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Impact of Land Use Change on Vegetation Carbon Storage During Rapid Urbanization: A Case Study of Hangzhou, China

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Abstract: Land use changes have significant impacts on the carbon balance in an urban ecosystem. When there is rapid development in urbanizing regions, land use changes have a dramatic effect on vegetation carbon storage (VCS). This study investigates the impact of land use change on VCS in a period of rapid urbanization in Hangzhou, China. The results show that: 1) from 2000 to 2015, land use in Hangzhou underwent huge changes, mainly reflected in decrease in cropland and wetland and the increased settlement. More than 34.58% of the land was transformed, and the land use changes are primarily characterized by a significant decrease in cropland due to the occupation by settlement. 2) over the 15 years, changes in land use led to a decrease of 3.93×10^5 t of VCS in the urban ecosystem. The large-scale transformation of cropland and wetland, which have a comparatively high carbon density, into land for settlement exerted a negative impact on VCS. 3) The central city, which with the Circle-E/I/O mode, had the lowest comprehensive land use dynamic degree, leading to moderate land use change and an increase in VCS; Yuhang and Xiaoshan, which with Multicore-E/O/I mode and Fan-E/O/I modes, had a higher comprehensive land use dynamic degree, drastic changes in land use, and a decrease in VCS. This study proposes a reliable method of estimating changes in VCS, clarifies the relationship between land use change and VCS during rapid urbanization, and provides recommendations for sustainable urban development.

Keywords: land use change; vegetation carbon storage (VCS); urbanization; GAIN-LOSS method; Hangzhou, China

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1 Introduction

Carbon storage in the terrestrial ecosystem is one of the important components of global carbon storage and plays a vital role in mitigating climate change (Gao et al., 2013). Changes in terrestrial ecosystem carbon storage are often affected by natural disturbances and human activities. However, the impact of land use change caused by human activities is far greater than that caused by natural disturbances (Liu et al., 2014). According to the Intergovernmental Panel on Climate Change (IPCC), land use change currently contributes 1.5×10^9 t carbon emissions per year, making it one of the biggest sources for the increase of carbon in the atmosphere, second only to the combustion of fossil fuels (Wen et al., 2010). Changes of land use directly affect the carbon sequestration capacity of vegetation, soil, and other substances, leading to dynamic change in carbon storage in terrestrial ecosystems (Liu et al., 2010; Chuai et al., 2013). Due to the significant differences in terms

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of carbon density between types of land use (Cantarello et al., 2010; Chuai et al., 2013), changes of use will lead to an increase or decrease in carbon storage, and are key drivers of change in terrestrial ecosystem carbon storage (Chen et al., 2010; Song et al., 2014).

Urbanization has developed rapidly in recent decades, and the urban population has increased greatly. It has been estimated that over half the world's population now lives in urban areas, and this is expected to rise to 67.2% by 2050 (Davies et al., 2013; United Nations, 2012; Zhao et al., 2013). Increases in the urban population promote further urban expansion, which has been recognized as a highly significant human-induced disturbance and one of the main threats to the sustainability of natural resources (Zhang et al., 2012; Muñoz-Rojas et al., 2015; Adhikari et al., 2019). Urbanization has changed not only land use but also the structure and function of the urban ecosystem (Raciti et al., 2014; Liu et al., 2016; Vasenev et al., 2018).

Studies have shown that the land use changes associated with urbanization can affect carbon storage changes in urban ecosystems (Hutyra et al., 2011), change regional biogeochemical cycles (Pataki et al., 2006), and influence micrometeorology and regional climate (Zhou et al., 2011). Changes in environmental factors caused by urbanization (such as expansion of settlements, rising CO_2 concentrations, nitrogen deposition, the heat island effect, and artificial vegetation management) significantly impact the carbon pool of urban ecosystems (Daniel et al., 2013). Specifically, the expansion of settlements and the heat island effect lead to a decline in urban carbon storage (Pouyat et al., 2003; Pouyat et al., 2006), while an increase in CO_2 concentration, nitrogen deposition, and artificial vegetation management all serve to increase rates of carbon fixation of vegetation and carbon storage (Daniel et al., 2013; Zhang et al., 2014). Among the environmental changes caused by urbanization, land use change has the most significant impact on the carbon pool of urban ecosystems (Zhang et al., 2014), and in recent decades we have learned a great deal about the interactions between urbanization and ecosystem functions (Tao et al., 2015; Lai et al., 2016; Han et al., 2017).

Nonetheless, understanding the impact of land use change in urban ecosystems remains a challenge because of the complexity of the urban landscape in terms of spatial heterogeneity, human disturbance or management, and non-linear interactions among physical and ecological components (Zhang et al., 2012; Daniel et al., 2013; Zhang et al., 2014; Yan et al., 2017). Some empirical studies have directly extrapolated the carbon density of intensively studied cities to the regional or national scale. However, this kind of scaling up generates uncertainties, as it fails to take account of diversity and spatial heterogeneity. Similarly, the use of old empirical data to calculate urban carbon storage may not accurately reflect recent changes. At the same time, previous studies have shown that the impacts of land use change on ecosystem carbon storage mainly depend on ecosystem type and land use transfer type (Zhu et al., 2019), ignoring the huge impact of developments in the spatial mode of land. Thus, to achieve sustainable urban development, there is a need to update carbon storage survey data and to analyze the impact of land use change on vegetation carbon storage (VCS) from new perspectives.

Hangzhou, located in Southeast China, is typical of cities that have undergone rapid urbanization over recent decades. In 2001, in order to alleviate the problem of limited development caused by lack of space in Hangzhou, the government adjusted the administrative division, incorporating the cities of Xiaoshan and Yuhang into Hangzhou. This development strategy has accelerated the urbanization process and promoted the expansion of settlements, which will inevitably have a huge impact on land use. Therefore, we take Hangzhou as an example to explore the impact of land use change on VCS, using satellite data, field data, and the GAIN-LOSS method to reveal the mechanism of the impact. The objects of this study are: 1) to analyze land use changes in Hangzhou from 2000 to 2015; 2) to estimate VCS changes using the GAIN-LOSS method; and 3) to clarify the impact of land use change on VCS. The results have important implications for the development of land use and sustainable urban development policymaking in Hangzhou.

2 Data and Methods

2.1 Study area

The city of Hangzhou, located in Southeast China, is the capital of Zhejiang Province and a key region on the Yangtze River Delta Economic Belt (Fig. 1). It is among the areas with the highest level of economic development and the fastest process of urbanization (Xu et al., 2014). Before 2001, Hangzhou's main center of development was to the east of West Lake. However, because the administrative area was small and limited geographically by the Qiantang River, the city's development was restricted. In order to expand Hangzhou's development space and ensure its economic sustainability, the municipal government adjusted the administrative divisions. In 2001, the cities of Yuhang and Xiaoshan were incorporated into Hangzhou City as two districts, forming a new city region. This adjustment has accelerated the process of urbanization in the city, and there is no doubt that it will increase the speed of land use change.

2.2 Data sources

2.2.1 Satellite data

The land use data in this study are derived from Landsat 5 Thematic Mapper (TM) images from 2000, 2005 and 2010 and Landsat 8 Operational Land Imager (OLI) images from 2015. Satellite images were downloaded from Geospatial Data Cloud (http://www.gscloud.cn/) with a spatial resolution of 30 m. The single scene image covers the whole city, with an average cloud coverage of less than 1% and good image quality.

2.2.2 Field data

The VCS data were obtained from field surveys, conducted in September 2013, 2014, and 2015 on 105 sample plots. To ensure the reliability of plot selection, areas with vegetation coverage below 80% and areas difficult to measure in the field (such as green roof spaces) were excluded. The sample plots were laid out in advance on the images, and the size of each plot was 30 m × 30 m. All plots were positioned using GPS, and the resolution was the same as that used in the Landsat remote sensing images. For the plot survey, we took the southwest point as the starting coordinate, and used a wooden ruler on the living stand (thorax diameter ≥ 5 cm) in the plot, recording tree species, diameter at breast height (DBH), tree height, and other factors. We also measured the shrub area in the plot. Because there was little variation in the annual growth of surface vegetation biomass during the survey period, we chose the average annual growth as a substitute. The carbon density of inherent vegetation and the carbon density of new vegetation in each local category were obtained by calculating the three-phase reset sample survey data.

2.3 Methods

2.3.1 Extraction of information about land use change

The IPCC guidelines classify land as settlement, forest, cropland, grassland, wetland, and other land. Since there is no large area of grassland in the study area and the impact of the biomass carbon pool is small, grassland was not treated as a sub-carbon pool in this study. Although bodies of water are classified in the IPCC guidelines as other land, their large extent in Hangzhou justifies considering them as a land use type in parallel

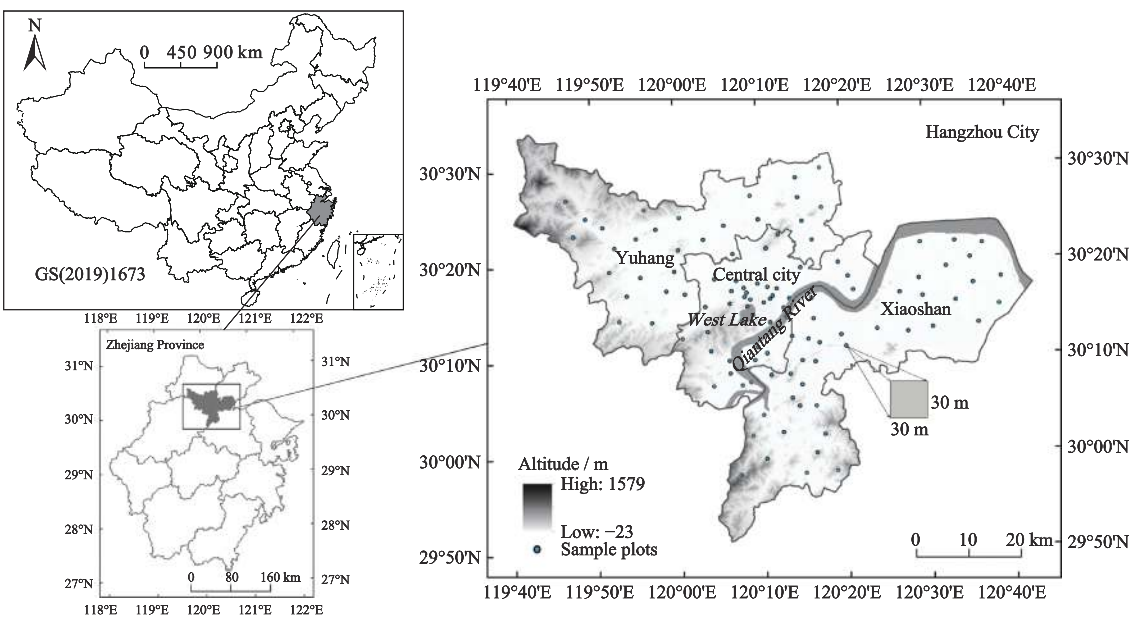

Fig. 1 Location of study area and sampling plots of VCS (vegetation carbon storage) data

with the other five. Therefore, in line with the research objectives, land use types in the Hangzhou were divided into five categories: settlement, forest, cropland, wetland, and water (Table 1). Satellite images were used to extract land use information. In order to reduce the influence of unfavorable factors on the images, geometric correction, radiometric calibration, atmospheric correction, and terrain correction processing were performed on the TM and OLI image data in the software ENVI. The supervised image classification method was employed with maximum likelihood classification.

2.3.2 Spatial mode of land use change

The spatial mode of land use change is represented here by land use expansion hotspot (Getis-Ord Gi^*) and land use expansion types. A land use expansion hotspot represents the degree of land use expansion in a region; the higher the hotspot value, the more drastic the change in land use. The types of land use extension include edge-expansion, infilling, and outlying, where infilling belongs to the compact development mode (Zhang et al., 2014). The expansion hotspots and expansion types were obtained using ArcGIS 10.2.

2.3.3 Dynamic degree of Land use

The dynamic degree of land use quantitatively describes the rate of land use change in a region, which facilitates the comparison of regional differences and the prediction of future trends. It includes single land use dynamic degree (K), which indicates the change in a particular land use type within a certain period, and comprehensive land use dynamic degree (LU), which reflects the overall change in land use. A high dynamic degree indicates a drastic change of land use (Yang et al., 2019). The formulas are as follows:

$$K = \frac{U_b - U_a}{U_a \times T} \times 100\% \quad (1)$$

$$LU = \left(\frac{\sum_{i=1}^{n} \Delta LU_{i-j}}{2\sum_{i=1}^{n} LU_i} \right) \times \frac{1}{T} \times 100\% \quad (2)$$

where U_b and U_a is land use type area at the end and the beginning of the study period; T is the study time; LU_i is initial land use type area; $\Delta LU_{i\text{-}j}$ is absolute value of land use type transformation area.

2.3.4 GAIN-LOSS method

The IPCC Guidelines state that the carbon cycle of terrestrial ecosystems is a carbon storage change caused by continuous processes (plant growth and decline) and discrete events (including disturbances such as land use change, harvesting, fire, and insect damage). The most commonly used estimation method on carbon storages change provided by the IPCC Guidelines is the GAIN-LOSS method, which requires the reduction of biomass carbon loss from biomass carbon increase to calculate changes in carbon storage. GAIN-LOSS method includes all the processes that cause VCS change in a carbon pool, can more effectively estimate VCS change caused by land use change. In this study, we used GAIN-LOSS methods to calculate changes in VCS. VCS is composed of two parts: aboveground and underground vegetation storage. Due to the unavailability of data, this research mainly focuses on aboveground vegetation storage, without considering the change of underground VCS. Studies of VCS in urban areas, mainly involves four types of land use: settlement, forest, cropland, and wetland, while the aboveground biomass of the water bodies is almost negligible. Therefore, the calculation model of VCS used in this paper is as follows:

$$\Delta C = \Delta C_{FL} + \Delta C_{CL} + \Delta C_{SL} + \Delta C_{WL} \quad (3)$$

where ΔC is the total carbon stock change, FL, CL, SL, and WL refer to forest land, cropland, settlements and wetlands, respectively.

Table 1 Classification of land use in Hangzhou, China

Categories	Categories definition
Settlement	It includes all developed land, including transport infrastructure and human settlements on any scale
Forest	Includes all land with woody vegetation that meets the threshold for defining national greenhouse gas inventories
Cropland	This includes agricultural land, agroforestry systems that contain paddy fields and vegetation structures below the threshold of woodland
Wetland	A lowland covered by an intermittent or permanent shallow layer of water. Including shallow lakes and ponds marked by emergent plants. Permanent bodies of water, such as rivers, reservoirs and deep lakes, are not included
Water	Including rivers, lakes, ponds, canals, *etc.*

The calculation model for VCS change for a specific land use type is as follows:

$$\Delta C = \Delta C_{B1} + \Delta C_{B2} \tag{4}$$

where ΔC refers to the total VCS change, ΔC_{B1} and ΔC_{B2} apply to areas maintained as a specific land use type and areas transformed to a new type of land use, respectively. They are calculated as:

$$\Delta C_{B1} = \Delta C_{G1} - \Delta C_L \tag{5}$$

$$\Delta C_{B2} = \Delta C_{G2} + \Delta C_T - \Delta C_L \tag{6}$$

where ΔC_{G1} is the increase of VCS caused by biomass growth in specific land without land use type transformation (t); ΔC_{G2} is the increase of VCS caused by biomass growth in the land use type where land use transformation occurs (t); ΔC_T is the change value of initial carbon storage in biomass after transformation to other land use types (t); ΔC_L is the reduction of VCS due to biomass loss (t), including wood cutting and green land pruning.

$$\Delta C_{G1} = A_i \times G_i \times CF \times T \tag{7}$$

$$\Delta C_{G2} = B_i \times G_i \times CF \times T \tag{8}$$

$$\Delta C_T = (X_i - Y_i) \times B_i \tag{9}$$

$$\Delta C_L = L_{\text{cutting}} + L_{\text{pruning}} \tag{10}$$

$$L_{\text{cutting}} = H \times BEF_R \times D \times CF + N \times F \times CF \tag{11}$$

$$L_{\text{pruning}} = \sum_{i=1}^{n} P \times S_n \tag{12}$$

where A_i, B_i are the area of land use type i without and with land use transformation, respectively (ha); G_i is the annual growth of vegetation biomass in land use type i (t/(ha·yr)); CF is conversion coefficient of biomass and carbon in vegetation (0.5 in this paper); T is interval of study period (yr); X_i is average carbon density of vegetation in land use type i after land transformation (t/ha); Y_i is average carbon density of vegetation in land use type i before land transformation (t/ha); L_{cutting} is carbon loss due to artificial wood cutting (t); H is annual wood cutting (m^3/yr); BEF_R is biomass expansion factor; D is basic wood density (t/m^3); N is annual bamboo cutting (strain/yr); F is bamboo biomass per plant (kg/strain); L_{pruning} is carbon loss due to artificial green land pruning (t); P is annual carbon loss due to pruning (t/(ha·yr)); S_n is green land area in year n (ha).

2.3.5 Parameter settings for the GAIN-LOSS method

Since the methods in the IPCC guidelines for estimating carbon storage changes focus on large-scale ranges such as climatic zone or continent, the specific parameters set by natural conditions, including natural belts and ecological regions, can not be applied directly to a city. For example, the IPCC method yields a carbon density of 180 t/ha (Penman et al., 2003), which is quite different from the actual situation in Hangzhou. Therefore, for the calculation of VCS change, some parameters of the VCS change model were based on the default values provided in the fourth volume of the 2006 IPCC Guidelines for National Greenhouse Gas Emission Inventory. The remaining parameters were sampled and referenced from the Hangzhou Statistical Yearbook (http://www.hangzhou.gov.cn/) and Guidelines for the compilation of greenhouse gas Inventories of Zhejiang Province (http://www.tanpaifang.com/).

The average vegetation carbon density before transformation, the average vegetation carbon density after transformation, and the average annual growth in surface vegetation biomass in the settlement, forest, cropland, and wetland of the study area were calculated from the existing plot data. The values are reported in Table 2.

When calculating the change of VCS caused by biomass loss (ΔC), it mainly considers harvesting, fire and human disturbance, among others. It needs to be defined and parameterized according to the specific conditions of the study area. According to the enquiry data, the number of forest fires in the study area is small, and the interference to the study area is negligible. Therefore, this study mainly considers the impact of human disturbance on the biomass carbon pool in the study area, including artificial wood cutting and green land pruning. Among them, the wood cutting data (H) were

Table 2 Dynamic change model parameters of VCS

Land use type	Y_i / (t/ha)	X_i / (t/ha)	G_i / (t/(ha·yr))
Forest	108	82	4.8
Wetland	56	36	3.8
Cropland	32	24	2.3
Settlement	15	11	2.0

Notes: The VCS related to settlement are mainly obtained by calculating the parks, green spaces and small urban forests within the settlement regions. X_i is average carbon density of vegetation in land use type i after land transformed; Y_i is average carbon density of vegetation in land use type i before land transformation; G_i is the annual growth of vegetation biomass in land use type i

8.12×10^4 m^3 (2000–2005), 6.72×10^4 m^3 (2005–2010) and 12.71×10^4 m^3 (2010–2015), and the bamboo cutting data (N) were 26.26 million strain (2000–2005), 41.04 million strain (2005–2010) and 77.93 million strain (2010–2015) (Hangzhou Statistical Yearbook). Biomass Expansion Factor (BEF_R) and Basic Wood Density (D) were 1.421 and 0.406 t/m^3, respectively by querying the Guidelines for the Compilation of Greenhouse Gas Inventories of Zhejiang Province (http://www.tanpaifang.com/). The bamboo biomass per plant (F) was 22.5 kg/strain, which was taken as the average value of Zhejiang Province. From 2000 to 2015, the total area of green land in Hangzhou were respectively 41 616 ha (2000–2005), 67 321 ha (2005–2010) and 111 055 ha (2010–2015) (Hangzhou Statistical Yearbook). P was based on the Wen's (Wen, 2010) calculation results of the urban green land vegetation pruning in Hangzhou 5.17 t/(ha·yr). As the cutting of woods and bamboos will reduce the carbon storage of forest, wetlands, and cropland, pruning is the main source of reduction of carbon stocks in settlement. Therefore, in the calculation of biomass loss, the carbon loss of vegetation is calculated according to different types of interference due to different interference reasons.

3 Results

3.1 Land use change

3.1.1 Changes of land use type and land use dynamic degree

As a result of rapid urbanization, land use in Hangzhou changed dramatically during the 15 years, mainly reflected in decreases in cropland and wetland and an increase in settlement, despite comparatively little change in forest and water (Fig. 2). As Table 3 shows, cropland decreased by 70 253.38 ha, with a rate of decrease of 43.57%. The decrease in wetland area was 13 230.48 ha (a rate of 33.92%). The change in settlement was the most remarkable, with an increase of 93 228.82 ha (a growth rate of 252.71%). As the single land use dynamic degree shows, the changes in settlement, cropland, and wetland were the greatest; the change in forest was moderate and the change in water unremarkable.

In the first period (2000–2005), the greatest change was in settlement (25.06%), followed by wetland (–10.47%) and cropland (–2.17%). However, from 2005 to 2010, the settlement and wetland areas underwent a smaller change, with dynamic degrees of 7.21% and 6.12%, respectively. The single dynamic degree of land use was lower than in the previous period, but the single

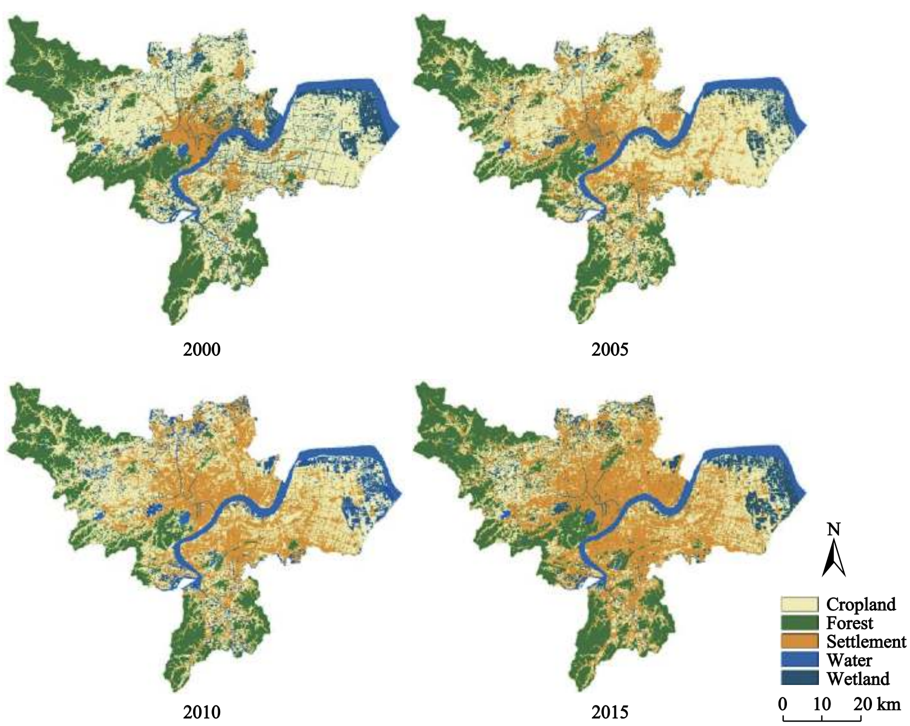

Fig. 2 Distribution of land use types in Hangzhou of China, 2000–2015

Table 3 Land use area change and single land use dynamic degrees in Hangzhou of China, 2000–2015

Land use type	2000		2005			2010			2015		
	Area / ha	Proportion/ %	Area / ha	Proportion / %	K / %	Area / ha	Proportion / %	K / %	Area / ha	Proportion / %	K / %
Cropland	161242.53	48.09	143768.20	42.88	–2.17	114153.39	34.05	–4.12	90989.15	27.14	–4.06
Forest	79140.39	23.61	71181.47	21.23	–2.01	66527.01	19.84	–1.31	70960.41	21.16	1.33
Settlement	36891.96	11.63	83120.73	24.79	25.06	113083.50	33.73	7.21	130120.78	38.81	3.01
Water	18983.13	5.66	18615.66	5.56	–0.39	17233.11	5.14	–1.49	17418.15	5.20	0.21
Wetland	39006.24	11.01	18578.19	5.54	–10.47	24267.24	7.24	6.12	25775.76	7.69	1.24

Notes: *K* is single land use dynamic degrees. '–' means that over a period of time the area of land has been reduced

dynamic degree for cropland was higher (–4.12%), indicating that cropland was changing more dramatically. From 2010 to 2015, for all other types of land, with the exception of forest, the single dynamic degree was lower than the previous period. Overall, from 2000 to 2015, settlement, cropland, and wetland saw the largest changes, but the rate of change continued to decrease, indicating a deceleration from drastic change of land use to moderate change of land use.

3.1.2 Changes of land use transfer type

We selected major land use transfer types to determine their proportion of the transfer area: from wetland to settlement, wetland to cropland, settlement to cropland, forest to cropland, and cropland to settlement. Together these accounted for more than 68.57% of the total area of transferred land (Fig. 3). From 2000 to 2015, transformations between land types were frequent, transfer from cropland to settlement was the main body of land use transfer type, with accounting for more than 39.3% of the total. From 2000 to 2005, wetland to cropland and wetland to settlement were the second and third largest land transfer types (15% and 13.21%, respectively), but after 2005 their proportion of the total gradually declined. The proportion of forest to cropland remained stable, whereas the proportion of settlement to cropland increased gradually over the 15 years, from 4.88% in 2005 to 10.36% in 2010 and 11.16% in 2015. This phenomenon was caused mainly by the reclamation of rural homestead under the guidance of land use planning, in line with the measures taken by the Hangzhou government to balance the demands of cropland occupation and compensation.

3.1.3 Land use change spatial mode

During the period under study, land use expansion trends in central city, Yuhang, and Xiaoshan were quite different (Fig. 4). From 2000 to 2015, the distribution of land use expansion hotspot in the central city was mainly distributed in the outer regions, especially in northeast part (Fig. 4a4), and was characterized by edge-expansion (more than 68%) and infilling (more than 16%). The proportion of outlying was relatively low (less than 10%), whereas the proportion of infilling rose (reaching 16.23%, 21.95%, and 22.92% in the three periods). In Yuhang, where we found characteristics of multicore distribution, the two main hotspots were found in the northeast and the southwest, close to the boundary of central city (Fig. 4b4), and the land use expansion consisted mainly of edge-expansion (more than 50%) and outlying (more than 19%). The distribution of the land use expansion hotspot in Xiaoshan was different from that of Yuhang and central city, spreading outward in one direction from the central region of Xiaoshan (Fig. 4c4) and characterized by edge-expansion (more than 66%) and outlying (more than 20%). Comparison of the land use expansion types shows that edge-expansion accounted for the largest proportion in

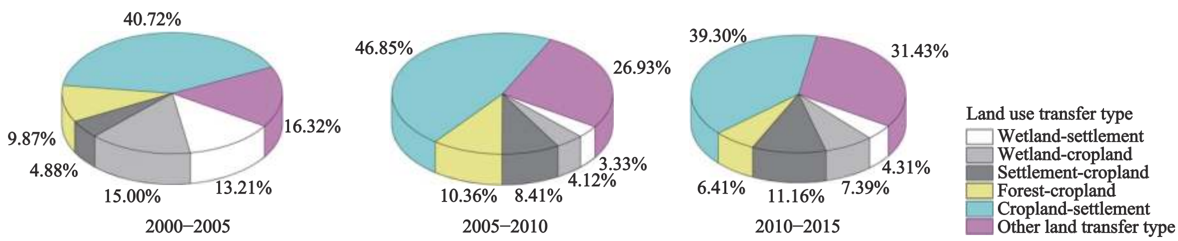

Fig. 3 Proportion of land use transfer types in Hangzhou of China, 2000–2015

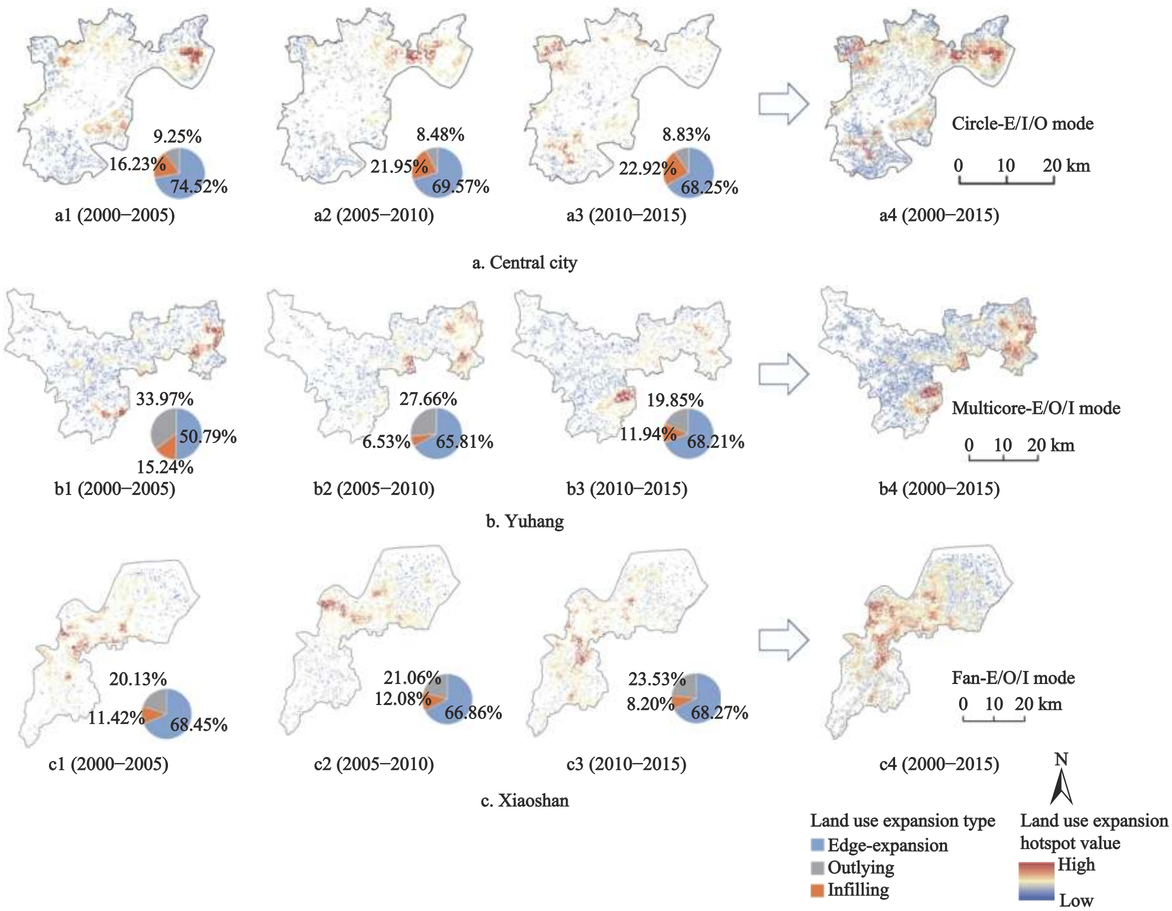

Fig. 4 Spatial mode of land use change in different regions in Hangzhou of China, 2000–2015. (a) Central city; (b) Yuhang; (c) Xiaoshan. E = edge-expansion, O = outlying (O), and I = infilling. E/I/O denotes relative proportions in which edge-expansion > infilling > outlying; E/O/I denotes edge-expansion > outlying > infilling

all three regions and was the main type in Hangzhou. However, the proportion of infilling in central city was relatively high and continued to rise, while the proportion of outlying in Yuhang and Xiaoshan was far higher than in the central city. Thus, the land use expansion type in the central city was dominated by edge-expansion with prominent infilling, whereas Yuhang and Xiaoshan were dominated by edge-expansion with prominent outlying. The spatial modes of land use change are shown as Circle-E/I/O mode for central city, Multicore-E/O/I mode for Yuhang, and Fan-E/O/I mode for Xiaoshan.

3.2 The changes of VCS

Our results indicate that in Hangzhou from 2000 to 2015, land use changes caused VCS to decrease by -3.93×10^5 t, demonstrating the carbon sequestration capacity of urban ecosystem is declining. Over the three study periods, the decreases in VCS were -9.56×10^4 t, -1.27×10^5 t, and -1.70×10^5 t, respectively, with the highest decrease between 2010 and 2015 (Table 4). In terms of VCS changes associated with different types of land use, we found that over the 15 years, cropland and wetlands lost VCS, while forests and settlements gained VCS. The year by year increases in forests and settlements played an important role in terms of carbon sinks. However, the VCS of cropland and wetlands are losing VCS because of land use change. It can be deduced that the decrease of VCS in cropland and wetland is the main reason for the decrease of VCS in Hangzhou overall.

The change in VCS in Hangzhou was notably uneven in spatial distribution (Fig. 5). From 2000 to 2005, the regions with increased VCS were concentrated in the central city around West Lake, west of Yuhang, and south of Xiaoshan. The spatial distribution of the region of increased VCS is consistent with the distribution of forest and wetland in Hangzhou. The regions with de-

Table 4 Changes of VCS with different land use types in Hangzhou of China, 2000–2015 (t)

Period	Cropland	Forest	Settlement	Wetland	Total
2000–2005	–91206.70	114834.35	48160.86	–167451.10	–95662.59
2005–2010	–168245.56	127549.61	55247.84	–141514.35	–126962.46
2010–2015	–237442.65	135844.58	68462.54	–137567.52	–170703.05
2000–2015	–496894.91	378228.54	171871.24	–446532.97	–393328.10

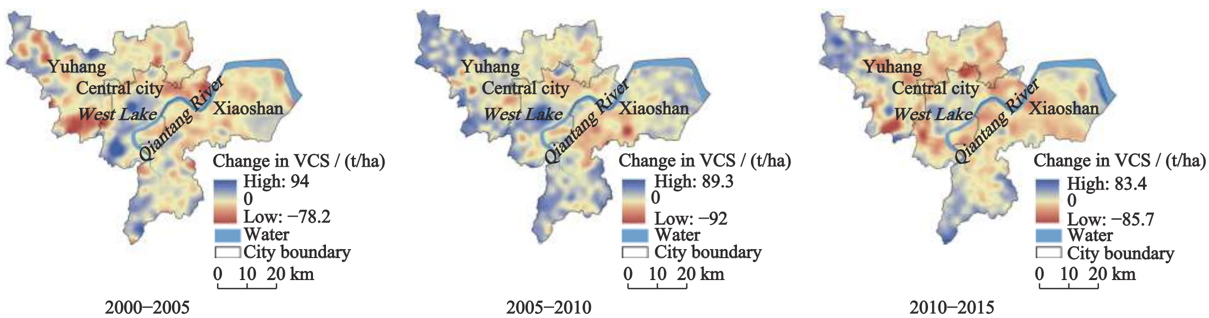

Fig. 5 Spatial distribution of VCS changes in Hangzhou of China, 2000–2015

creased VCS were concentrated in the east of Yuhang and west of Xiaoshan, close to the city boundary with the central city. The distribution of VCS changes from 2005 to 2010 was similar to that from 2000 to 2005, but with the region of decrease spreading more obviously in Hangzhou, especially to the south of the Qiantang River. The region around the West Lake in central city continued to show an increase in VCS, but the region of increase was more fragmented and smaller than before. From 2010 to 2015, the distribution of the change in VCS was similar to the previous period, with the reduction of VCS expanding outward from the central city. On the whole, the regions around West Lake, to the west of Yuhang, and to the south of Xiaoshan were the main regions of VCS increase; the regions of VCS decreases were more widely distributed in Hangzhou, and the expansion trend was clear.

4 Discussion

4.1 Mechanism of the influence of land use change on VCS change

At present, the influence of human activities on the carbon cycle of terrestrial ecosystems is stronger than before (Lu et al., 2016), the region of land use change caused by human activities is often the hotspot distribution region of VCS change, and here the impact of land use change on VCS change was reflected in two main ways. First, from the perspective of the whole region of Hangzhou, transformations between land types with different vegetation carbon densities were the main reason for the changes in VCS in Hangzhou. Second, from the perspective of the local region of Hangzhou (the central city, Yuhang, and Xiaoshan), different land use change spatial mode can not only changes the comprehensive land use dynamic degree, but also changes the properties of aboveground vegetation, thus changing the regional VCS and carbon balance (Stumpf et al., 2018). Therefore, this study has established that land use change has an impact on VCS change through transformations between land use types with different vegetation carbon density and differences in the spatial mode of land use change (Fig. 6).

4.2 Impact of land use transfer types on VCS change

The impact of land use change on VCS is mainly reflected in an increase/loss of carbon storage caused by transformation of land use type. According to our analysis of land use transfer types (Table 5), we found that from 2000 to 2015 the transformation of cropland reduced VCS by 9.60×10^5 t, mainly because a large area of cropland was transferred to settlement. Although the transformation of cropland to forest and wetland led to an increase in VCS, the area transferred to forest and wetland was smaller than the area transferred to settlement, so the impact of cropland transformation on VCS was negative overall. The transformation of forest reduced VCS by -1.18×10^6 t, making it the land use type

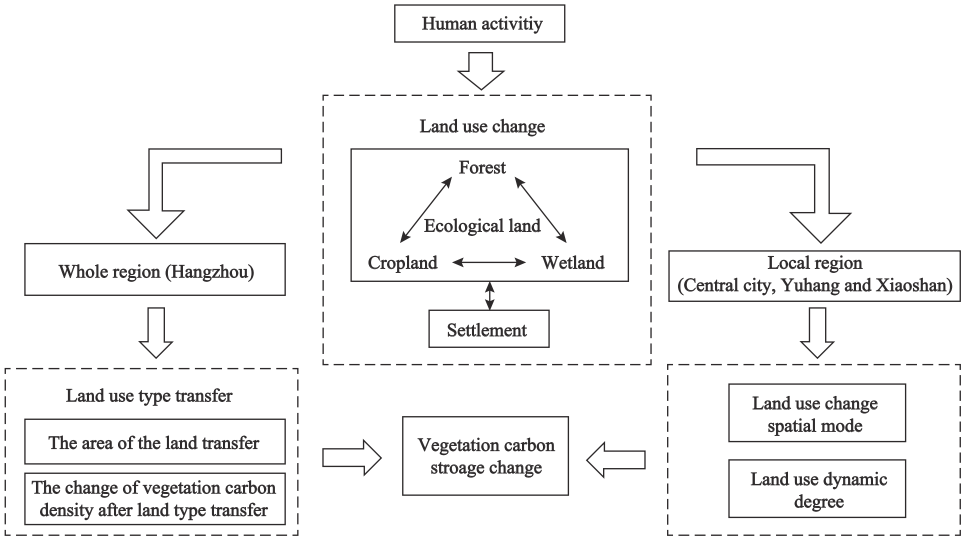

Fig. 6 Mechanism of the influence of land use change on VCS change

Table 5 The change of VCS caused by the transformation between different land use types in Hangzhou of China, 2000–2015

Land usetransfer type	Cropland	Forest	Settlement	Wetland	Total
Cropland	–	4568.76 (246763.85)	76137.75 (–1294364.48)	6754.48 (88268.20)	87460.99 (–959332.43)
Forest	7577.37 (–624639.67)	–	5553.54 (–538 230.85)	6485.25 (–16630.03)	19616.16 (–1179500.55)
Settlement	8529.35 (43560.36)	842.31 (32024.40)	–	1145.67 (15156.70)	10517.33 (90741.46)
Wetland	3985.47 (–261676.73)	248.26 (13243.45)	6957.54 (–848626.63)	–	11191.27 (–1097059.91)

Notes: The data not in brackets represent the area of land use transfer (unit: ha), and the data in brackets represent changes in VCS caused by land use type transformation (unit: t); '–' represents the reduction in VCS

with the largest loss of VCS. Although the area transformed from forest was smaller than the area transformed from cropland, forest plays an important role in terms of carbon sinks because it has the highest carbon density. Therefore, the transformation of forest leads to a decrease in VCS, which is not conducive to the formation of carbon sinks. In addition, the transformation of settlement increased VCS by 9.07×10^4 t, mainly because settlement is the land type with the lowest vegetation carbon density, which increases VCS when it is converted to other types with high carbon density. The transformation of wetlands reduced VCS by 1.10×10^6 t, mainly because large areas of wetland were transformed into settlement and cropland.

Our results indicate that the transformation of settlement in Hangzhou was conducive to an increase in VCS, while the transformation of forest, cropland, and wetland led to a decrease in VCS. Our analysis of the relationship between VCS and land use change shows that the transfer of other land types to ecological land promoted VCS, perhaps because ecological land such as forest and wetland has high a vegetation carbon density. When land use shifts to a type with a higher carbon density, an increase in carbon storage occurs, and this is conducive to the formation of carbon sinks. The occupation of cropland, forest, and wetland by settlement will bring about obvious carbon emission effects, which is consistent with the results of previous research (Lin et al., 2015; Wu et al., 2016). After the adjustment of the administrative division of Hangzhou, rapid economic development led to rapid urbanization, promoted the expansion of settlement, and transformed a large amount of land of different types into settlement. In urbanizing regions, the amount of vegetation is typically greatly reduced and replaced with impervious surfaces, resulting in both a loss of VCS and a reduction in the terrestrial uptake potential.

It should be noted that the vegetation carbon density of cropland is the lowest of all types of ecological land; the VCS loss per unit of area caused by cropland transfer into settlement is the lowest of all transfer types and has the least negative impact on an urban ecosystem. However, when a large area of cropland is transferred into settlement, there is a substantial loss of VCS, which causes great disturbance to the carbon balance in the urban ecosystem. To address conflicts between urban expansion and food production, Hangzhou has proposed a balance between occupation and compensation for cropland projects, ensuring that compensated land and occupied land are of equal quality and quantity (Wang et al., 2019). Thus, the transformation of settlement into cropland has to some extent alleviated the loss of VCS in Hangzhou.

4.3 Impact of land use change spatial mode on VCS change

After municipal government of Hangzhou adjusted the administrative divisions in 2001, the scale of development in Hangzhou has been expanding with rapid population growth and urban sprawl. Under this background, the central city, Yuhang and Xiaoshan have three different land use change spatial modes respectively. The analysis in Fig. 4 shows that the spatial mode of land use change in central city, Yuhang, and Xiaoshan have different characteristics. Therefore, to clarify the impact of changes on the VCS, we explored its relationship with comprehensive land use dynamic degree and VCS change.

Comparison of the land use change spatial mode and comprehensive dynamic degree in the three regions (Fig. 7) showed that the central city (Circle-E/I/O mode) had the lowest comprehensive land use dynamic degree (less than 3.67%). Yuhang (Multicore-E/O/I mode) had the highest (over 4.87%), and Xiaoshan (Fan-E/O/I mode) was slightly lower (over 4.52%). This indicates that the land use change in Yuhang was the most dramatic, followed by Xiaoshan and then the central city. In terms of changes in VCS, the central city had the lowest comprehensive land use dynamic degree, with increases in VCS over the 15 years of 1.05×10^5 t, 1.08×10^5 t, and 1.21×10^5 t, respectively. While the comprehensive land use dynamic degree of Yuhang and Xiaoshan was higher than that of the central city, VCS decreased over the 15 years (4.28×10^5 t in Yuhang and 3.00×10^5 t in Xiaoshan). Yuhang had a higher comprehensive land use dynamic degree and greater loss of VCS than Xiaoshan (Fig. 7a). The main reason for these differences is that the central city, as the most economically developed and densely populated region in Hangzhou, had entered the later stages of urbanization and was already facing a shortage of land resources and cropland protection. Accordingly, it had adopted the Circle-E/I/O mode, which has a higher proportion of infilling, belongs to the compact development mode, can improves utilization efficiency, and reduces occupation of ecological land. With relatively low levels of large-scale human disturbance, the carbon density of vegetation in the central city tended to rise, making it a carbon sink. It is worth noting that although central city with settlement as the main type of land have been regarded as a significant source of carbon, vegetation in settlements, including urban green spaces, parks, and small areas of urban forest, can play an important role in carbon sequestration.

In Yuhang and Xiaoshan, the main areas of ongoing urbanization in Hangzhou, transfer of cropland to settlement was the main type of transformation. With the development of technology, the Qiantang River was no

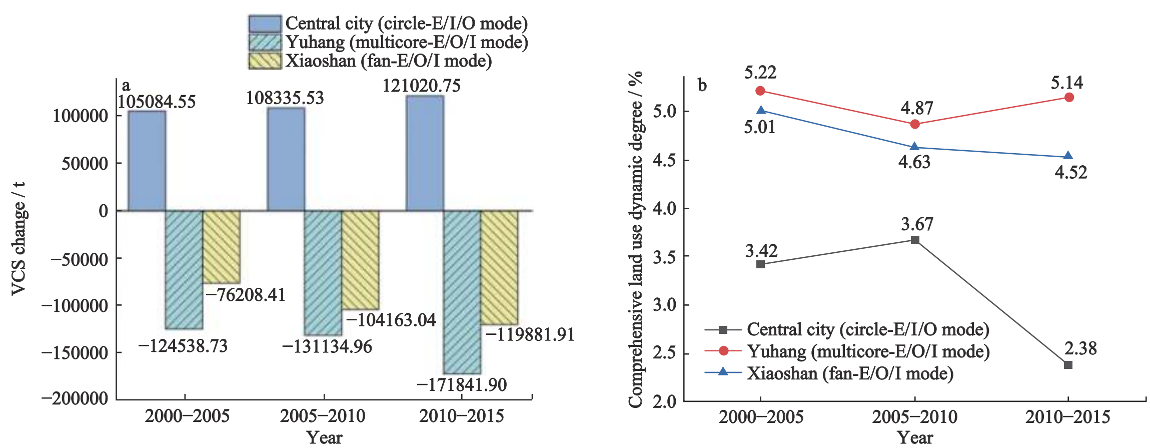

Fig. 7 VCS change (a) and the comprehensive land use dynamic degree (b) under different land use change spatial mode in Hangzhou of China, 2000–2015

longer a geographical barrier, and large numbers of people and industries had migrated from the central city to Yuhang and Xiaoshan, resulting in drastic changes in land use there. These regions choice of the outlying mode reflects the fact that they were in the early stages of urbanization and had more abundant land resources than the central city. Thus, the transformation of large amounts of cropland, wetland, and forest to settlement caused a reduction in VCS. This indicates that in the Circle-E/I/O mode, the comprehensive land use dynamic degree is lower, land use change is more moderate, and VCS tends to increase. In the Multicore-E/O/I and Fan-E/I/O modes, the comprehensive land use dynamic degree is higher, land use change is more drastic, and VCS tends to decrease. Moreover, it should be noted that the Multicore-E/O/I mode in Yuhang leads to bigger changes in land use and higher speed of land use than the Fan-E/O/I mode in Xiaoshan, which is more likely to cause the reduction of VCS. This phenomenon also reminds us that when choosing the multicore urban development mode, more attention should be pay to the coordination between urban development and ecological environment, limit the scale and quantity of urban expansion, and reduce the occupation on ecological land. On the whole, these results prove that different modes of land use change have different effects on the dynamic degree of land use change; at higher dynamic degrees, VCS tends to decrease.

5 Conclusions

Taking Hangzhou of China as an example, and using the GAIN-LOSS method, this paper estimated the impact of land use change on VCS and identified the main reasons for changes in VCS. It also explored the dynamic change in VCS for different spatial modes of land use, thereby developing a new perspective for understanding the relationship between land use change and VCS. The results have implications for urban managers seeking to optimize land transfer and modes of land use for healthy and sustainable urban development.

During rapid urbanization, land use in Hangzhou underwent a drastic change. The transformation of large amounts of cropland and other ecological land into settlement resulted in a reduction in surface vegetation carbon density and a decrease in VCS, which is not conducive to the carbon balance of the urban ecosystem. By comparing three regions with different spatial modes of land use, we established that the central city, in the Circle-E/I/O mode, had the lowest comprehensive land use dynamic degree, leading to moderate land use change and increasing VCS. Yuhang and Xiaoshan, in the Multicore-E/O/I and Fan-E/O/I modes, had a higher comprehensive land use dynamic degree, drastic land use change, and continuous reduction in VCS. The decrease of VCS in Yuhang and Xiaoshan played a decisive role in the decrease of VCS in Hangzhou overall.

The overall effects of urbanization were determined by the balance between the carbon loss during land transformation and the amount of carbon accumulated in urban ecosystems after urbanization. By taking positive actions and giving enough time, urban ecosystems will gradually compensate for or exceed the carbon loss during land transformation. Given the irreversible nature of urbanization, and a significant impact of land use change on regional carbon balance, the Hangzhou City should be adopt 'smart growth' mode, by combining the urban land use function, limiting urban growth boundary, improving land use efficiency and protecting the ecological land, to solve the social economy and resource environment problems, and reduce the negative impact of land use change on urban ecosystem. In central city, policy makers should choose the most compact mode of urban development consistent with meeting the demands of urban expansion, the extent of the urban area should be controlled, and the level of intensive utilization of settlement land should be improved by exploiting more fully the potential of existing settlement land. These measures will reduce the occupation of ecological land and maintain the surface vegetation coverage. For areas like Yuhang and Xiaoshan, which have lost large amounts of cropland, greater efforts must be made to balance the management of occupation and compensation. Extending green coverage on settlement land and strengthening the protection of urban forests will enhance VCS.

In this study, carbon density data were obtained from a combination of field measurements and existing research. This is in contrast to previous studies of urban carbon storage, most of which used carbon density data at the regional or national levels, leading to inaccurate results. Thus, the carbon density data acquisition in the field survey of this study will help to improve the accuracy of VCS results for urban ecosystems. At the same time, in the future study, it is not only necessary to strengthen the simulation on urban expansion, moreover, other ecosystem services, such as water conservation, soil erosion, habitat quality and so on, should be quantitatively studied to explore the impact of land use change on ecosystem services, to provide a more scientific reference basis for economic and ecological environment coordinate sustainable development for policymaking in Hangzhou.

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