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Vegetation growth enhancement in urban environments of the Conterminous United States

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Abstract

Cities are natural laboratories for studying vegetation responses to global environmental changes because of their climate, atmospheric, and biogeochemical conditions. However, few holistic studies have been conducted on the impact of urbanization on vegetation growth. We decomposed the overall impacts of urbanization on vegetation growth into direct (replacement of original land surfaces by impervious built-up) and indirect (urban environments) components, using a conceptual framework and remotely sensed data for 377 metropolitan statistical areas (MSAs) in the conterminous United States (CONUS) in 2001, 2006, and 2011. Results showed that urban pixels are often greener than expected given the amount of paved surface they contain. The vegetation growth enhancement due to indirect effects occurred in 88.4%, 90.8%, and 92.9% of urban bins in 2001, 2006, and 2011, respectively. By defining offset value as the ratio of the absolute indirect and direct impact, we obtained that growth enhancement due to indirect effects compensated for about 29.2%, 29.5%, and 31.0% of the reduced productivity due to loss of vegetated surface area on average in 2001, 2006, and 2011, respectively. Vegetation growth responses to urbanization showed little temporal variation but large regional differences with higher offset value in the western CONUS than in the eastern CONUS. Our study highlights the prevalence of vegetation growth enhancement in urban environments and the necessity of differentiating various impacts of urbanization on vegetation growth, and calls for tailored field experiments to understand the relative contributions of various driving forces to vegetation growth and predict vegetation responses to future global change using cities as harbingers.

KEYWORDS
direct effect, enhanced vegetation index, global environmental change, indirect effect, remote sensing, urban intensity, urban-rural gradients, vegetation growth

1 | INTRODUCTION

Human society is entering into an increasingly urbanized era. City dwellers accounted for 54% of the world's population in 2014 (United Nations, 2015). Land changes from green spaces to impervious surfaces to support the demands of increasing urban populations. Meanwhile, cities account for 78% of carbon emissions, 60% of residential water use, and 76% of wood used for industrial purposes (Grimm et al., 2008). Urbanization leads to various changes in the environment such as urban heat island (Zhou, Zhao, Liu, Zhang, & Zhu, 2014), atmospheric chemistry (Pan et al., 2016), hydrology (Suriya & Mudgal, 2012), biogeochemical cycles (Kaye, Groffman, Grimm, Baker, & Pouyat, 2006), and biodiversity including species homogeneity (Hope et al., 2003; Valiela & Martinetto, 2007). These changes are rightly surrogates for the most significant global environmental changes (IPCC, 2013). The various changes in urban environments have made cites ideal natural laboratories for global change studies (Farrell, Szota, & Arndt, 2015; Grimm et al., 2008; Zhao, Liu, & Zhou, 2016). Using urban habitats around the globe to develop and test hypotheses on future climate change impacts would complement manipulative experiments and predict how ecosystems would be altered in the future (Youngsteadt, Dale, Terando, Dunn, & Frank, 2015).

It has been long argued whether vegetation growth is abated or enhanced in urban environments compared with its counterpart in the rural settings. Earlier horticultural studies believed that vegetation growth would be suppressed by severe environmental conditions in cities (e.g., higher air temperature, lower soil water content; Quigley, 2002, 2004). While field experiments or satellite-based studies showed that vegetation growth in urban environments was enhanced due to fertilization, irrigation, introduction of non-native species, urban heat island, climate change, and atmospheric chemistry change such as O_3 and CO_2 (Gregg, Jones, & Dawson, 2003; Imhoff et al., 2004; Pretzsch et al., 2017; Zhao et al., 2016; Zhou, Zhao, Zhang, & Liu, 2016).

Satellite-based approaches provide opportunities for monitoring the spatial and temporal dynamics of vegetation productivity due to their extensive observations and representation of a wide range of physical and biological processes (Schaefer et al., 2012; Wang et al., 2010). Moreover, numerous studies have demonstrated that the greenness indices from remotely sensed data, especially for enhanced vegetation index (EVI), is an effective indicator of vegetation productivity as it is proportional to photosynthesis and regarded as a proxy for being regarded as proxies of both light use efficiency and the fraction of photosynthetically active radiation (fPAR) absorbed by the vegetation canopy (Gitelson et al., 2006; Sims et al., 2006; Wu, Niu, & Gao, 2010; Yuan et al., 2007).

We have proposed a generic framework for assessing vegetation growth in urban environments (Zhao et al., 2016). After applying the framework to 32 major cities in China, we found that vegetation growth enhancement in cities was a widespread phenomenon (Zhao et al., 2016). An important question one would ask is "can this widespread vegetation growth enhancement observed in China be seen in other places?" because cities are experiencing different urbanization processes in different countries. As the largest developed country, the United States of America has witnessed the long-term evolution of humans and environments within urban ecosystems that is quite different from that in China. This paper aims to explore the vegetation growth in 377 USA metropolitan statistical areas (MSAs). Our research questions are: (i) Does the widespread enhancement of vegetation growth exist in the cities of the United States? (ii) Does the relationship between vegetation growth and urban intensity vary in time and space? (iii) What are the similarities and differences of vegetation growth responses in cities of China and US?

2 | MATERIALS AND METHODS

2.1 | Study area

A total of 377 MSAs in the Conterminous United States (CONUS) were included in this study (Figure 1). MSAs were defined as a central urban area with population at least 50,000, plus adjacent territory that has a high degree of social and economic integration with the core as measured by commuting ties (OMB, U.S. Census Bureau, Census Geographic Glossary). The CONUS covers a broad range of climate and vegetation types. To explore the possible regional differences of vegetation responses, the CONUS were divided into nine climatically consistent regions identified by the scientists of National Centers for Environmental Information (Karl & Koss, 1984). The Northeast (NE, covered 50 MSAs) and Southeast (SE, covered 70 MSAs) are mainly covered by forests; the East North Central (ENC, covered 31 MSAs) and Central (C, covered 86 MSAs) region are covered by a large cropland area; the West North Central (WNC, covered 12 MSAs) and the South (S, covered 48 MSAs) region are heavily covered by crops, pasture and grassland; the Southwest (SW, covered 29 MSAs) is dominated by shrubs; and the West (W, covered 29 MSAs) and Northwest (NW, covered 22 MSAs) are mostly covered by forests and shrubs. More detailed information about MSAs can be found in the Supporting Information.

2.2 | The framework for analyzing the urbanization effect on vegetation growth

To maintain methodology consistency, we applied the framework of Zhao et al. (2016) to 377 MSAs in CONUS. The total impacts of urbanization on vegetation growth could be decomposed to direct and indirect impacts. The direct impact referred to the change of vegetation index (VI) due to the replacement of original land surfaces by impervious built-up. The indirect impact referred to the change of VI resulted from the change of the growth environments. Conceptually, the observed VI could be decomposed into two parts (Equation 1):

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

where V_{obs} was the observed VI of the urban pixel, V_v was the background vegetation index without urbanization (the VI of a pixel within a MSA that has zero built impervious surface), V_{nv} is the VI of the pixel completely filled by non-vegetative surfaces. β is urban intensity, i.e., the percent developed imperviousness. ω conceptually abstracts the impact of urbanization on the vegetation growth. It should be noted that V_v might include fully vegetated pixels within the urban area, whose vegetation growth might have been affected by urbanization. However, the number of these pixels is relatively small compared with that in the rural area, and therefore their impact on the background vegetation index should be minimal.

The zero-impact line ($\omega = 0$), representing the situation that urbanization has no indirect effect on vegetation growth, was determined by two VI values corresponding to background vegetation

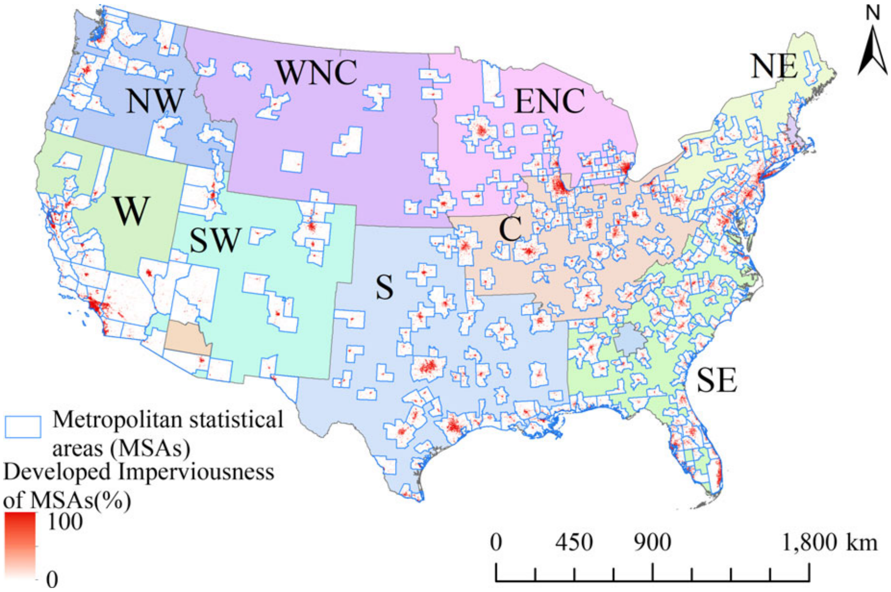

FIGURE 1 Spatial distribution of the 377 metropolitan statistical areas (MSAs) in the Conterminous United States, together with percent developed imperviousness (2011) and climate regions: Northwest (NW), West (W), Southwest (SW), West North Central (WNC), East North Central (ENC), South (S), Central (C), Northeast (NE), and Southeast (SE) (Karl & Koss,1984) [Colour figure can be viewed at wileyonlinelibrary.com]

($\beta = 0$, VI = V_v) and fully urbanized pixels ($\beta = 1$, VI = V_{nv}):

$$V_{zi} = (1 - \beta)V_v + \beta V_{nv} \tag{2}$$

The relative direct urbanization impact on vegetation growth was calculated as:

$$\omega_d = \frac{V_{zi} - V_v}{V_v} \times 100\% \tag{3}$$

The relative indirect urbanization impact on vegetation growth was calculated as:

$$\omega_i = \frac{V_{obs} - V_{zi}}{V_{zi}} \times 100\% \tag{4}$$

In order to quantify how much the growth change due to indirect impact on the remaining vegetation partly compensated for (or exacerbated) the reduced productivity due to the replacement of original land surfaces by impervious built-up, we defined the ratio of the absolute indirect (i.e., $V_{obs} - V_{zi}$) and direct (i.e., V_v–V_{zi}) impact as growth offset (τ, Equation 5). The offset value τ represented how much the growth of the remaining vegetation patches can offset (if τ was positive) or worsen (if τ was negative) the EVI reduction due to the replacement of original land surfaces by impervious built-up.

$$\tau = \frac{V_{obs} - V_{zi}}{V_v - V_{zi}} \times 100\% \tag{5}$$

2.3 | Calculation of the observed EVI during growing season

Due to the large spatial heterogeneity of growing season in CONUS, we derived the growing season for each pixel in 377 MSAs using NOAA's 1981–2010 U.S. climate normals (available from the National Climate Data Center, including probabilities of first/last occurrence of minimum temperature events and growing season length for 5,808 U.S stations). The growing season is determined by the days between the average date of last spring frost-freeze (0°C) and first autumn frost-freeze (0°C) (Arguez, 2012). The average date of last spring frost-freeze and first autumn frost-freeze from 1981 to 2010 for each pixel within each MSA was obtained by interpolating the climate normals from 5,808 stations at a resolution of 250 m × 250 m across CONUS using a natural neighbor technique in Arcgis software.

We used EVI 250 m product (MOD13Q1) from the Moderate Resolution Imaging Spectro-radiometer (MODIS) to characterize the spatial variability of the EVI in MSAs (https://lpdaac.usgs.gov). The MODIS is an optical sensor onboard the Terra and Aqua satellite as part of the NASA Earth Observing System. MODIS scans the entire earth surface every one-two days and acquires data in 36 spectral bands, containing the surface reflectance values of red band (620–670 nm), near infrared band (841–875 nm) and blue band (459–478 nm) used for the calculation of EVI. MOD13Q1 product has 23 sixteen-day composites in a year, starting on January 1st each year. We averaged the growing season EVI in the 377 MSAs of the Conterminous United States in years 2001, 2006, and 2011, respectively, to examine the annual variations of vegetation growth.

2.4 | Calculation of the urban intensity

Following Zhao et al. (2016), urban intensity of a pixel was defined as the percentage of developed imperviousness surfaces within the pixel, ranging from 0 (fully vegetated surfaces) to 1 (nonproductive surfaces). The Percent Impervious Surfaces Product was downloaded from https://www.mrlc.gov/ with the spatial resolution of 30 m in years 2001, 2006 and 2011 (Homer et al., 2007, 2015; Xian et al., 2011a,b). To be consistent with EVI pixel, imperviousness percentages layer at 30 m was aggregated and resampled to 250 m × 250 m pixel using Arcgis software, thus each output pixel contained the mean of the input pixels that were encompassed by the extent of that pixel. Then after averaging, pixels that were water body, or those with elevations more than 50 m above the highest elevation of urban core (imperviousness percentage was above 50%), were excluded to avoid the effect of water body or elevation on urbanization impact.

2.5 | The determination of the zero-impact line: mean EVIs for background vegetation and fully urbanized pixels

The mean EVIs corresponding to background vegetation (V_v) and fully urbanized pixels (V_{nv}) are the key parameters for each city to determine the zero-impact line. There are two ways to determine the V_v. One uses the mean or median EVI of all the fully vegetated pixels for each MSA. The other uses the intercept of the regression between EVI and urban intensity (β) (Zhao et al., 2016). We tried both ways and found trivial difference in most cases except that the second approach was more stable because it relied on the trend of EVI change and minimized the effect of EVI outliers. To develop the EVI~β relationship, the EVI mean value within each urban intensity β bin (interval of 0.01) was derived for MSA. This approach ignores physical locations of the pixels, which makes the continuous measure of urban gradient possible, independent of city shape and developing direction. The EVI~β relationship was fitted by a cubic polynomial model for each MSA: $y = V_v + a_1x + a_2x^2 + a_3x^3$, where y was the observed EVI and x was β. The order of polynomial was determined empirically as we found that lower orders (order <3) could not faithfully capture the trend while higher orders would increasingly entertain the outliers. The good fit of the cubic polynomial model (adjusted $R^2 = 0.83\sim 0.99$, $P < 0.01$ for all cities and years) indicated significant correlation between vegetation growth and urban intensity and the suitability of V_v's determination across all MSAs.

Zhao et al. (2016) set V_{nv} to 0.05 according to Huete et al. (2002). This study determined V_{nv} by the mean EVI value of fully urbanized pixels (β = 1) across 377 MSAs in CONUS in years 2001, 2006 and 2011. Then the high-resolution Google Earth imagery was used to manually check the pixels where β = 1 to assure that there was no vegetation activity to avoid the uncertainties from imperviousness data. The resultant average V_{nv} was 0.064, and there was no vegetation activity under this threshold.

3 | RESULTS

3.1 | National vegetation responses to urbanization

There were strong patterns of EVI~β relationships from the combined observations of 377 MSAs in CONUS in all years. Generally, the observed EVI declined along the urban intensity gradient regardless of background EVI values (Figure 2a–b). The intercepts of the specific EVI response curves to β (V_v), representing background vegetation conditions, varied across MSAs. And prevalent vegetation growth enhancement can be seen from the MSAs (Figure 2c–d). Overall, 88.4%, 90.8%, and 92.9% of urban intensity bins recorded growth enhancement, while the remaining bins showed abatement in 2001, 2006, and 2011, respectively. The growth enhancements due to indirect impact offset about 29.2%, 29.5%, and 31.0% of the vegetation loss due to direct effects on average in 2001, 2006, and 2011, respectively (Equation 5; Figure 2e). The offset value could be larger than 100%, because the observed EVI were higher than V_v in relative low urban bins especially for some arid MSAs. Notably, higher variations of offset values were associated with lower urban intensity, and vice versa.

3.2 | Temporal stability of national vegetation responses to urbanization

The differences of the coefficients in the polynomial models across years can be used to assess the temporal variability of the EVI~β relationship. The intercepts of the regression (V_v) varied from 0.06 to 0.57 for all 3 years. The median of the V_v was 0.42, 0.43, and 0.43 in 2001, 2006, and 2011, respectively. The coefficient of an MSA in 2001 was a good predictor of its coefficient in 2006 or 2011, with this relationship across all MSAs falling near the 1:1 line (Figure 3). This finding indicated that vegetation growth responses to urbanization presented a rather stable temporal pattern in 2001, 2006, and 2011. However, the points were not in completely alignment with the 1:1 line and some points scattered off the line.

3.3 | Regional vegetation responses to urbanization

Substantial differences in the urban vegetation growth offset were observed among nine climate regions (Figure 4). Generally, the growth offset in the west was higher than that in the east. In 2011, the offset value was highest with 142.6% in SW, second highest with 62.9% in WNC, third highest with 52.4% in S, followed by NW (42.8%), ENC (37.3%), W (37.3%), C (28.2%), NE (23.7%), and SE (19.9%). And we also found that the offset values varied in larger range with lower urban intensity, which might be related the various background vegetation conditions. The offset medians of urban intensity bins showed a gradual descending pattern along the urban intensity, which was largely caused by the higher loss of VI due to the surface replacement with higher urban intensity. The vegetation growth presented similar responses throughout the three periods. In NE region, C region and SE region, the regional growth offset showed a slightly increasing pattern over time, while WNC region presented a decreasing pattern over time, and other regions presented fluctuating patterns. Overall, the temporal variability was rather small for most climate regions.

We also plotted the relative urban indirect impact (ω_i) on EVI changes for nine regions in 2011 (Figure 5). Results showed that

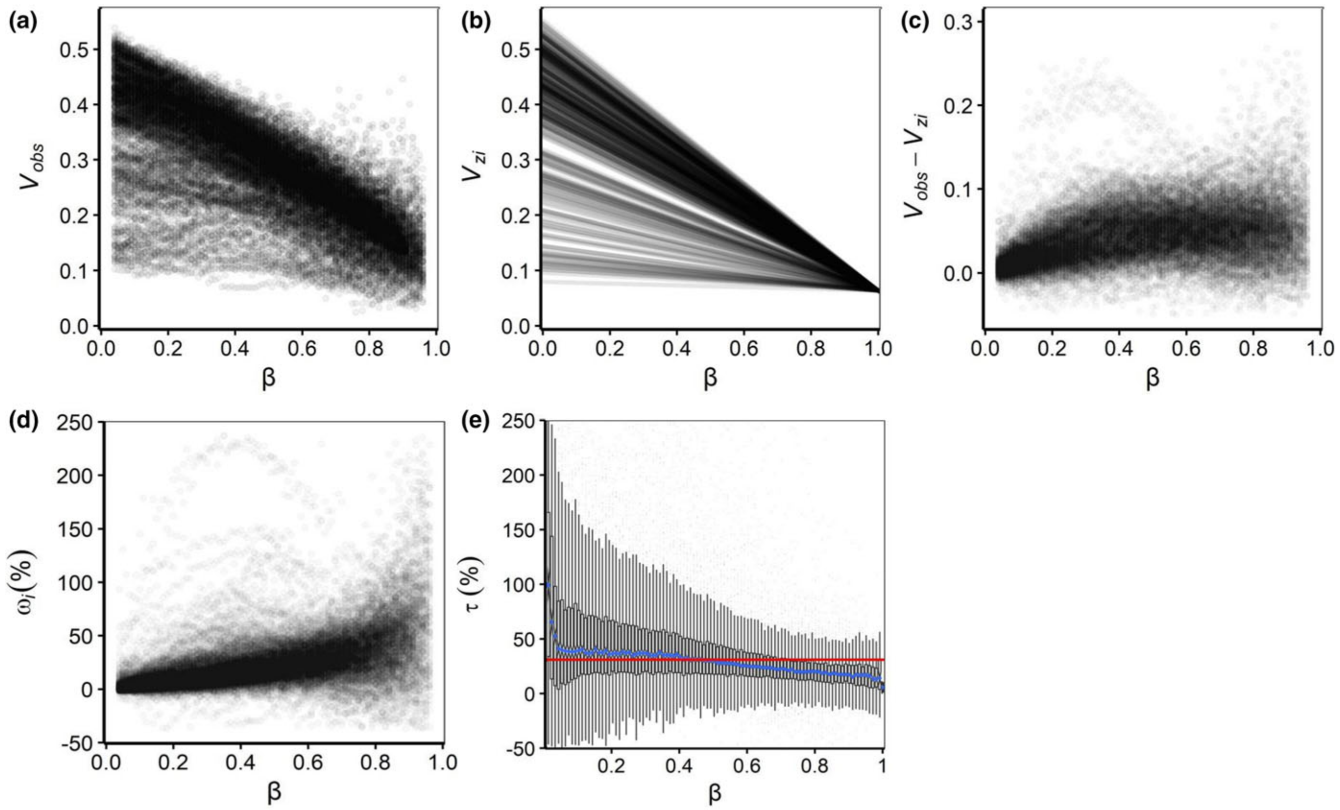

FIGURE 2 Generalized patterns of urbanization impact on EVI across 377 MSAs in 2011: (a) V_{obs} (the observed EVI) along β (urban intensity), (b) V_{zi} (EVI on zero- impact line), (c) the absolute EVI change ($V_{obs} - V_{zi}$), (d) ω_i (the relative indirect impact), calculated as $(V_{obs} - V_{zi})/V_{zi}$, and (e) τ (the growth offset), represented how much the indirect impact can offset (if τ was positive) or worsen (if τ was negative) the EVI reduction due to direct replacement of original land surfaces by impervious built-up, calculated as $(V_{obs} - V_{zi})/(V_v - V_{zi})$. The boxplot for τ in each urban bin showed 25th and 75th percentiles (gray points were outliers, the medians for each bin was depicted by the blue line and the mean of the medians was 31.0%, showed by the red line) [Colour figure can be viewed at wileyonlinelibrary.com]

for the central and eastern regions (e.g., ENC, S, NE, C, and SE), the relative indirect impact on EVI increased along the urban intensity. While for most MSAs in western regions (e.g., NW, WNC, SW, and W), the relative indirect impact on EVI reached highest in medium-high urban intensity bins and showed a hump shape.

We further compared MSA-specific regression coefficients of the EVI~β relationship for each climate region (Figure 3). The median of V_v values (i.e., background of vegetation growth) in 2011 was the largest in NE region (0.50, V_v ranging 0.43 to 0.55), followed by C region (0.47, V_v ranging 0.34 to 0.55). The median V_v was 0.46 in ENC region, 0.42 in SE region, 0.37 in NW region, WNC region and S region, 0.27 in W region and 0.13 in SW region, respectively. Similarly, the coefficient of an MSA in each region in 2001 was a good predictor of its coefficient in 2006 or 2011, with this relationship across all MSAs of each region falling near the 1:1 line, indicating the relative temporal stability across each region. However, the coefficients in some regions varied across years, e.g., V_v in ENC region was higher in year 2006 than other years, in accordance with the lower offset value in year 2006 for ENC region. We also noticed that there were some off-group points in Figure 3b–d.

3.4 | Vegetation responses to urbanization for MSAs

The detailed relationship between EVI and urban intensity β across 377 MSAs in CONUS in 2011 were depicted in Figure 6 and Supporting information Figure S1–S8. We found that almost all the pixels in MSAs were above the zero-impact line, which indicated the overall prevalent vegetation growth enhancement in urban environments. Only a few pixels of MSAs like Madera (CA) and Santa Cruz-Watsonville (CA) in West region with low urban intensity were below the zero-impact line (indicating growth abatement). It was noteworthy that in some MSAs in western USA such as Idaho Falls (ID), Reno (NV), Denver-Aurora-Lakewood (CO), Ogden-Clearfield (UT), Provo-Orem (UT), Pueblo (CO), Riverside-San Bernardino-Ontario (CA), and Salt Lake City (UT), EVI values with medium-high urban intensity were even larger than background values, which caused the higher offset for vegetation growth. We also calculated V_v, median of observed EVI and mean of the medians of growth offset along all urban intensity bins for 377 MSAs (Supporting information Table S1). For example, the background vegetation index for Phoenix-Mesa-Scottsdale (PMS, AZ) was 0.11, and the median value of observed EVI among all urban bins was 0.12, causing 211.8%

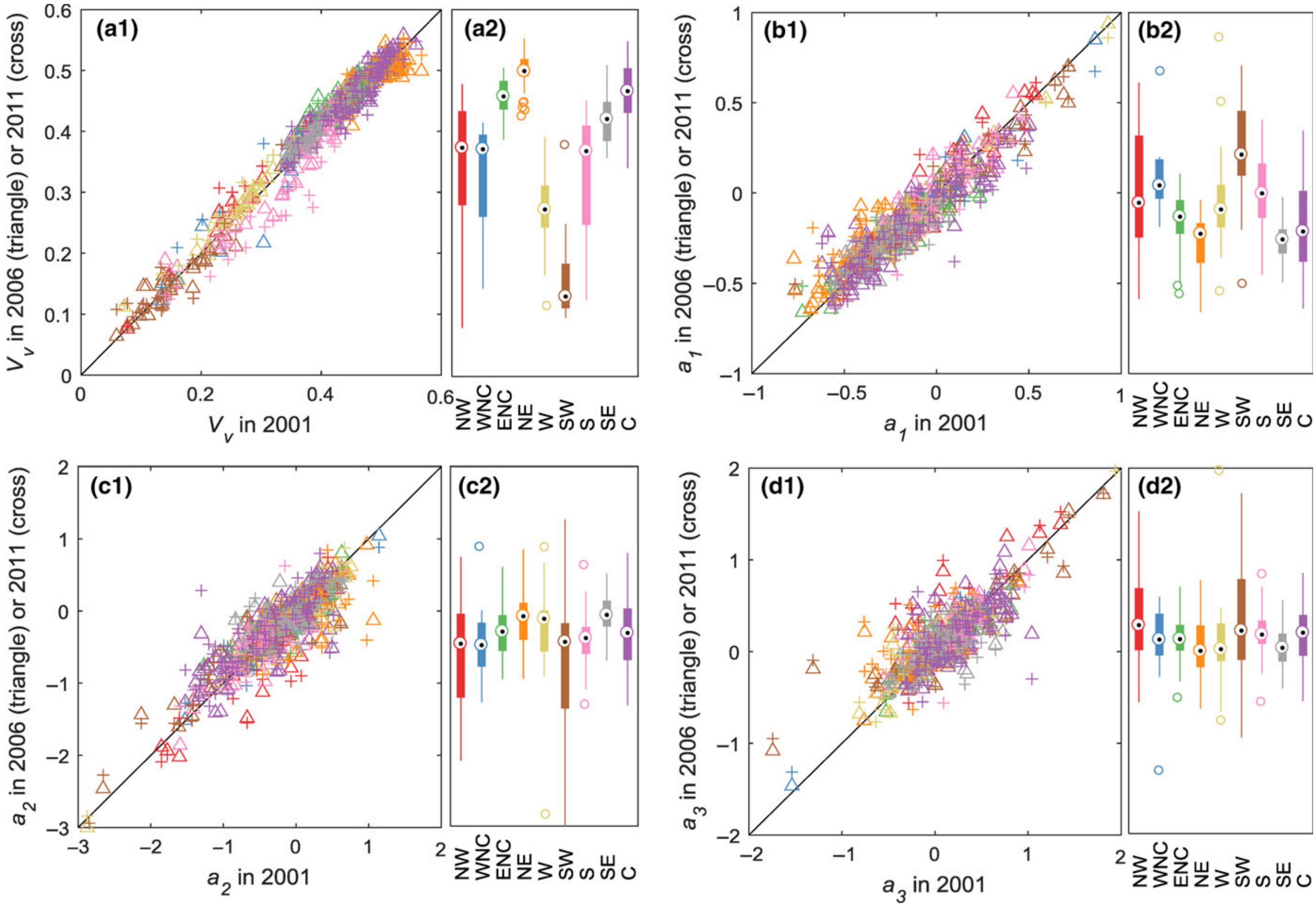

FIGURE 3 Comparisons of the MSA-specific regression coefficients between the EVI and urban intensity across three time periods (one data point represented one MSA). In panel (a–d)−1, the *x* axes and *y* axes presented the four coefficients (i.e., V_v, a_1, a_2, and a_3). Panel (a–d)−2 were the coefficients boxplots in 2011 for nine regions [Colour figure can be viewed at wileyonlinelibrary.com]

offset for the loss of vegetated area. And for Boston-Cambridge-Newton (BCN, MA-NH) in northeast region, background vegetation index was 0.5, and the median of observed EVI among all urban bins was 0.39, the overall effect of urbanization was negative, while vegetation was enhanced which offset 47.5% of the loss vegetation.

4 | DISCUSSION

4.1 | Impacts of urbanization on vegetation growth in US at national and regional scales

Previous studies based on remote sensing approaches observed that the overall net impacts of urbanization on vegetation growth were negative in China (Pei, Li, Liu, Wang, & He, 2013; Zhao et al., 2016), the southeastern USA (Milesi, Elvidge, Nemani, & Running, 2003), and the USA (Imhoff et al., 2004). Our study found that EVI declined with urban intensity for most of MSAs in CONUS, which is consistent with former findings. We also found some MSAs such as Idaho Falls (ID), Reno (NV), Denver-Aurora-Lakewood (CO), Ogden-Clearfield (UT), Provo-Orem (UT), Pueblo (CO), Riverside-San Bernardino-Ontario (CA), and Salt Lake City (UT) where EVI values with medium-high urban intensity were even higher than background values.

Besides the overall impact, it is necessary to differentiate urbanization effects into direct and indirect ones (Zhao et al., 2016). Most of the previous regional scale studies did not explicitly quantify the indirect impact (i.e., effects other than the replacement of vegetation with impervious built-up surfaces) of urbanization on vegetation growth. Our results indicated the indirect vegetation growth enhancement was observed on 88.4%, 90.8%, and 92.9% of urban bins in 2001, 2006, and 2011, respectively. And these growth enhancements due to indirect effects offset about 29.2%, 29.5%, and 31.0% of the growth reduction due to direct effects on average in 2001, 2006, and 2011, respectively. The vegetation responses to urbanization showed temporal stability, which was also seen in Chinese cities (Zhao et al., 2016). Our results were consistent with the existing ground-based experiments which demonstrated mostly vegetation growth enhancement in urban environments compared to the rural counterparts. For example, Searle et al. (2012) observed an eightfold increase in biomass of red oak seedlings in urban environments relative to those at rural sites. Gregg et al. (2003) found that the cottonwood growth in urban areas doubled that at rural sites. Briber et al. (2015) found that *Quercus rubra* tree's basal area increment nearly doubled following urban development across eastern Massachusetts. Pretzsch et al. (2017) found that urban trees tended to

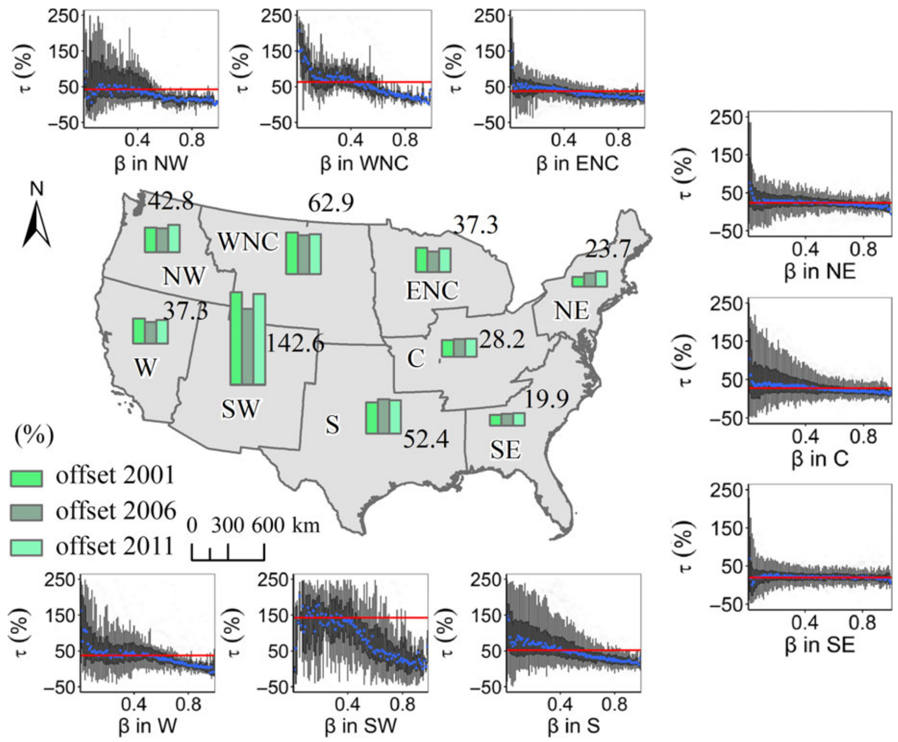

FIGURE 4 Vegetation growth offset in 2001, 2006, and 2011across nine climate regions: Northwest (NW), West (W), Southwest (SW), West North Central (WNC), East North Central (ENC), South (S), Central (C), Northeast (NE), and Southeast (SE) (Karl & Koss,1984; https://www.ncdc.noaa.gov/monitoring-references/maps/us-climate-regions.php). The numbers beside the bars and the offset data in boxplots were in 2011 [Colour figure can be viewed at wileyonlinelibrary.com]

grow more quickly than their counterparts in the rural surroundings in ten metropolises worldwide based on tree ring analyses. There existed a few studies observing the negative of urbanization impact. Meineke, Youngsteadt, Dunn, and Frank (2016) reported that urban warming was associated with an estimated 12% loss of carbon sequestration for mature trees using factorial experiment, in part because photosynthesis was reduced at hotter sites. Pretzsch et al. (2017) found that temperate-zone cities in European among ten metropolises worldwide were the only case where urban trees grew significantly slower than rural trees, because the adverse urban zone effects seem to constrain tree growth in temperate climate cities. We did suggest the abatement effect in a small fraction of bins along the urban intensity gradient as well. Nevertheless, field experiments were usually at the individual level and limited in spatial scope, lacking comprehensive understanding of direct impact of surface replacement on vegetation. Our study applied remote sensing approaches to analyze the community responses to urbanization, providing a new approach for studying holistic ecosystem responses to urbanization processes. Uncertainty still exists due to the complexity of city and difficulty of capturing human management activities in space.

From the regional perspective, the overall impact of urbanization on vegetation was generally lower in the eastern America where the background vegetation index was higher than other regions. The lowest growth offset values were observed in the northeast (23.7%) and southeast region (19.9%) where the background vegetation grew better than other regions.

Prevalent vegetation growth enhancement in MSAs in CONUS could be attributed to various factors. The urban-to-rural gradients incorporate local to regional variations in terrain, soils, species, and air pollutants, presenting a myriad of driving factors such as elevated temperature, CO_2 enrichment, N deposition, ozone, air pollutants, and traffic volume (Carreiro & Tripler, 2005; Gregg et al., 2003; Imhoff et al., 2004; Pei et al., 2013; Takagi & Gyokusen, 2004). These factors co-vary in space and time and their interactions among one another make the plant growth environments complicated.

4.2 | Comparison of vegetation growth enhancement between China and the US

Zhao et al. (2016) found 84%, 85%, and 86% of urban bins were observed with vegetation growth enhancement in 32 major cities in China in 2001, 2006, and 2011, respectively, while our results showed 88.4%, 90.8%, and 92.9% of urban bins in which growth enhancement were observed in 2001, 2006, and 2011, respectively, in all 377 MSAs in CONUS. The vegetation enhancement in CONUS showed more variations than that in Chinese cities. This might be related to the differences in sample size, urbanization level, and geospatial coverage of these two datasets. Most of the cities in Zhao et al. (2016) were located in the east of China, and the climate and vegetation conditions were similar to the east CONUS. However, only a few cities from the arid and semi-arid west, such as Lhasa and Urumqi, were included in Zhao et al. (2016), and the urbanized

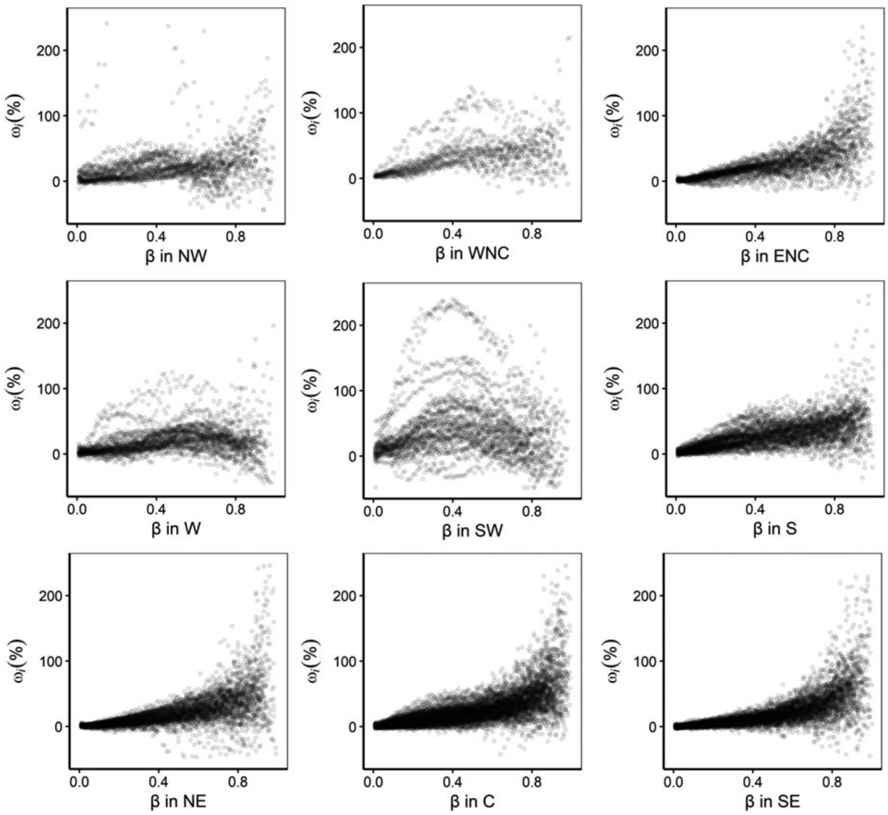

FIGURE 5 The relative urban indirect impact (ω_i) for EVI changes for nine regions in 2011

processes in western China was much slower than those in the east (Wang & Pan, 2016). In these cities, urbanization indirect impact on vegetation was higher than the east probably due to the exotic species and improved management practices (Zhao et al., 2016).

The vegetation growth enhancement offset about 40% of the direct surface-replacement impact in 32 major cities of China, while in CONUS that offset 29.2%, 29.5%, and 31.0% across MSAs in 2001, 2006, and 2011, respectively. This might be mainly related to the background vegetation value V_v. The background EVI during April–October in Chinese cities ranged ca. 0.10–0.40, while most background EVI in MSAs during growing season ranged 0.10–0.57. With higher background vegetation value, the offset of urban vegetation enhancement in CONUS was lower than that in Chinese cities.

We also found that the EVI changes were highest in medium-high urban intensity bins (0.38–0.60) for most MSAs in the arid western regions (e.g., NW, WNC, SW, and W) in CONUS, which were not observed in Chinese cities and in most eastern regions in CONUS. The different response patterns (hump-shaped vs. monotonic) were largely determined by the background climate and natural vegetation conditions of cities. In arid regions, the production of natural vegetation was low compared to that in humid regions, which favored the formation of the hump-shape response curves through the following disparity of human intervention on vegetation along the urban intensity gradient. In general, replacing natural vegetation of low productivity or desert in some cases through planting and management practices (e.g., irrigation) in arid urban environments could effectively promote vegetation growth via improvement of quantity/density (i.e., vegetated area) and quality (i.e., more productive per unit leaf area due to fertilization and irrigation). However, such a growth enhancement was not uniform along the urban intensity gradient. A plausible interpretation of the hump-shaped response curve was provided as follows. There was too much land in the urban fringe to plant and manage practically and most land remained in background vegetation conditions. Therefore, the average growth enhancement would be low in these urban fringe areas. On the other end of the gradient, there was too little land to vegetate in areas with high urbanization intensity to produce sizable effect. Only the most of open spaces in areas with intermediate urbanization intensity (manageable size compatible with the urban intensity) could be planted and managed, producing the maximum vegetation enhancement. The combination of these three sectors along the urban intensity gradient produced the hump-shape response curves in the arid regions. In contrast, replacing natural vegetation with other vegetation in humid cities would not generate such a hump-shape curve as the vegetation productivities were similar in general. It should be noted that our approach quantifies the total effect of urbanization on vegetation index, including contributions from vegetation alternation (i.e., man-made quantity changes in species, vegetated area, and density) and growth change induced by urban environment shifts (i.e., environment-induced quality change of leaf traits). How to separate these contributions is important, particularly in arid regions, but still challenging.

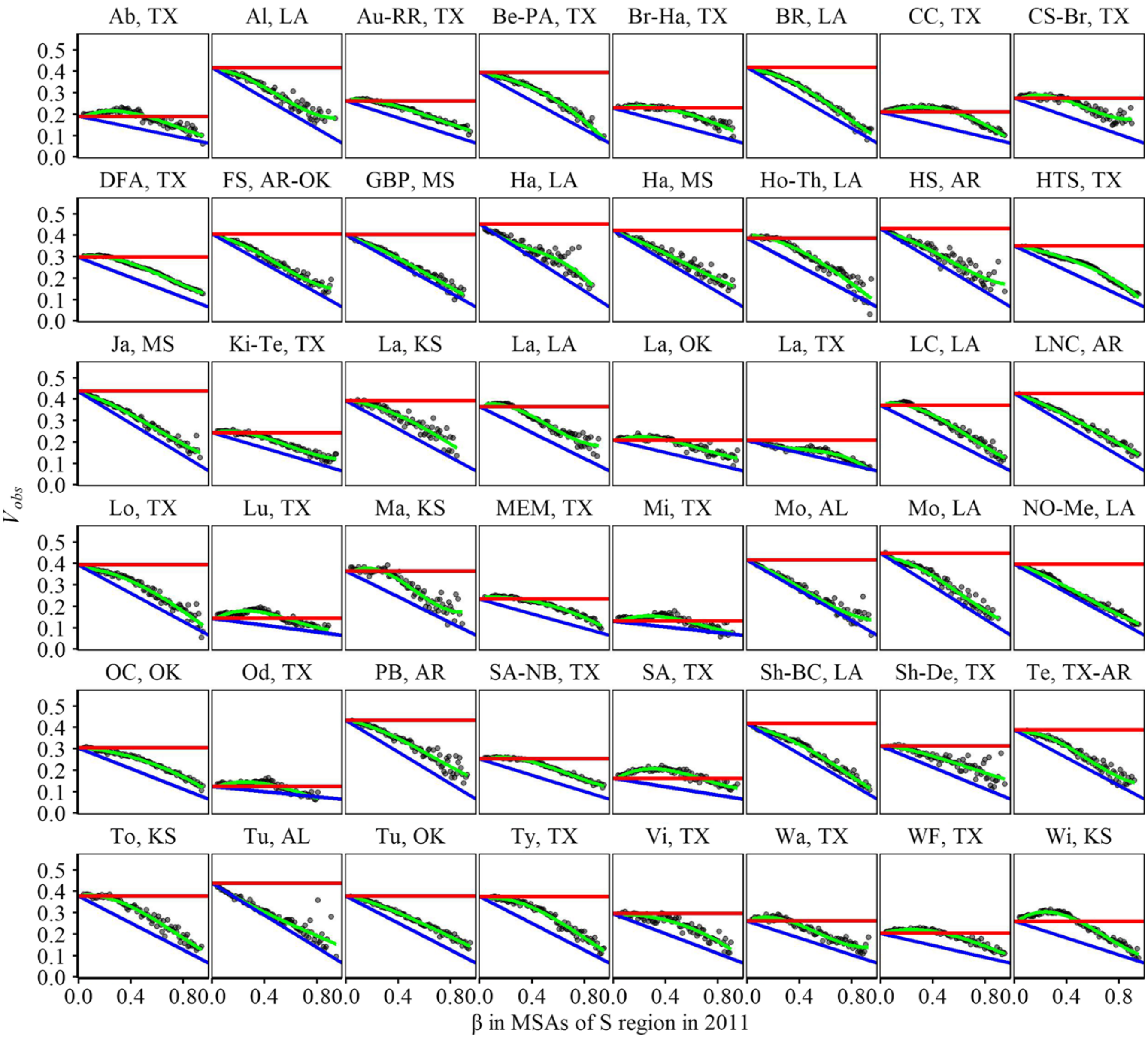

FIGURE 6 The relationships between the EVI and urban intensity β across MSAs in South (S) region of Conterminous United States in 2011. The cubic regression lines (green) of the observed EVI (circles) were shown along with the background EVI values V_v (i.e., the horizontal red lines) and zero-impact lines (blue). The abbreviations of MSAs were in Table S1 in the Supporting Information. The rest EVI response figures to urban intensity for 377 MSAs were shown in the Supporting Information [Colour figure can be viewed at wileyonlinelibrary.com]

4.3 | Implications to global change studies

The surface replacement resulted from urbanization has brought substantial consequences to ecosystems at local to global scale, which in turn has affected land surface situations and processes such as carbon and water cycles (Liu et al., 2017). Cities are experiencing elevated temperature and atmospheric CO_2 concentration, among other environmental changes, and they have been rightfully regarded as the harbinger of the future global change (Grimm et al., 2008). Growth enhancement in contemporary plant communities in urban environments could provide valuable information for the future vegetation growth areas with low urbanization in the next several decades as climate change and urbanization processes continue. Our results show the overall impacts of urbanization on vegetation growth, and the extrapolation of the results to future vegetation should be cautious as the specific situations will likely be different. For example, the observed growth enhancement could not be translated directly to future non-urban background vegetation as the observed effect is driven by a combination of factors including warming, CO_2 fertilization, elevated N deposition, and intensive management, and some of these factors (e.g., irrigation) will not be present in the background vegetation. The effect could not be translated as well to areas whose primary background vegetation (e.g., cropland) is qualitatively different urban vegetation. Nevertheless, results from urban areas are likely very useful for inferring effects of climate change on vegetation growth in the future if the overall effect is quantitatively attributed to individual driving variables such as CO_2 increasing and warming.

Vegetation productivity is a significant part of the carbon biogeochemical cycle. One implication of this result is that EVI enhancement in urban environments could be an indicator of the increasing productivity globally under future environmental conditions (e.g., increased CO_2 and high temperature) as EVI is proportional to photosynthesis (Wu et al., 2010; Yuan et al., 2007). This could lead to changes of carbon sources and sinks at a variety of spatial and temporal scales. More broadly, vegetation response to urbanization could provide the insight into the long-term effects and interactions of multiple global-change drivers and adaptation strategy by plants. Current manipulative experiments rely on micro- to plot-scale facilities to manipulate one or more factors at a time to monitor the plant responses (Bagley et al., 2015; Dieleman et al., 2012; Kupper et al., 2011; Löw et al., 2006; Ma et al., 2017; Nunn et al., 2005). In addition, manipulative experiments usually employ abrupt changes of variables (e.g., 50% precipitation reduction, doubling of CO_2) rather than gradual changes, which might result in instantaneous and pulsatile plant responses (Zhao et al., 2016). Using urban habitats around the globe as natural laboratories to develop and test hypotheses about future climate change impacts would complement the manipulative experiments (Youngsteadt et al., 2015).

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