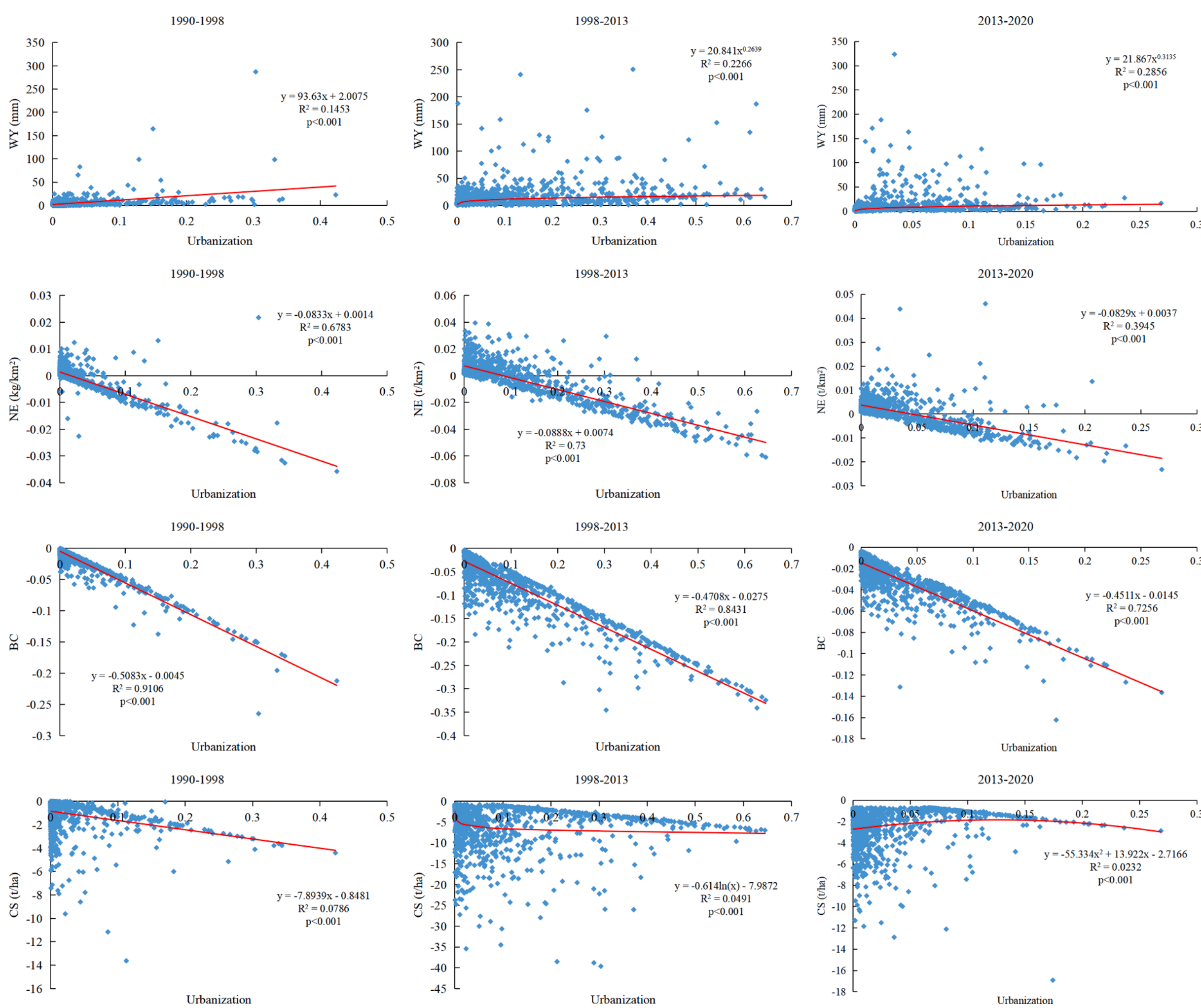

Fig. 6. Relationship between urbanization and ESs in different urbanization stages.

urbanization stage, CS decreased rapidly at first and then slowly. In contrast, CS first increased and then decreased with urbanization in the moderate urbanization stage.

We also explored the impact of wetland loss and restoration on ESs. There was a significant linear relationship between wetland loss and ESs ($p < 0.01$), except for CS (Fig. 7). With wetland loss, WY increased significantly, and the fitted R^2 values exceeded 0.90 in all urbanization stages. The effect of wetland loss on WY was slightly greater in the moderate urbanization stage than in the slow and rapid urbanization stages. In other words, wetland loss resulted in a significant reduction in FM ($p < 0.01$). Similarly, we can see that with wetland loss, NE increased; that is, wetland loss led to a decrease in WP. At the moderate urbanization stage, the same percentage of wetland loss had the greatest impact on WP, while at the slow urbanization stage, the same percentage of wetland loss had the least impact on WP. Similarly, wetland loss brought about a significant decrease in BC ($p < 0.01$). However, the impact of wetland loss on BC was strongest in the slow urbanization stage and weakest in the moderate urbanization stage. In particular, there were obvious differences in the impact of wetland loss on CS in different urbanization stages. In a certain range, wetland loss was conducive to the increase in CS, and when wetland loss reached a certain extent, CS decreased. In the rapid urbanization stage, CS did not significantly increase due to wetland loss ($p > 0.05$). In the intermediate urbanization stage, the impact of wetland loss on CS was more complex, showing an N-shaped trend.

The impact of wetland restoration on ESs varied with ES type and urbanization stage (Fig. 8). There was a significant negative correlation between WY and wetland restoration in all urbanization stages ($p < 0.01$). In other words, wetland restoration was conducive to improving FM. The effect of wetland restoration on FM was the largest in the rapid urbanization stage and the smallest in the moderate urbanization stage. Similarly, with wetland restoration, BC significantly increased ($p < 0.01$), but the variation trend of BC differed in different urbanization stages. In the slow urbanization stage, the increasing rate of BC was constantly increasing. In the rapid urbanization stage, BC had a linear relationship with wetland restoration, while in the moderate urbanization stage, the increasing rate of BC was constantly decreasing. NE was negatively correlated with wetland restoration in the slow and rapid urbanization stages; that is, wetland restoration improved WP, but there was no significant relationship between NE and wetland restoration in the moderate urbanization stage ($p > 0.05$). The effect of wetland restoration on WP was greater in the rapid urbanization stage than in the slow urbanization stage. There was no significant relationship between CS and wetland restoration in all urbanization stages ($p > 0.05$).

4. Discussion

4.1. Impact of urbanization on ESs

From 1990 to 2020, HJH experienced slow urbanization (1990–1998), rapid urbanization (1998–2013), and moderate urbanization (2013–2020). From 1990 to 1998, urban land was in a state of natural expansion. China joined the World Trade Organization in 2001, which has further accelerated urbanization (Mao et al., 2019). In 2014,

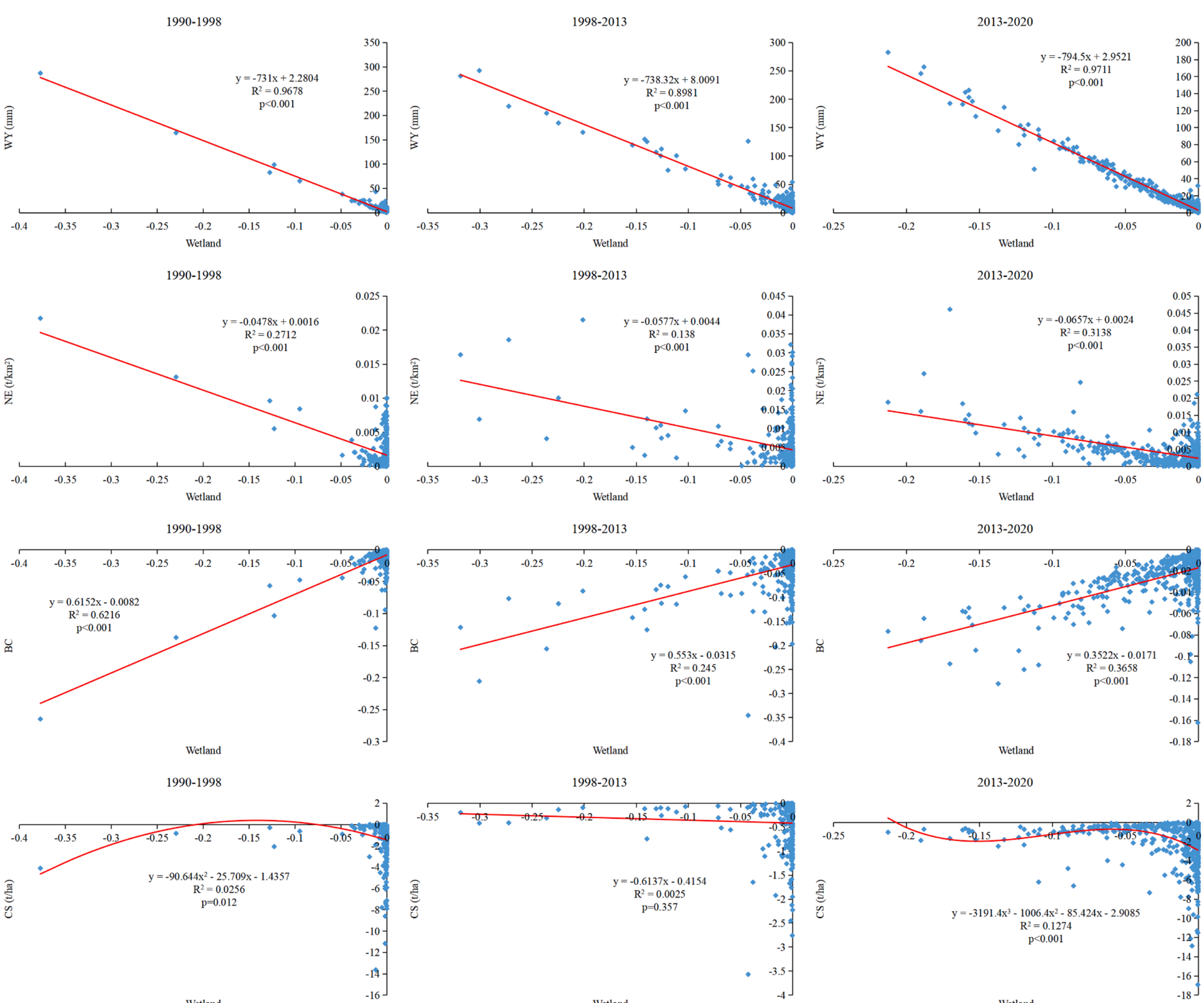

Fig. 7. Relationship between wetland loss and ESs in different urbanization stages.

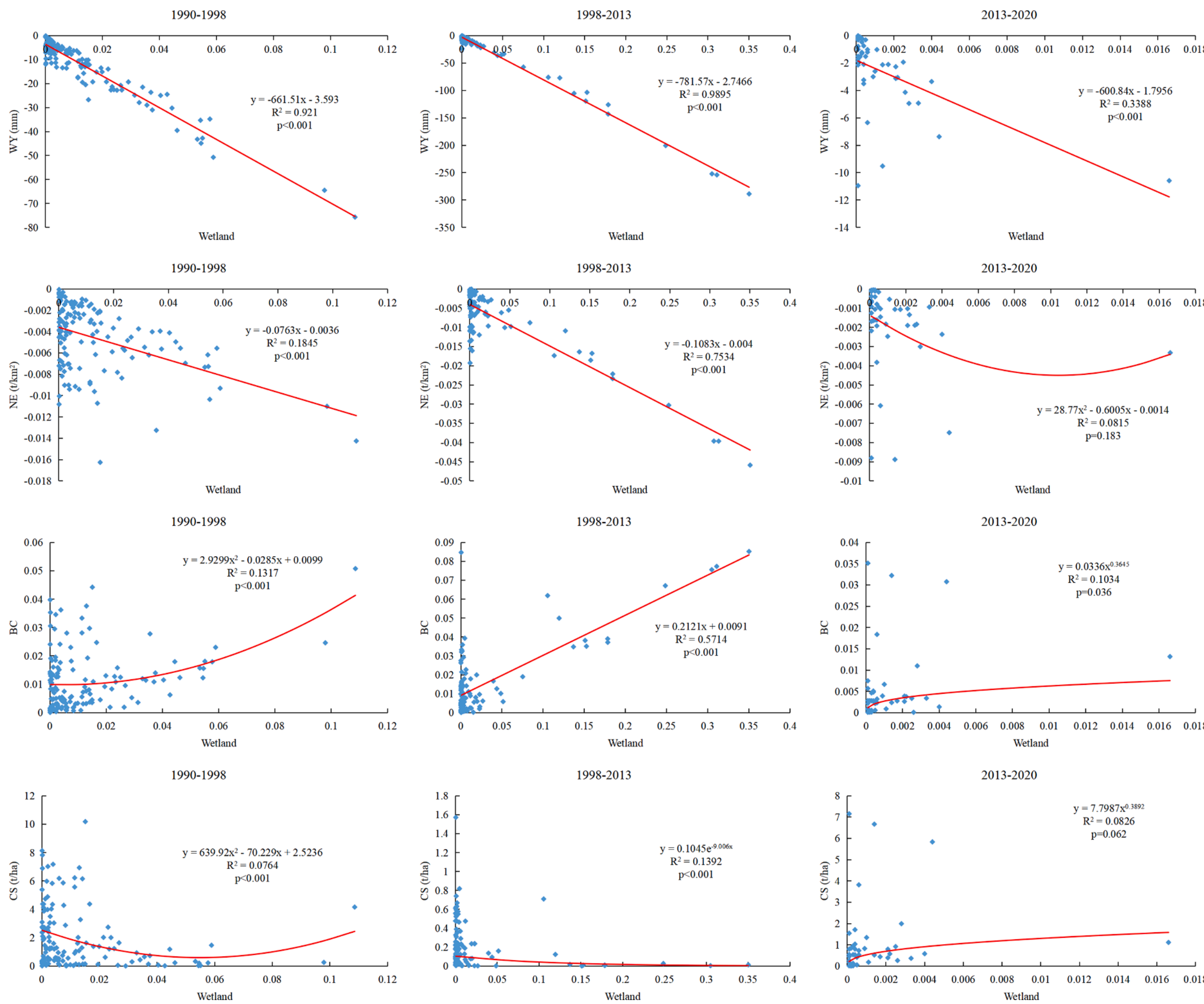

Fig. 8. Relationship between wetland restoration and ESs in different urbanization stages.

the National New-type Urbanization Plan (2014–2020) was issued to promote the peaceful development of urbanization and ecology, which slowed urbanization to a certain extent (Yu, 2021). The development of urbanization in this study is generally the same as these nodes. Our results show that the impact of urbanization on ESs was almost the same in different urbanization stages. Urbanization increased WY but decreased CS and BC, similar to previous findings (Bai et al., 2019; Li et al., 2020; Liu et al., 2019). According to the Budyko curve, WY is approximated as precipitation minus evaporation over long time scales, while the impermeable layer has low evaporation and low permeability; therefore, urbanization can lead to an increase in WY (Guo et al., 2021). New urban land is often converted from natural and seminatural ecosystems, and the biomass of these ecosystems is often higher (Zhang et al., 2022c). Moreover, CS is closely related to biomass; therefore, urbanization could reduce CS. On the one hand, urbanization encroached on natural and seminatural ecosystems with larger habitats; on the other hand, urbanization brought habitat fragmentation and reduced interactions between species, which eventually led to the decline of BC (Li et al., 2022). Surprisingly, urbanization reduced NE and improved WP, which is debatable. Because urban land is an important pollution source, urbanization may increase NE when urban land is transformed from natural ecosystems, while urbanization may decrease NE when it is transformed from cropland because agricultural nonpoint source pollution is more serious (Guo et al., 2021). According to the LULC transfer matrix, the newly added urban land in the HJH region mainly comes from cropland. Spatially, these results are similar.

When urbanization comes from different LULC types, its impact on ESs is also different. In the rapid and moderate urbanization stages, WY first accelerated and then gently increased with urbanization, which may be because small urbanization areas came from areas with very low WY, such as wetland and forestland, while large urbanization areas came from cropland with high WY (Ma et al., 2022a). Similarly, this can explain the rapid decline in CS followed by a slow decline in the rapid urbanization stage. However, CS first increased and then decreased with urbanization in the moderate urbanization stage. This may be due to the existence of wetland restoration or afforestation in urbanization areas, which offset some or all of the negative impacts of urbanization (Zhang et al., 2022a; Zhang et al., 2022b). The reason for the slight difference in the urbanization effect in different urbanization stages may be the amount of newly added urban land. In the rapid urbanization stage, urbanization tends to be dominated by large-area agglomeration expansion, while slow and moderate urbanization is mostly small-area scattered expansion. In addition to the abovementioned reasons, landscape fragmentation in urban areas is also an important factor affecting ESs, which may also lead to differences in the impact of urbanization in different urbanization stages (Li et al., 2021; Ma et al., 2022d).

4.2. *Impact of wetland change on ESs*

Wetland in the HJH experienced loss-recovery-loss during 1990–2020. Previous studies have proven that urbanization results in the loss of wetlands (Mao et al., 2018; Yang et al., 2022). However, in the HJH region, the area of wetlands converted to cropland is much larger than that converted to urban land. The food pressure caused by the surging population requires more cropland, which is the single most important reason for wetland reclamation (Ma et al., 2021a). In addition to urbanization, the warming climate has also led to the shrinkage of wetlands on a certain scale (Wang et al., 2021a). However, in 1998, severe floods occurred along the middle and lower reaches of the Yangtze River, leaving tens of millions homeless and causing economic losses of more than 30 billion dollars (Zheng et al., 2019). Wetland reclamation was an important cause of the disaster. Therefore, since 1998, China has implemented a large-scale afforestation and wetland restoration policy (Ma et al., 2021a; Xiang et al., 2020). Due to the policy of returning farmland to wetlands, the wetlands in HJH increased during 1998–2013. With time, the impact of wetland restoration policies has decreased. This study demonstrates the success of wetland restoration policies in the past.

We found that wetland loss and restoration may have the same or different effects on ESs. Our results showed that wetland loss increased WY and NE and reduced BC; that is, wetland loss could bring about a decrease in FM, WP, and BC, while wetland restoration could improve these ESs. It is easy to understand that the evaporation of wetlands is higher than that of seminatural ecosystems such as farmland; therefore, wetland loss may increase WY, whereas wetland restoration may decrease WY (Ma et al., 2021a). Wetland is a transition zone between land and water that is rich in both terrestrial and aquatic animal and plant resources, and approximately 40% of species live in wetlands; therefore, the BC of wetlands is very high (Guo et al., 2022; Qu et al., 2022). Therefore, wetland changes and BC changes are easily related. There is evidence that wetland ecosystems can absorb nitrogen and phosphorus nutrients in water; therefore, wetland restoration is conducive to improving WP (Guo et al., 2021; Luo et al., 2021). There is no doubt that wetland restoration is beneficial to CS. It has been reported that the carbon density of wetlands is higher than that of LULC types such as cropland and urban land (Mao et al., 2015; Zhang et al., 2022c). However, it is important to point out that in the slow and rapid urbanization stages, wetland loss also brought about an increase in CS. It is generally believed that wetland loss can lead to a decrease in CS, as shown in the moderate urbanization stage. Combined with the LULC transition matrix, we found that the wetlands lost in the moderate urbanization stage were mainly converted to cropland and urban land, but some of the wetlands lost in the slow and rapid urbanization stages were also converted to forestland (Table 3). In HJH, forestland has a high CS, and when wetland is converted to woodland, it may promote an increase in CS (Tian et al., 2021). Therefore, the CS loss caused by wetland conversion to other LULC types was offset in the slow and rapid urbanization stages. Similarly, this also explains why the nonlinear relationship between wetland loss/restoration and CS differed in different urbanization stages. In addition, the nonlinear relationship between wetland changes and ESs is related to the size of wetland change, LULC type, and wetland fragmentation (Li et al., 2022; Ma et al., 2022d).

4.3. Implications for ecosystem management in urbanization regions

Although this study revealed the negative impact of urbanization and wetland loss on ESs, it also pointed out their beneficial side. We propose some ecosystem management measures based on our results. First, urbanization needs to be developed under the guidance of science. It is necessary to shift the focus of urbanization from extensive expansion to improving the quality of cities. Urbanization not only encroaches on surrounding forestland and wetlands but also destroys large areas of high-quality farmland, threatening food security (Chen, 2007). It is important to strictly control the development of urbanization and set the boundaries of urban expansion (Hong et al., 2017). Urban landscape patterns need to be optimized to promote the coordinated development of the economy and ecology (Ma et al., 2022b). Green infrastructure construction should be increased in highly urbanized areas to reduce the negative effects of urbanization. Second, forestland, wetland, and other ecological land should be protected. Ecological land provides multiple ESs, while urbanization has placed great pressure on water-related ecosystem services, especially FM (Wang et al., 2022b). Priority protected areas can be established in urbanized regions to ensure a sustainable supply of ESs (Ma et al., 2021b; Peng et al., 2019a).

Our study found that although there were ecological restoration programs such as afforestation and wetland restoration in HJH, deforestation, and wetland loss have been particularly serious in recent years (Wang et al., 2022a). The decline in some ESs has not been reversed by ecological restoration programs. China has implemented the NWCP for nearly 20 years, and the wetland increased in the past 5 years (Mao et al., 2022). But wetland is still under threat, especially in rapid urbanization regions. Therefore, it is urgent to strengthen the implementation intensity of these programs to improve ecological benefits. Most importantly, the restoration of vegetation and wetlands needs to enhance connectivity and reduce fragmentation to efficiently improve multiple ESs (Li et al., 2022). Furthermore, high-quality cropland also needs to be protected to ensure food security. Farm shelterbelts and agroforestry ecosystems are effective ways to improve multiple ESs (Ma et al., 2022c).

4.4. Limitations

Due to the availability of data and the applicability of the model, only some ESs were considered in this study, and future research needs to consider important ESs in urbanized areas, such as cooling services and cultural services. The data used and its respective resolution can affect the ES assessment. More accurate data would facilitate the variability of ESs. Low-resolution data can lead to a lack of detail in mapping ESs. Although the resampling method used in this study makes the results smoother, it may change the original raster values. Therefore, more reliable and higher spatial resolution primary data needs to be collected for future studies. The use of urban land as an indicator of urbanization in this study is not sufficiently comprehensive, and urbanization has also brought great contributions to socioeconomic indicators such as population and the economy (Wang et al., 2022b). More urbanization indicators should be considered in the future. At the grid scale, this study only explored the relationship between ESs and urbanization/wetland changes from the perspective of the urban land/wetland ratio, while urbanization and wetland changes may also lead to fragmentation and connectivity changes in urban land and wetlands (Li et al., 2022). Therefore, future studies need to strengthen the impact of urban land/wetland fragmentation and connectivity processes on ESs. In addition, regression was used in this study to reveal the quantitative relationship between urbanization/wetland changes and ESs, but it could not reflect the causal relationship between them. Thus, future research needs to strengthen the exploration of influencing mechanisms. This study found that there may be a nonlinear relationship between ESs and urbanization/wetland changes, and the nonlinear relationship reflects the existence of a threshold (Ma et al., 2021c). The impact threshold value of urbanization/wetland changes on ESs needs to be further studied. Finally, ESs have a scale effect, and the relationship between urbanization/wetland changes and ESs at different scales needs to be clarified (Bai et al., 2020; Wang et al., 2022a).

5. Conclusion

It is important for urban land planning to explore the impacts of urbanization/wetland changes on ESs in different urbanization stages. This study evaluated the changes in four important ESs and revealed the relationship between urbanization/wetland changes and ESs in different urbanization stages. The results showed that HJH experienced slow urbanization, rapid urbanization, and moderate urbanization from 1990 to 2020. Wetland restoration mainly occurred in the rapid urbanization stage, while wetland loss occurred in the slow and moderate urbanization stages. CS and BC decreased in all urbanization stages, FM decreased in the slow and moderate urbanization stages and increased in the rapid urbanization stage, and WP increased in the slow and rapid urbanization stages and decreased in the moderate urbanization stage. Urbanization led to a decrease in FM, CS, and BC in all urbanization stages, while wetland restoration improved these ESs. The impact of urbanization and wetland restoration on ESs reached a maximum in the rapid urbanization stage. Wetland loss reduced FM, BC, and WP in all urbanization stages in the slow and rapid urbanization stages and decreased CS in the moderate urbanization stage. The positive effects of wetland restoration on FM in the rapid urbanization stage offset the negative effects of urbanization and wetland loss. Different urbanization and wetland changing processes have linear and nonlinear effects on ESs, which are related to LULC conversion, change size, and landscape fragmentation. Ecological control lines need to be set to limit urban sprawl. Wetland restoration is an effective way to improve multiple ESs in urbanization regions. This study can provide important information for the sustainable management of urban and wetland ecosystems.

CRediT authorship contribution statement

Xiaomian Zhang: Data curation, Investigation, Formal analysis, Validation, Methodology, Conceptualization, Visualization, Writing – original draft, Writing – review & editing. **Jun Wang:** Investigation, Formal analysis, Validation, Methodology, Visualization. **Chunlei Yue:** Supervision, Investigation, Writing – original draft, Writing – review & editing. **Shuai Ma:** Investigation, Conceptualization, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Luyao Hou:** Investigation, Formal analysis, Software, Validation. **Liang-Jie Wang:** Software, Supervision, Investigation, Writing – original draft, Writing – review & editing.

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.

Data availability

Data will be made available on request.

Acknowledgments

This study was supported by “Pioneer” and “Leading Goose” R&D Program of Zhejiang (2022C02038), Zhejiang Forestry Science and Technology Project (2022SY06), and Zhejiang Forestry Science and Technology Project (2021SY03).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2023.110382.

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