Prevalent vegetation growth enhancement in urban environment

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Urbanization, a dominant global demographic trend, leads to various changes in environments (e.g., atmospheric CO_2 increase, urban heat island). Cities experience global change decades ahead of other systems so that they are natural laboratories for studying responses of other nonurban biological ecosystems to future global change. However, the impacts of urbanization on vegetation growth are not well understood. Here, we developed a general conceptual framework for quantifying the impacts of urbanization on vegetation growth and applied it in 32 Chinese cities. Results indicated that vegetation growth, as surrogated by satellite-observed vegetation index, decreased along urban intensity across all cities. At the same time, vegetation growth was enhanced at 85% of the places along the intensity gradient, and the relative enhancement increased with urban intensity. This growth enhancement offset about 40% of direct loss of vegetation productivity caused by replacing productive vegetated surfaces with nonproductive impervious surfaces. In light of current and previous field studies, we conclude that vegetation growth enhancement is prevalent in urban settings. Urban environments do provide ideal natural laboratories to observe biological responses to environmental changes that are difficult to mimic in manipulative experiments. However, one should be careful in extrapolating the finding to nonurban environments because urban vegetation is usually intensively managed, and attribution of the responses to diverse driving forces will be challenging but must be pursued.

urban–rural gradients | urbanization | direct impact | indirect impact | vegetation growth

Urbanization, one of the most dramatic forms of land conversion, leads to various changes in atmospheric and climatic conditions (e.g., atmospheric CO_2 increase, urban heat island), vegetation community structure, species abundance and diversity, and biogeochemical cycles (1–4). Cities experiencing elevated temperature (i.e., urban "heat island" warming), CO_2, and nitrogen deposition decades ahead of the projected average global change are regarded as the "harbingers" of the future global change (5, 6). It is for this reason that cities have been regarded as ideal natural laboratories for global change studies and particularly valuable to elucidate the potential responses of other nonurban ecosystems to future climate and environmental changes (2, 6, 7).

It has long and widely been believed, particularly in the horticultural and landscaping communities, that trees grow slower in cities than in rural settings because of the heightened environmental stresses experienced by urban trees (e.g., higher temperature, lower air humidity, lower soil moisture content) (e.g., 8, 9). Field observations seem to challenge this belief. For example, Gregg et al. (10), using manipulative paired experiments, found that tree seedlings in New York City grew twofold faster than their rural counterparts. Recently, Briber et al. (11) found that the growth rates of trees in remnant forests were mostly accelerated after urbanization in Boston. Imhoff et al. (12) compared the vegetation index, a holistic surrogate for vegetation growth productivity, in urban, suburban, and rural environments and found that urbanization may enhance or inhibit vegetation production depending on the locality of the city and its background climate.

Field and remote sensing-based studies on vegetation growth changes in urban environments in comparison to their rural counterparts are limited (8, 10, 11, 13–17). It is challenging to compare and synthesize the existing results because these studies range from leaves, trees, and forest remnants to urbanized regions, and, consequently, the impact of urbanization on vegetation growth is not well understood. Here, we first developed a conceptual framework for assessing vegetation growth performance under various urbanization intensities. Then, the framework was applied to quantify the holistic vegetation growth responses to urbanization in 32 major cities across China (Fig. S1). These 32 cities, including municipalities, provincial/autonomous regional capitals, and the city of Shenzhen, cover a broad range of climate and preurbanization vegetation types. Finally, we combined results from our study with previous observations to show the general impact of urbanization on vegetation growth.

A Conceptual Framework for Analyzing the Urbanization Effects

To quantify the impact of urbanization on vegetation growth systematically, we first lay out the following theoretical framework and give a few necessary definitions. Numerous studies have demonstrated that the vegetation greenness index (VI) from remotely sensed data, such as the normalized difference vegetation index or enhanced vegetation index (EVI), is an effective indicator of vegetation productivity (e.g., 18, 19). Conceptually, the VI of an urban pixel can be decomposed into contributions from vegetation and nonvegetative surfaces:

$$V_{obs} = (1+\omega)(1-\beta)V_v + \beta V_{nv}, \quad [1]$$

where β is urbanization intensity, expressed as the fraction of nonvegetative surface in the pixel, V_{obs} is the observed VI of the pixel, and ω is the overall impact of urbanization on the VI. V_v is the VI

Significance

Cities experiencing elevated temperature (i.e., urban "heat island" warming), CO_2, and nitrogen deposition decades ahead of the projected average global change are regarded as the "harbingers" of the future global change. It is for this reason that cities have been regarded as ideal natural laboratories for global change studies and particularly valuable to elucidate the potential responses of other nonurban ecosystems to future climate and environmental changes. However, the impacts of urbanization on vegetation growth are not well understood. We demonstrate, conceptually and empirically, that urbanization generates direct and indirect effects on vegetation growth at the landscape to regional scales.

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of the background vegetation before urbanization or the VI of the fully vegetated area. V_{nv} is the VI of the pixel completely filled by built-up surfaces.

Extending the concept of the urbanization impact on the VI from a single pixel to all of the pixels in a city and plotting the V_{obs} values of all pixels against their corresponding urban intensity β values along the urban intensity gradient from 0 to 1, several distinct features on the impacts of urbanization intensity on vegetation would emerge (Fig. 1).

A zero-impact straight line, defined by the two characteristic VI values corresponding to fully vegetated ($\beta = 0$, VI = V_v) and fully urbanized ($\beta = 1$, VI = V_{nv}) pixels, represents the conditions that urbanization does not affect the VI (i.e., $\omega = 0$ in Eq. **1**):

$$V_{zi} = (1-\beta)V_v + \beta V_{nv}. \quad \textbf{[2]}$$

Any points above the zero-impact line in the VI~β plane would indicate positive impacts of urbanization on vegetation growth, whereas any points below the zero-impact line would indicate negative impacts.

With this framework, we can use the following general concepts to quantify the direct, indirect, and total impacts of urbanization on vegetation growth.

The direct surface-replacement impact of urbanization is the loss of the VI after replacing, partially or completely, vegetative with nonvegetative surfaces, and it does not include the indirect impact of urbanization. It can be calculated as

$$\omega_d = \frac{V_{zi} - V_v}{V_v} * 100\%. \quad \textbf{[3]}$$

It can be seen that the direct impact of urbanization on vegetation growth is always negative.

Vegetation growth can be altered by urbanization, and the impact is indirect, contrasting with the direct surface-replacing impact of land conversion. The indirect impact can be measured by the relative change of the VI from the zero-impact VI line.

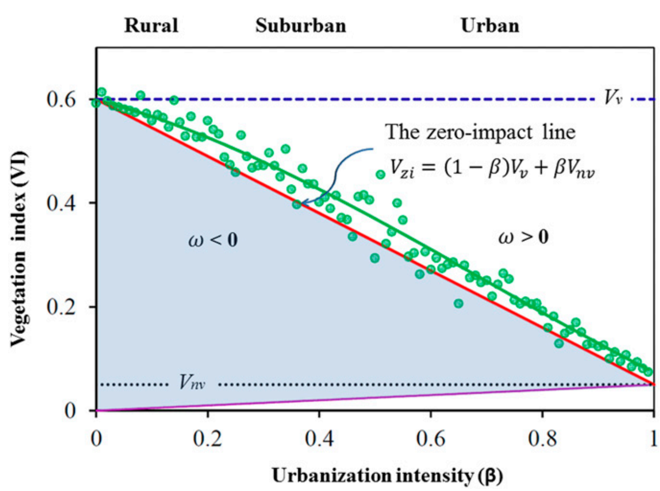

Fig. 1. Conceptual diagram showing the impacts of urbanization on vegetation conditions along the urban intensity gradient. Here, vegetation condition is represented by the VI (dimensionless), which is measured by satellites (e.g., enhanced VI from the MODIS). The green points and the green line represent the observed VI values and their regression line, respectively. V_v and V_{nv} are the VI values of rural or potential vegetation and nonvegetative urban surfaces, respectively. The solid purple line indicates the contribution of nonvegetative urban surfaces to the total VI along the urban intensity gradient (βV_{nv}). No impact (V_{zi}) is represented by the sloping red line (i.e., the zero-impact line), negative impacts ($\omega < 0$) would be indicated by the VI falling under the zero-impact line, and positive enhancement ($\omega > 0$) would be indicated by the VI values shown above the zero-impact line.

The total realized impact of urbanization on the VI is the change of the VI after urbanization, including both indirect and direct impacts. In addition, the indirect VI change caused by urbanization (i.e., $V_{obs} - V_{zi}$) can be compared with the direct VI change by surface replacement (i.e., $V_v - V_{zi}$) using the concept of growth offsetting coefficient τ:

$$\tau = \frac{V_{obs} - V_{zi}}{V_v - V_{zi}} * 100\%. \quad \textbf{[4]}$$

Obviously, a positive τ suggests enhanced vegetation growth by urbanization; therefore, the negative direct impact of urbanization (i.e., $V_v - V_{zi}$) is offset by growth enhancement to a certain degree (i.e., τ). On the other hand, if τ is negative, the negative direct urbanization effect is exacerbated by indirect reduced vegetation growth. It is important to note that τ is the coefficient showing how much growth of the remaining vegetation patches can offset (if τ is positive) or worsen (if τ is negative) the direct vegetation removal loss by urbanization; it is not a ratio over the total impact of urbanization (Fig. S2).

In this study, we first quantify the indirect impacts of urbanization in China and then put existing observational evidence from this and previous studies into the theoretical framework to examine the impact of urbanization on vegetation growth systematically.

Results

The VI~β Relationship and Its Variability Across Cities. Fig. 2 shows the relationship between the VI and built-up or urbanization intensity (β) by city in 2011. Several observations can be made from these figures. First, as expected, the VI decreased with built-up intensity due to the increasing share of nonvegetative, built-up surface in the pixels along the β gradient. However, considerable variation exists in the shape of the relationship across cities. Second, the scattering of the VI observations along the β gradient increased as the city area decreased because of the decreasing number of 1 × 1-km pixels for each β bin. For example, Lhasa, the smallest city in this study with an urbanized area of 53 km^2, demonstrated the highest irregularity or scattering in the VI~β relationship among all cities. In contrast, the VI~β relationship was rather smooth in Beijing because of large pixel frequency in each β bin resulting from its large area. Third, the cubic regressions of the VI~β curves were statistically significant ($\alpha = 0.05$) for all cities except Lhasa; the latter was probably related to the second observation above. Fourth, the y-intercept of the VI~β relationship demonstrated a large variability across cities. The y-intercept effectively represents the maximum VI of a city that is largely determined by the regional background climate regime.

Most importantly, the observed EVI values in all cities were mostly higher than the zero-impact EVI line across (Fig. 2), suggesting the existence of widespread EVI enhancement in various urban environments. About 84%, 85%, and 86% of the urban intensity bins recorded positive growth enhancements in the 32 cities for 2001, 2006, and 2011, respectively. Among these overwhelming growth enhancements, growth abatement did exist in about 15% of the urbanization intensity gradient as indicated by the smaller number of points below the red zero-impact lines (Fig. 2).

Temporal Stability of the VI~β Relationship. To check the stability of the VI~β relationship across years, we overlaid the relationships in the three time periods (Fig. S3) and also plotted the pairwise regression coefficients of the VI~β response curve for three time periods (Fig. S4). These figures demonstrated that the VI~β relationships for the 32 Chinese cities demonstrated a strong temporal stability. Of course, the scattering of the pairwise comparison of the coefficients along the 1:1 line suggests that the city-specific VI~β relationships varied temporally to certain degrees, which may be

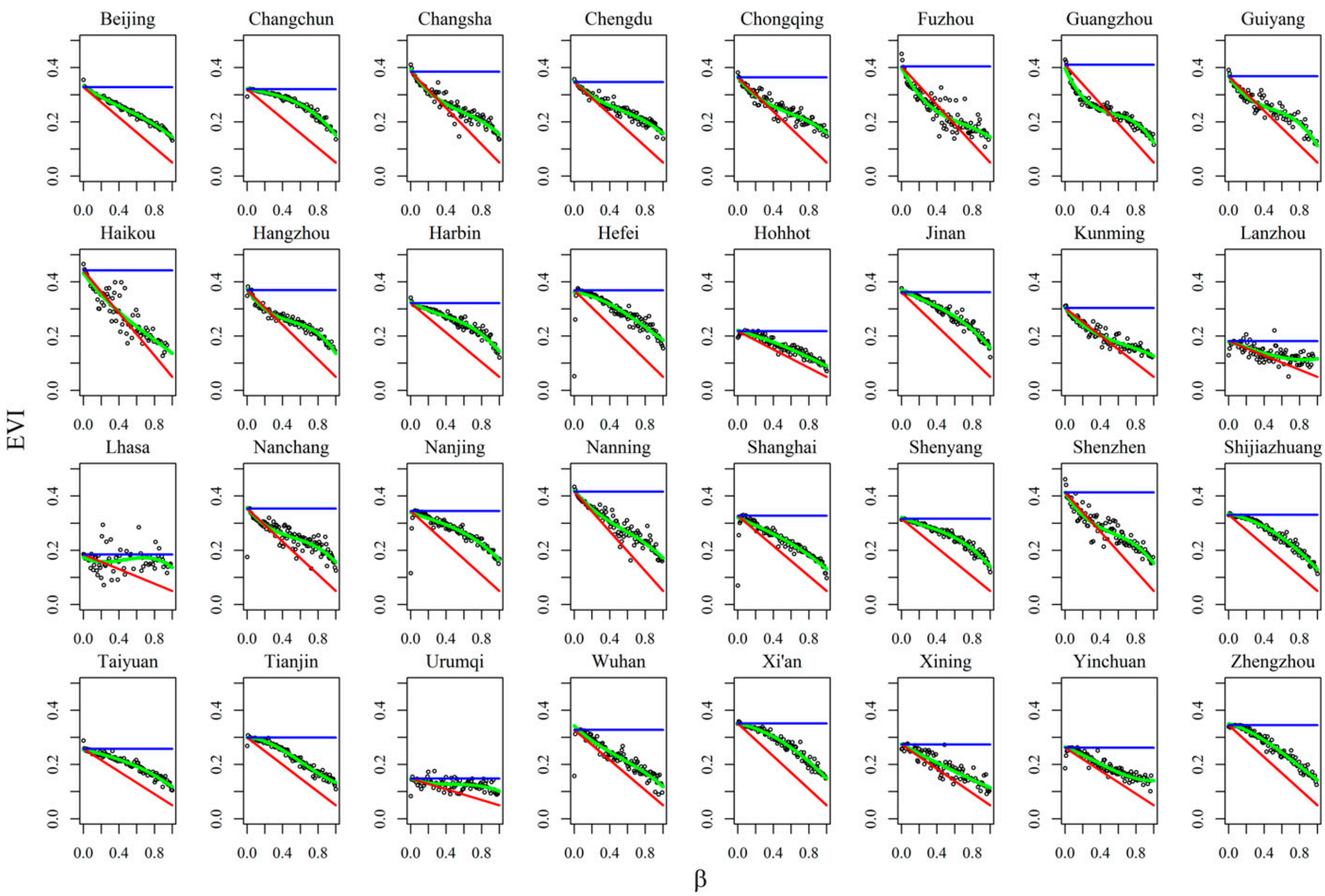

Fig. 2. Illustrative example showing various responses of the MODIS EVI (dimensionless) to urban intensity (β, dimensionless) across 32 Chinese cities in 2011. The green, blue, and red lines are the cubic regression of the observed EVI (circles), background EVI V_v (i.e., the y-intercept of the regression), and V_{zi} or EVI without urban impact, respectively. All regressions are significant ($\alpha = 0.05$) except Lhasa.

attributed mainly to two factors: the local to regional interannual climate variability and the small number of pixels falling into some built-up intensity bins. These variabilities were nevertheless not significant ($P < 0.05$). This overall temporal stability suggests the temporal stability of the impacts of urbanization on vegetation growth along the built-up intensity gradient for each city.

Generalized Indirect Impact in China. Once the observations from all cities are combined, strong patterns emerge from the seemingly diverse urbanization impacts across cities (Fig. 3). The previous findings of the overall decline of the EVI along the urban intensity gradient (Fig. 3*A*), the varying background V_v across cities (Fig. 3*B*), and the widespread presence of a positive impact (i.e., growth enhancement) or a negative impact (i.e., growth abatement) (Fig. 3*C*) that we have seen from individual cities still hold. In addition, we can see that the indirect impact of urbanization on vegetation growth increased superlinearly (i.e., the speed of increase increased with urbanization intensity) (Fig. 3*D*) and can reach up to over 200%. This growth enhancement offset about 40% of the direct surface-replacement impact on average. Surprisingly, the mode of offset percentage was almost invariant across years and the urban intensity gradient (Fig. 3*E*). Of course, vegetation may also exacerbate the direct, negative surface-replacing effect of urbanization on vegetation growth at some locations of the urban landscape as demonstrated by the negative τ values. However, the probability of occurrence of the negative growth impact was much lower than the probability of occurrence of the growth enhancement. Furthermore, it is apparent that the variability of the impact of urbanization on vegetation growth decreased along the urban intensity gradient. This impact probably resulted from the smaller values of the direct surface-replacing impact $V_v - V_{zi}$, the denominator of the equation used to calculate τ (Eq. **4**), at the low end of the urbanization intensity and a gradual increase along the intensity gradient.

Discussion

The Necessity of Differentiating Various Impacts of Urbanization on Vegetation Growth. Conceptually and empirically, we demonstrated that urbanization generates direct and indirect effects on vegetation growth at the landscape to regional scales. The direct impact refers to the loss of productivity resulting from converting vegetated productive surfaces into nonproductive, impervious surfaces, such as buildings and roads. The magnitude of the direct loss is proportional to the surface area converted and the productivity of the land before urbanization. The indirect impact of urbanization refers to the effects of urbanization on plant growth, which can be assessed by comparing plant growth in urban and rural conditions. Indirect impacts, although not explicitly defined hitherto, have nevertheless been measured using manipulative experiments or pairwise rural–urban comparative studies (e.g., 5, 10, 17).

Urbanization impacts on vegetation growth have been studied at a wide range of spatial scales. Studies at the leaf to ecosystem levels are usually designed to understand the indirect impacts of urbanization on plants, and not to address the direct impacts of converting productive lands to impervious surfaces or buildings on productivity at the landscape scale. On the other hand, landscape to regional growth metrics from remote sensing are holistic measures of the

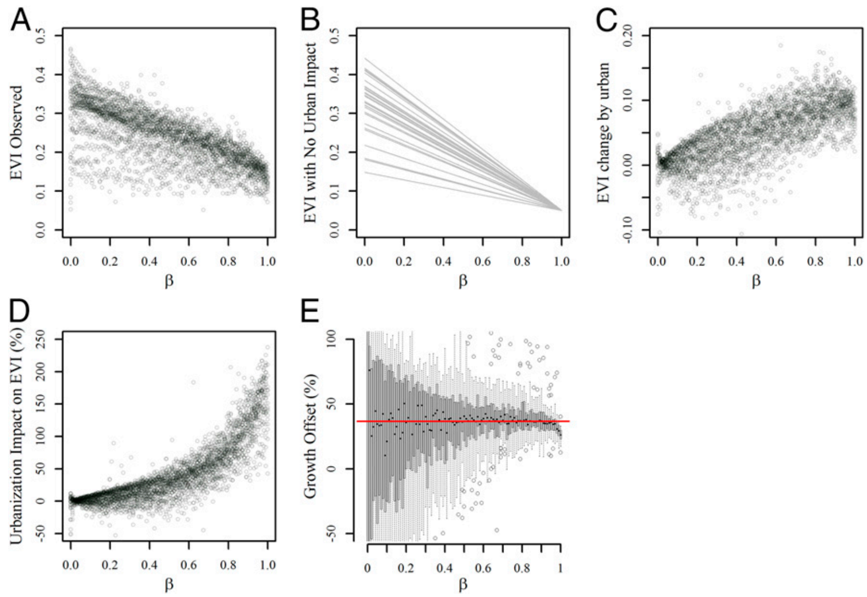

Fig. 3. Relationships between EVI and urban intensity β: observed EVI (*A*), EVI without urbanization impacts (*B*), EVI change caused by urbanization (*C*, the difference between *A* and *B*), relative impact of urbanization on EVI (*D*), and EVI offset (τ) by urbanization (*E*, the mean of the medians is shown by the red line) for 32 Chinese cities in 2011.

overall impact of urbanization (12, 14, 20). There is an obvious need to separate the overall impact into direct and indirect impacts. Otherwise, the responses of plant growth to altered environmental conditions (i.e., the indirect impact of urbanization), a major research interest for global change research communities, cannot be adequately investigated and quantified, and the idea of using urban ecosystems as natural laboratories to study the growth impacts of future global change to other ecosystems cannot be capitalized on, at least at the landscape to regional scales.

Urbanization Effects on Vegetation Growth: Evidence from Direct Measurements. Two broad categories of approaches have been used to observe and understand the responses of vegetation productivity to urbanization. The first includes all of the ground-based approaches covering physiological, species, site, and urban to rural gradient studies, and the other is the remote sensing approach. Field studies are used to observe the impacts of urbanization on vegetation growth directly, and those studies are limited in number and spatial scope because, after a rather comprehensive literature search (Table 1), most of them have been from the United States. The majority of existing observations (10 of 12 cases in Table 1) have demonstrated enhancement of vegetation growth in urban environments relative to their rural counterparts. The degree of enhancement depends on the location of a city (Table 1), the species (8, 10, 17), and the intensity of urbanization (5). For example, Searle et al. (17) observed an eightfold increase in biomass production of *Quercus rubra* seedlings in New York City relative to the rural rates, which was much higher than the doubling of biomass in eastern cottonwood seedlings observed in the same region (10). Another study along a rural-urban gradient in Baltimore showed that ecosystem productivity in secondary succession fields increased 60% and 115% for the suburban and urban sites, respectively, relative to the rural site (5). Growth enhancement in urban settings has also been reported in the conifer western red cedar (*Thuja plicata*) in Seattle (21) and in pine and oak forests in the Florida Panhandle (22). These isolated field studies corroborated our findings from remote sensing that enhancement of the EVI is overwhelmingly positive across cities.

It should be recognized that a small fraction of the studies (i.e., 2 of the 12 studies in Table 1) did suggest negative impacts of urbanization. The much higher occurrence of enhancement compared with abatement shown by these field

Table 1. Summary of impacts of urbanization on vegetation growth, tree size, or carbon storage

Variable	Site	Impact	Ref.
Leaf photosynthesis	*I. rotunda* leaves (Fukuoka, Japan)	Positive	Takagi and Gyokusen (34)
Biomass or productivity	Fallow site (urban Baltimore)	115% increase	Ziska et al. (5)
	Fallow site (suburban Baltimore)	60% increase	Ziska et al. (5)
	Urban lawns (Denver–Boulder, CO)	Positive	Golubiewski (15)
	Urban lawns (CO)	Four- to fivefold increase	Kaye et al. (26)
	Eastern cottonwood (New York)	Double	Gregg et al. (10)
	Q. rubra seedlings (New York)	Eightfold increase	Searle et al. (17)
	Pine and oak forests (FL)	Positive	Enloe et al. (22)
Tree DBH	Multiple species (Columbus, OH)	Negative	Quigley (8)
	15 tree species (Columbus, OH)	Negative	Quigley (9)
	Western red-cedar (Seattle)	Positive	O’Brien et al. (21)
	Q. rubra (Boston)	Positive	Briber et al. (11)
Carbon stock	Green spaces (Denver–Boulder, CO)	Positive	Golubiewski (15)

DBH, diameter at breast height.

measurements agreed well with the remote sensing observations from our study. In addition, the phenomenon that the growth enhancement could exceed 200% in certain urban environments according to our results corresponds well with some of the field observations (e.g., 11, 17).

Urbanization Effects on Vegetation Growth: Evidence from Satellite Observations. Remote sensing approaches are effective in observing the overall impacts of urbanization on vegetation growth over large areas. From existing studies, we can see that ecosystem net primary productivity (NPP) is negatively affected by urbanization in large areas, including the United States (12), China (20), and humid and warm regions such as the southeastern United States (14) and southeastern China (16). However, urbanization might increase NPP in arid and semiarid regions through urban greening using exotic species and improved management practices (20, 23) and in cold regions through localized "urban heat island" warming that can effectively elongate the length of the growing season (12, 24, 25). Nevertheless, previous remote sensing studies did not attempt to quantify the indirect impact as defined in this study, a metric that measures the response of vegetation to urban environmental change.

Implication to Urban Carbon Cycle. Vegetation productivity is an important component in the carbon cycle and urban biogeochemical cycles (26, 27). Other aspects of the carbon cycle, such as autotrophic and heterotrophic respiration, might not correlate well with these vegetation indices. To understand the vegetation responses to urbanization at the leaf, species, and ecosystem level requires an additional set of approaches than what we have seen so far. This EVI enhancement likely leads to increased photosynthetic activities in cities because the EVI is proportional to photosynthesis (18, 19). In addition, the enhancement in photosynthesis might suggest growth enhancement if the ratio of autotrophic respiration to gross primary production is similar in urban and rural settings. However, more field studies should be conducted to investigate autotrophic respiration in paired urban–rural environments because environmental changes, such as enhanced temperature in cities (i.e., the urban heat island), might enhance autotrophic respiration as well. More importantly, whether this photosynthetic enhancement translates into net carbon gain at the ecosystem level is still an open question because temperature increase can accelerate soil carbon decomposition, which would offset the positive impact of EVI enhancement on carbon sequestration.

Complementary to Manipulative Experiments. One of the main scientific thrusts of our time is to understand how vegetation growth would be affected by projected changes of temperature, atmospheric CO_2 concentration, and other factors (28). Numerous expensive manipulative experiments have been designed for this purpose at species and ecosystem levels (e.g., 29, 30). Although these experiments have provided various types of evidence, they have suffered from several issues that are intrinsically associated with the methods themselves. First, the changes of the environmental variables in the experiments were abrupt (e.g., doubling of CO_2 and 2 °C increase in temperature) rather than gradual as they would occur in reality. Consequently, the observed responses may be instantaneous and pulsatile in nature, unable to represent the expected gradual responses. Second, most of the manipulative experiments have been at the species level, a few have been at the ecosystem level [e.g., the free-air CO_2 enrichment (FACE) experiments], and none have been at the landscape scale because of the high maintenance cost of the experiments. Third, most of the manipulative experiments deal with only a single factor (e.g., CO_2 enrichment, warming), which is not effective to understand the simultaneous holistic impacts of multiple factors (29).

Our study shows that remote sensing studies can provide complementary capabilities to the manipulative experiments in observing urban ecosystem responses to environmental changes. Remote sensing approaches provide holistic overall evidence on ecosystem responses over large areas, whereas manipulative experiments advance mechanistic understanding of the responses at process and ecosystem levels. Remote sensing and experimental scientists must come together to make their research complementary to advance our understanding of the impacts of environmental changes on urban ecosystems.

Attribution to Driving Forces. Studying the impacts of urbanization on vegetation growth is one of the main components of urban ecology (3, 10, 27, 31). It has important implications for global change studies because many of the changes in urban areas, including the responses of vegetation to these changes, can be harbingers or indicators of anticipated global changes and responses in other ecosystems (2, 4, 6). The research is complicated and challenging because vegetation growth in urban environments is affected by a myriad of driving factors (e.g., plant species, temperature, water, CO_2, O_3, N deposition) that have demonstrated extreme heterogeneities in space and time (3, 4, 6, 32).

The impacts of urbanization on vegetation growth need more attention because (*i*) the growth response of vegetation may vary by spatial (i.e., individual, species, community, ecosystem, region) and temporal scales and (*ii*) attribution of the varying responses is difficult because of the simultaneous presence of many possible driving forces. The driving forces of the urban vegetation growth enhancement in general are diverse and difficult to attribute without elegant experimental designs. For example, an increase in temperature in the urban environments can advance the start and delay the end of the growing season, and therefore make the growing season longer in urban areas relative to rural surroundings (33). Takagi and Gyokusen (34) observed that the maximum photosynthetic rate of *Ilex rotunda* enhanced with the increase of urbanization intensity, and was highest in the central district, where sunlight was lower, than in the suburbs. Furthermore, they found that the maximum photosynthetic rate was positively related to the concentrations of air pollutants (e.g., NO_2, SO_2) and traffic volume. These factors might be partially attributed to the increase of diffusive light in urban settings, which can effectively enhance photosynthesis in forest canopies (35). In addition to increasing the fraction of diffusive radiation, other biochemophysical effects of the elevated presence of aerosols and air pollutants on vegetation growth should be studied further and differentiated from CO_2 enrichment and/or temperature increase.

Materials and Methods

The scope of this study was 32 major cities in China (Fig. S1). The land cover classification at a resolution of 30 m was done previously for all cities using Landsat imagery (36, 37), and the urban land cover and extent maps for the years 2000, 2005, and 2010 were used to derive urban development intensity (β) for each city at these times accordingly using a 1-km window size that is defined by the version 5 Moderate Resolution Imaging Spectroradiometer (MODIS)/Terra EVI (MOD13A2) data. Urban intensity β was defined as the fraction of pixels falling into the urban land or built-up class within a 1 × 1-km window in the land cover map.

We used MODIS EVI data of those 32 cities for three time periods from 2000 to 2002, from 2005 to 2007, and from 2010 to 2012, respectively, to examine the temporal consistency of the observed patterns. To characterize the VI change along an urban intensity gradient, we binned MODIS VI values according to β classes. An interval of 0.01 was used for the β bins. The frequency (i.e., number of 1-km windows) and mean VI for each β class were calculated and analyzed. The specific VI response curve to β for each city, represented by a cubic polynomial model, was derived by regressing the averaged MODIS VI with the averaged β of the binned values (Fig. 2). The cubic model was used because it can better fit the various shapes of

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responses demonstrated across all 32 cities than either the linear or quadratic model.

In reality, V_v is nonfactual for any disturbed pixels. However, it can be approximated by the average VI in the rural areas around the city. In this study, we defined V_v as the intercept of the specific VI response curve to β. We set the built-up VI (i.e., V_{nv} for nonvegetative surfaces) to be 0.05 across all cities because there is no vegetation activity under this threshold (19, 38–40). The metrics for measuring the impacts of vegetation as described in the conceptual framework were calculated for all cities. Geospatial and statistical analyses were performed using ArcGIS (41) and the R environment (42), respectively.

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