Quantifying the indirect effects of urbanization on urban vegetation carbon uptake in the megacity of Shanghai, China

Shuyun Wei, Qiuji Chen, Wanben Wu and Jun Ma

1 Xi’an University of Science and Technology, Xi’an 710054, People’s Republic of China
2 Ministry of Education Key Laboratory for Biodiversity Science and Ecological Engineering, National Observations and Research Station for Wetland Ecosystems of the Yangtze Estuary, School of Life Sciences, Fudan University, #2005 Songhu Road, Shanghai 200438, People’s Republic of China
* Author to whom any correspondence should be addressed.
E-mail: ma_jun@fudan.edu.cn

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Abstract

Urbanization causes the expansion of urban land and changes to urban environments, both of which have significant impacts on the carbon uptake of urban vegetation. Although previous studies have proposed that the impact of the changes in the environmental conditions of vegetation carbon uptake by urban expansion are generally indirect, the processes of this impact are still unclear. In this study, we quantified the indirect effects of urbanization on urban vegetation carbon uptake for unchanged vegetation areas. We extracted unchanged vegetation areas based on multisource remote sensing data from the Google Earth Engine cloud computing platform. The influence of urbanization on vegetation carbon uptake and urban environmental factors in 2004, 2010, and 2016 along with the urban−rural gradient was calculated. In addition, we investigated the relative contribution of urban environmental factors to vegetation carbon uptake to study the relationship between them using a boosted regression tree method. The results showed that urbanization promoted vegetation carbon uptake, which varied with different years in Shanghai. Besides, the promoting effect of urbanization on the carbon uptake of vegetation was mainly due to the increase in temperature and the fragmentation of vegetation landscape patterns in Shanghai. The changes of soil moisture and radiation had little effect on the vegetation carbon uptake. Among the influencing factors, the relative contribution of the vegetation landscape pattern to vegetation carbon uptake was about 85%. Considering the crucial role of landscape patterns in the carbon uptake of vegetation, urban managers should consider reducing the negative influence of urbanization on vegetation through landscape design, which will further promote the sustainable development of urban ecology.

1. Introduction

China has experienced rapid urbanization in the past few decades, at a rate much faster than most countries (Kuang et al 2014, Zhao et al 2015a, 2015b, Zeng et al 2016). Meanwhile, urban land expansion is altering the regional climate, atmospheric environment, and so on (Gu et al 2011, Zhang et al 2014). For example, the effect of the heat island effect caused by the expansion of impervious surfaces in urban spaces has been studied extensively in recent years (Zheng et al 2015a, Hu et al 2017, Monteiro et al 2021). In addition, human activities, including the management of the environment and vegetation landscape pattern, have caused changes to the urban environment and ecosystem (Seto et al 2012, Zhang et al 2014, Qiu et al 2020, Wang et al 2020). The widely used indicator for reflecting these changes is vegetation carbon uptake, which is closely associated with the urban vegetation growth and the surrounding environment (Xia et al 2015, Cui et al 2017, Ma et al 2019, Zhong et al 2019). Urban vegetation provides plentiful ecosystem
services such as eliminating air pollution, reducing noise, and mitigating the urban heat island effect. Therefore, accurately quantifying the impact of urbanization on vegetation carbon uptake can help urban managers to improve urban ecosystem services (Lo and Jim 2010, Cohen et al 2014, Chen 2015, Zhou et al 2017b, 2019).

Urbanization is proven to have both direct and indirect effects on vegetation growth and carbon uptake (Zhao et al 2016, Guan et al 2019, Zhong et al 2019). On the one hand, the expansion of urban land directly leads to partial vegetation loss, resulting in the reduction of the carbon uptake capacity per unit area (Zhou et al 2015b, Liu et al 2018, Nuarsa et al 2018, Ma et al 2019). On the other hand, urban land expansion transforms urban environments and reshapes the spatial patterns of urban vegetation, which causes a further indirect impact on vegetation carbon uptake (Kaye et al 2005, Shen et al 2008, Briber et al 2015, Callapietra et al 2015, Ren et al 2019, Sun et al 2019, Yang et al 2019). For instance, Gregg et al (2003) revealed that vegetation growth caused a larger increase in urban compared to rural areas. Zhao et al (2016) proposed a new conceptual framework to quantify the indirect impact of urbanization on vegetation and found that the change of the urban environment promoted vegetation growth across 32 typical urban areas in China. Urban impervious surface expansion leads to a reduction in soil moisture, which decreases the carbon uptake capacity of vegetation (Quigley 2004). On the contrary, urbanization is also accompanied by human management activities (for example, irrigation, fertilization, etc) and heat island effects on vegetation, which makes urban environments more conducive to vegetation growth, thus promoting vegetation carbon uptake (Zhou et al 2014a, 2016, 2019, Qian et al 2019).

However, it remains difficult to differentiate the relative contributions of varied environmental variables to carbon uptake responses. Therefore, it is necessary to investigate the response of vegetation carbon uptake to environmental variables, which can help us to understand the impact of urbanization on the growth of vegetation better.

Generally, vegetation growth is closely related to environmental conditions concerning light, water, temperature, and landscape patterns (Zhang et al 2017a, Zhou et al 2017a, Wang et al 2019). There are a few studies that investigate the effects of various environmental factors on vegetation (Ziska et al 2004, Searle et al 2012). For example, based on the urban–rural gradient, Ziska et al (2004) explored the relationship between environmental factors and plant productivity by selecting samples. Sun et al (2019) reported that the change of aboveground carbon storage in cities was closely related to landscape structure. However, most studies observing the indirect effects of urbanization on vegetation by the urban–rural gradient have only been extended for one year. Considering that the areas that are not influenced by the transformation of urban vegetation areas under urbanization can better reflect the indirect effects of urbanization on vegetation, the unchanged vegetation areas provide an efficient space to explore the interannual indirect effects of urbanization on vegetation carbon uptake.

In this study, Shanghai was selected as the study area, which is a metropolis that has witnessed rapid urbanization, making this city appropriate for the assessment of the impacts of urbanization on vegetation. We focused on the unchanged vegetation areas during 2004–2016 to quantify the indirect impacts of urbanization on vegetation carbon uptake capacity, represented by gross primary productivity (GPP). The analysis of variations of environmental factors and vegetation carbon uptake was conducted based on an urban–rural gradient at different distances from the downtown area to quantify the indirect effects of urbanization on urban vegetation carbon uptake. The relationships between water, temperature, light, and human activities caused by urbanization and vegetation carbon uptake changes were investigated to determine the quantity of indirect influence. The main objects of this study were to (1) explore the interannual changes of the indirect impact on vegetation carbon uptake during the urbanization process and the regularity of the change of vegetation carbon uptake and major environmental factors on the urban–rural gradient, and (2) analyze the direct relationship between major environmental factors caused by urbanization and vegetation carbon uptake. This study can help us to gain a better understanding of the impact of urbanization on vegetation growth and provide a reasonable approach for urban vegetation management.

2. Materials and methods
2.1. Study area
Shanghai, a megacity in eastern China (120°52′—122°12′E, 30°40′—31°53′N) covering an area of about 6340 km², is part of the alluvial plain of the Yangtze River Delta, with an average elevation of about 4 m. Shanghai has a subtropical monsoon climate, with four distinct seasons and abundant sunshine and rainfall (figure 1(a)). The mean annual temperature in Shanghai is 17.61 °C, the total yearly precipitation is about 1308.15 mm, and the annual evaporation is 867.25 mm. Shanghai has witnessed significant urbanization over the past several decades. In particular, since the beginning of the 21st century, the population in Shanghai has increased steadily, from 1.6 million in 2000 to 24.2 million in 2016 (Shanghai Statistical Bureau 2017). Meanwhile, industrial zones and functional areas have become dramatically prominent due to the demand for land resources in the central urban area, propelled by the utilitarian housing policy and the real estate
industry since 1998 (Zhang and Zhou 2011), which jointly led to an increase in the impervious surface area. The impervious surface in Shanghai also dramatically increased by 95%, from 1587.64 km$^2$ in 2000–3097.83 km$^2$ in 2016, and the newest generated impervious surface was converted from urban vegetation, including forest land, grassland, and cropland. Of these, the amount of cropland converted into the impervious surface area was the highest (Zhang et al 2011). The development of urbanization in Shanghai can be divided into three stages (namely, 2000–2004, 2004–2013, and 2013–2016) according to the development degree of the impervious surface. The impervious surface of Shanghai was still in the stage of obvious expansion during 2004–2013, while the expansion of the impervious surface slowed down during 2013–2016 (Zhong et al 2019). In addition, the development of urbanization

Figure 1. (a) The location of Shanghai in the Yangtze River delta, with the distribution of unchanged vegetation in 2004–2016 and buffer zones in the unchanged vegetation areas in Shanghai. The land use and of Shanghai in (b) 2004, (c) 2010, and (d) 2016.
in Shanghai has damaged the ecological environment; therefore, urban managers have become increasingly aware of the importance of the ecological environment. Shanghai’s Five-Year Plans and environment protection policies provided more favorable growth conditions for urban green space to create a better urban environment in the late stage of urbanization development (Wang et al. 2013).

2.2. Data

2.2.1. Unchanged vegetation areas map of Shanghai from 2004 to 2016
The unchanged vegetation areas map was derived from the cloud-free Landsat TM/OLI images with a moderate spatial resolution of 30 m through Google Earth Engine (GEE). We selected samples on Google Earth Pro and utilized the appropriate index spectral data. After obtaining this information, we employed the Random Forest method to interpret the land use types of Shanghai based on Landsat images in 2004, 2010, and 2016 (figures 1(b)–(d)). The accuracy of the interpretation of the land use map achieved the desired result (table S1 available online at stacks.iop.org/ERL/16/064088/mmedia) (Foody 2002). We chose the areas in which the vegetation distribution did not change in 2004, 2010, and 2016 as the unchanged vegetation areas on the basis of the land use map of Shanghai (Zhou et al. 2014a).

2.2.2. Annual gross primary production dataset
A new, global, 500 m eight-day GPP dataset made based on the vegetation photosynthesis model (VPM) model was used in this study, which was produced based on an improved light use efficiency theory and was driven by satellite data from MODIS and climate data from NCEP Reanalysis II (Zhang et al. 2017b). The datasets were used with the aim of solving several key problems and to provide an alternative GPP estimate for regional to global carbon cycle research and were openly accessed from https://doi.pangaea.de/10.1594/PANGAEA.879558?format=html#download. The unit of GPP is g C m$^{-2}$, which means that the measurement of GPP is normalized per unit area. Some studies have compared the VPM-based GPP dataset with solar-induced chlorophyll fluorescence remote sensing products for urban areas including Shanghai and found a good consistency between the two datasets (Cui et al. 2017, Ma et al. 2018). Meanwhile, the development of urbanization in Shanghai was divided into three stages (namely, 2000–2004, 2004–2013, and 2013–2016) (Zhong et al. 2019). Based on this situation, we aggregated the eight-day GPP data into annual GPP and extracted values from 2004, 2010, and 2016 to explore and compare the indirect impact of urbanization on vegetation carbon uptake. Specifically, we compared the annual GPP in our study.

2.2.3. Land surface temperature, vegetation temperature condition index, photosynthetically active radiation, and vegetation landscape datasets
The MOD11A2 and MYD11A2 level 3 1 km land surface temperature (LST) products were collected from GEE. The LST products adopted a general split-window optimization algorithm with an accuracy close to 1 K for terrestrial materials of known emissivity (Wan et al. 2004).

The MOD09GA products were based on the normalized difference vegetation index (NDVI) (Tucker 1979). The vegetation temperature condition index (VTCI), which is regarded as an effective drought indicator to monitor the soil moisture of a region, was used in this study (Patel et al. 2012). The VTCI dataset was calculated using the triangular spatial features of LST and NDVI scatter plots. The range of values of VTCI is from 0 to 1. Generally, lower values of VTCI indicate higher magnitudes of drought stress:

\[
VTCI = \frac{\text{LST}_{\text{NDVI}_{\text{max}}} - \text{LST}_{\text{NDVI}_{\text{i}}}}{\text{LST}_{\text{NDVI}_{\text{max}}} - \text{LST}_{\text{NDVI}_{\text{min}}}},
\]

where \(\text{NDVI}_{\text{i}}\) represents the NDVI of a pixel; \(\text{LST}_{\text{NDVI}_{\text{max}}}\) represents the surface temperature of a pixel with the NDVI value of NDVI; \(\text{LST}_{\text{NDVI}_{\text{max}}}\) represents the maximum surface temperature of all pixels in the study area when the value of NDVI is NDVI; \(\text{LST}_{\text{NDVI}_{\text{min}}}\) represents the minimum surface temperature of all pixels in the study area when the value of NDVI is NDVI; and \(a, b, a', \text{and } b'\) were approximately obtained from the NDVI and LST scatter plot of the study area.

Photosynthetically active radiation (PAR) is the spectral component of solar radiation that is effective for photosynthesis in plants. The Breathing Earth system simulator PAR product, driven by MODIS data with a global spatial resolution of 0.05°, was resampled into a 1 km resolution and used in this study. This PAR dataset was produced based on an atmospheric radiative transfer model and an artificial neural network (ANN), was tested by observational data from 77 flux tower networks, and showed high accuracy for the global scale (Ryu et al. 2017). The range of PAR in Shanghai was 63–75 W m$^{-2}$ during 2004–2016.

The vegetation landscape connectivity (VLC) was driven by Landsat images on account of the land use map and calculated based on the following equations for moving ‘windows’ of 15 × 15 pixels. The VLC was calculated by dividing a pixel pair number that included at least one vegetation pixel by a pixel pair number that included two vegetation pixels in basic directions in a 15 × 15 pixel window (Riitters et al. 2015).
The value of VLC ranges from 0 to 1, which indicates the vegetation connectivity:

\[
\text{VLC} = \frac{D_f}{D_f},
\]

where \(D_f\) represents the pixel pair number with at least one vegetation pixel and \(D_f\) represents a vegetation pixel corresponding to the two basic directions of \(D_f\).

The LST, VTCI, PAR, and VLC datasets for 2004, 2010, and 2016 were extracted and used to reflect the impacts of temperature, soil moisture, radiation, and landscape patterns on the vegetation GPP in our study area.

2.3.1. Mapping the urban–rural distance gradient buffer of unchanged vegetation in Shanghai

Urban–rural gradients can exclude the influence of climatic factors and reflect the indirect impact of urbanization on the environment and vegetation. Based on the unchanged vegetation areas, a series of buffers extending 0–2, 2–4, 4–6, 6–8, 8–10, 10–12, 12–14, 14–16, 16–18, 18–20, 20–22, 22–24, 24–26, 26–28, 28–30, 30–32, 32–34, and 34–44 km from the downtown of Shanghai were created (figure 1(a)). In addition, to quantify the indirect impact of urbanization on vegetation, it was necessary to select the area of Shanghai that was least affected by urbanization as the reference (rural) area. Although Chongming’s population increased from 0.63 million in 2004 to 0.69 million in 2016 and Chongming experienced a certain degree of urbanization, the national government’s strategic positioning of Chongming Island as an ‘ecological island’ made it more suitable as a reference area than other places in Shanghai. Thus, Chongming Island was finally selected as the reference area (Zhao et al 2006).

2.3.2. Identifying the indirect impact of urbanization on the vegetation carbon uptake

Taking Chongming as the reference area, the indirect impact of urbanization on vegetation could be defined as follows:

\[
\Delta \text{GPP} = \frac{(\text{GPP}_B - \text{GPP}_C)}{\text{VC}},
\]

\(
\text{DGPP} \text{ represents the indirect effects of urbanization on vegetation, GPP}_B \text{ means the average value of GPP in each buffer zone, and GPP}_C \text{ equals the average GPP in the unchanged vegetation areas of Chongming, excluding the influence of VC. Urbanization promoted vegetation growth when } \Delta \text{GPP was positive and vice versa. Meanwhile, the exponential function model in the Origin software was used to fit the trend of } \Delta \text{GPP changing with the distance from the downtown area of Shanghai (DFD) to observe the overall trend of the indirect influence of urbanization on vegetation. DFD is the distance from each buffer to the downtown of Shanghai.}

2.3.3. Identifying the impact of urbanization on the urban environments

The development of urbanization unavoidably brought about a change in the urban internal environment. The impact of urbanization on the environment can be expressed as follows:

\[
\Delta E = E_B - E_C.
\]

This equation reflects the spatial heterogeneity of urban environmental factors in a specific time, where \(E_B\) represents the average value of \(T\), VTCI, PAR, and VLC in each buffer zone, and \(E_C\) represents the average value of environmental factors in the unchanged vegetation areas of Chongming. A positive value of \(\Delta E\) indicates that urbanization increased this environmental factor.

2.3.4. Analyzing the relationship between GPP and the urban environmental factors

We used the boosted regression tree to analyze the relationship between GPP and environmental factors. The boosted regression tree is built on the basis of the traditional classification regression tree algorithm, which can continuously generate multiple regression trees through random selection and self-learning methods to improve the stability and prediction accuracy of the model. The biggest advantage of the boosted regression tree is that it does not need to consider the interaction between independent variables. The data can have default values, the data types are flexible, and the outputs of independent variable contributions and response curves are more intuitive. The generalized boosted regression method is used to fit the nonlinear relationship (Elith et al 2008). In our study, the response of vegetation growth to the environment was often nonlinear and interactive (Verwijst and Von Fircks 1994, Cregg and Dix 2001).
Besides, the traditional linear model was not able to predict the relative contribution of each environmental factor to GPP, while the boosted regression tree method was able to do so. Thus, the main controlling factors of the indirect impact of urbanization on vegetation were determined (Ridgeway 2015). The marginal effect of urban environmental factors on urban vegetation carbon uptake was also calculated, and we ranked the urban environmental factors by the contribution rate from high to low.

3. Results

3.1. The dynamic of environmental factors with the urban–rural gradient in 2004, 2010, and 2016

Urbanization reduced the vegetation landscape’s connectivity, sunlight, soil moisture, and increased the internal temperature, which was closely related to vegetation carbon uptake in Shanghai. As shown in figure 2, urban temperatures were at least 1 °C higher than in rural areas within a range of 0–5 km from the downtown area, and the ∆T in 2010 was the lowest relative to the other two years (figure 2(a)). The ∆VLC of Shanghai was the smallest in the downtown area of Shanghai and gradually rose along with the urban–rural gradient. The average of ∆VLC was −0.14 in 2004, −0.17 in 2010, and −0.13 in 2016 (figure 2(d)). Similarly, PAR and VTCI also tended to increase with the urban–rural gradient (figure 2(b)). The ∆VTCI in 2010 was the highest relative to the other 2 years (figure 2(c)).

3.2. The dynamic of GPP with the urban–rural gradient in 2004, 2010, and 2016

Figure 3 illustrates the difference between urban and rural vegetation carbon uptake in various years; i.e. the indirect impact of urbanization on carbon uptake and its interannual change. ∆GPP was positive in the downtown area (0–20 km), which indicated that urbanization promoted vegetation growth. Figure 3 also shows that the value in 2010 was higher than that in 2004 and 2016. Meanwhile, the region showing a promotion effect on vegetation growth was about 0–20 km from the downtown area in 2004, but in 2010 and 2016, it was 0–40 and 0–27 km. The averages of ∆GPP were 310.39, 958.04, and 486.68 g C m⁻² in 2004, 2010, and 2016, respectively (figure 3(b)).

3.3. The impact of environmental factors on GPP in Shanghai

From the data in figure 4, we can see the relationship between the changes of environmental factors caused by urbanization and the change of vegetation carbon uptake based on the urban–rural gradient. These results revealed the largest relative contribution
to the change of vegetation carbon uptake was from VLC, followed by temperature. The response rates in 2004, 2010, and 2016 of ΔVLC were 77%, 81%, and 85%, respectively. Meanwhile, ΔVLC and ΔGPP were negatively correlated. The relative contributions of ΔT were 10%, 13%, and 12% in 2004, 2010, and 2016, respectively, and ΔT and ΔGPP were positively correlated. ΔVTCI and ΔPAR accounted for a very small proportion of the total; that means that their changes of ΔVTCI and ΔPAR were not able to explain changes in vegetation carbon uptake. As the curve marginal effect of environmental factors is illustrated in figure 4, the contribution of the temperature to vegetation carbon uptake was mainly reflected in the downtown area. However, the contribution of VLC to vegetation carbon uptake was mainly reflected in the downtown area and the transition zone between urban and rural areas.

4. Discussion

4.1. Indirect impacts of urbanization on vegetation carbon uptake

Our result provides a different approach to quantify the indirect impact of urbanization on vegetation using remote sensing images along with the gradient of urban and rural areas, which deepens our understanding of the effect of urbanization on vegetation carbon uptake. These findings are consistent with the results of Zhong et al (2019) and Zhao et al (2016). Urbanization was able to promote the growth of the vegetation near the city center of Shanghai through urban climate and human management. Meanwhile, Guan et al (2019) found the indirect effect of urbanization in Kunming from 1978 to 2014 on vegetation to fluctuate over the years, showing no obvious trends, which was generally in agreement with our results. The promotion effect of urbanization on vegetation varied in different years. It seems that this result is due to the diverse urban microclimate environments and policies in different periods. In particular, with the opportunity of the 2010 World Expo, Shanghai improved its green space network system, built a stable plant community, and managed the green space according to the law. These measures made the urban vegetation suitable for growth. Thus, this led to the highest curve being present in 2010. Meanwhile, from the point of intersection of the curve and zero value, the promoting effect of urbanization on vegetation was expanded in 2010. In addition, in 2004 and 2016, Shanghai showed different stages of urbanization development. The emphasis on the ecological environment in Shanghai made the ecological environment in the city more conducive to vegetation growth in the later stage of urbanization. Therefore, the promotion scope and amount in 2016 was larger than in 2004 (Zhang 2013, Zhong et al 2019).

4.2. Relationship between the changed urban environment and carbon uptake under urbanization

Urbanization was found to have caused a rise of construction land, urban internal temperature, surface runoff, and the fragmentation of urban vegetation in several studies (Menglin et al 2011, Sun et al 2013, Yang et al 2014), which also accorded with our research results. In particular, the Shanghai government extended and forwarded its environmental proposals in order to hold the Shanghai Expo 2010, and Shanghai thus made progress in implementing its three-year Environmental Action Plan (EAP). In this ecological process, a significant proportion of the heavily polluting industry was banned and adjusted. Green space was also further developed; in particular, for preservation, it was proposed that construction sites should be given special attention because the protected vegetation commonly lacked proper care (Hao et al 2011, Huang et al 2013, Zhang 2013). The implementation of these measures alleviated the greenhouse effect and heat island effect, resulting in a low temperature of vegetation in 2010; for this reason, together with human management, the water holding capacity of vegetation therefore increased, which prompted the increase of soil moisture.

These environmental factors had an influence on the carbon uptake of urban vegetation. Our results indicated that urbanization promoted the vegetation carbon uptake in the downtown area and the transition zone between urban and rural areas, mainly by modifying the spatial pattern of vegetation to change.
Figure 4. The relative influence of $\Delta T$, $\Delta$PAR, $\Delta$VTCI, and $\Delta$VLC on $\Delta$GPP. Each dependency plot represents the marginal effect on $\Delta$GPP.

The carbon uptake capacity of urban vegetation in the downtown and suburban transition zone. The impact of urbanization on the vegetation landscape was generally manifested as a reduced connectivity of vegetation, which was positively associated with the vegetation carbon uptake ability. Compared with vegetation with a high connectivity, the vegetation with a low connectivity was exposed to a different microclimate that typically included wind, high temperature, light, and nutrient resource availability (Weathers et al 2001, Remy et al 2016). Meanwhile, the places with low VLC were often in the center of Shanghai or near the center, which were the places where vegetation management was increased (Zhang et al 2017a, Sun et al 2019). Some studies have reported that urban vegetation might be decoupled from the regional climate due to management and subsidies (such as irrigation and fertilization), which shows that urban ecology management has been playing an increasingly decisive role in the growth
of vegetation with the development of urbanization (Paolini et al 2019). In general, the impact of human management or marginal microclimates on urban vegetation has been increasing with the development of urbanization. Many previous studies have reported that the heat island effect has had a key impact on urban vegetation, which is in sharp contrast with our study (Ziska et al 2004, Wang et al 2019). The impact of temperature increases on the indirect effect was not found to be decisive in our study. Moreover, frequent human activities in urban areas led to a significant increase in buildings and aerosol particles, which led to a reduction in available radiation. The reduction in the effective utilization of radiation inhibited vegetation growth (Xu et al 2002, Zielinska-Dabkowska and Xavia 2019).

4.3. Ecological insights on urban sustainable development and uncertainties

Urban vegetation can provide urban residents with a variety of benefits. The study of the impact of urbanization on vegetation and its influencing factors can guide the development of the best urban green space planning and management practices (Douglas et al 2017, Wood et al 2017). Urbanization leads to an increase in the proportion of impervious surfaces, which reduces the VC in this area, thus reducing the carbon uptake capacity of the area. Although we concluded that the landscape fragmentation caused by the urban expansion promoted the carbon uptake of vegetation, the vegetation carbon uptake promoted by urbanization to vegetation was still less than the carbon uptake capacity loss caused by urban land occupation. Thus, the sustainability of the urban landscape should be considered in urban landscape planning; that is, a balance should be struck between land use and ecosystem services within the city (Termorshuizen et al 2007, Trammell et al 2018). For example, urban expansion land should be planned to minimize the carbon loss of urban green spaces, protect the structure of urban green spaces to the maximum extent, and increase and attach importance to the planning of urban green spaces in the stage of rapid urban development. However, uncertainties remain in this study. In addition to temperature, radiation, soil moisture, and so on, other factors related to urbanization, such as nitrogen deposition, photoperiod, carbon dioxide, and plant species, may affect the carbon uptake of urban vegetation (Shen et al 2008, Stoy et al 2014, Qiu et al 2017). Critically, future research must aspire to quantify the relationships between urban environments and vegetation carbon uptake at local, regional, and global scales.

5. Conclusions

In this study, we used time-series Landsat images to extract the unchanged vegetation areas in Shanghai from 2004 to 2016. Landsat, MODIS images, and GPP datasets from 2004, 2010, and 2016 were applied to observe the changing trend of vegetation GPP and environmental factors with urban—rural gradients and the relationship between vegetation GPP and environmental factors based on the unchanged vegetation areas. All values of ΔGPP were positive in downtown Shanghai, indicating that the indirect effect of urbanization on vegetation was promoted. A comparison of the ΔGPP fitting curves in 2004, 2010, and 2016 suggested that urban policies and microclimate conditions were constantly changing with the development of urbanization. In addition, a regression analysis of ΔGPP and environmental factors showed that temperature was the main impacting factor promoting vegetation growth near the center of Shanghai, and the temperature contributed between 12% and 13% to GPP. The main controlling factor for the indirect influence of urbanization on vegetation in the urban—rural transition zone was VLC. The contributions of VLC to vegetation carbon uptake in 2004, 2010, and 2016 were 77%, 81%, and 85%, respectively. Thus, it can be seen that the landscape pattern’s indirect impact on vegetation is crucial. Therefore, we should pay increased attention to future landscape design measures. This study quantified the indirect impact of urbanization on vegetation and the relationship between environmental factors and carbon uptake by vegetation, which could provide a reasonable basis and ecological insights for urban ecological management and sustainable urban development.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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ORCID iD

Jun Ma https://orcid.org/0000-0003-3412-7766

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