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NDVI indicated characteristics of vegetation cover change in China's metropolises over the last three decades

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Abstract How urban vegetation was influenced by three decades of intensive urbanization in China is of great interest but rarely studied. In this paper, we used satellite derived Normalized Difference Vegetation Index (NDVI) and socio-economic data to evaluate effects of urbanization on vegetation cover in China's 117 metropolises over the last three decades. Our results suggest that current urbanization has caused deterioration of urban vegetation across most cities in China, particularly in East China. At the national scale, average urban area NDVI ($NDVI_u$) significantly decreased during the last three decades ($P <$ 0.01), and two distinct periods with different trends can be identified, 1982–1990 and 1990–2006. $NDVI_u$ did not show statistically significant trend before 1990 but decrease remarkably after 1990 ($P < 0.01$). Different regions also showed difference in the timing of $NDVI_u$ turning point. The year when $NDVI_u$ started to decline significantly for Central China and East China was 1987 and 1990, respectively, while $NDVI_u$ in West China remained relatively constant until 1998. $NDVI_u$ changes in the Yangtze River Delta and the Pearl River Delta, two regions which has been undergoing the most rapid urbanization in China, also show different characteristics. The Pearl River Delta experienced a rapid decline in $NDVI_u$ from the early 1980s to the mid-1990s; while in the Yangtze River Delta, $NDVI_u$ did not decline significantly until the early 1990s. Such different patterns of $NDVI_u$ changes are closely linked with policy-oriented difference in urbanization dynamics of these regions, which highlights the importance of implementing a sustainable urban development policy.

Keywords China's cities · Normalized Difference Vegetation Index (NDVI) · Urbanization · Vegetation cover change

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Introduction

In 2007, 50% of the world's population lives in cities (UN HABITAT 2006; Grimm et al. 2008). It is also projected that the global urban population will reach five billion by 2030 (UN HABITAT 2006). Fast urbanization imposes growing demands on water, energy, and mineral materials for urban areas. For example, cities consume two thirds of world's energy and produce more than 70% of world's CO_2 emission (International Energy Agency 2008). Thus, the environmental sustainability of urban areas has drawn increasing attention in recent years and become a hotspot in urban environment and ecology research (Breuste 2002; Jung et al. 2003; Martin et al. 2004; Zhang et al. 2004; Myeong et al. 2006; Grimm et al. 2008). Green vegetation patches in urban areas have significant environmental functions such as microclimate adjustment (Zhou et al. 2004), heat island effect mitigation (Fung and Siu 2000), noise reduction (Fang and Ling 2003), air pollution mitigation (Currie and Bass 2005), and aesthetic appreciation (McPherson et al. 2005). For example, Zhou et al. (2004) suggested that decreasing urban vegetation may be responsible for the increasing minimum temperature of the urban area in southeastern China. A recent report (Churkina et al. 2010) also found that carbon density in urban areas is comparable to that of some natural forests. The dynamic of urban vegetation may leave footprints in global biogeochemical cycles (Grimm et al. 2008). However, the sensitivity of urban vegetation to urbanization, a process marked by urban area expansion with intensive land use change, economic development, and rapid population growth (Antrop 2000; Weber and Puissant 2003), has not yet been systematically studied.

China has experienced the world's most remarkable urbanization since the 1980s (United Nations 2006). Its urbanization rate (the ratio of the urban population to the total population of a given region) increased from 21% in 1982 to 45% in 2007 (Shen 2005; National Bureau of Statistics 2008), and it is still rising. The number of metropolises, defined as cities with population more than one million, has quadrupled in 30 years (Chen and Xu 2007). In the meantime, the downsides of fast urbanization such as deteriorated air and water quality have also been widely noticed (Zhao et al. 2006a, b). Urbanization can also exert a profound influence on vegetation cover and productivity (Fang et al. 2003). For example, although most areas in China have experienced an increase in vegetation productivity since the early 1980s, the Yangtze River and Pearl River deltas showed a significant decrease in vegetation productivity due to rapid urbanization (Piao et al. 2004). Despite increasing concern among scientists and policy makers, however, our understanding of urban vegetation cover change under intensive urbanization in China is still very limited primarily due to the lack of a multiyear and national scale observational data.

Normalized Difference Vegetation Index (NDVI), defined as the ratio of the difference between near-infrared reflectance and red visible reflectance to their sum, is an indicator of vegetation productivity (Tucker et al. 2005). NDVI has been widely used in analyzing the dynamics of vegetation (Zhou et al. 2001) and in some urban studies (Fung and Siu 2000; Wilson et al. 2003; Zhou et al. 2004; Myeong et al. 2006). In this study, we use NOAA/AVHRR NDVI data from the early 1980s to 2006 to evaluate the effects of urbanization on vegetation cover in China's metropolises over the last three decades.

Dataset and methods

Sites and datasets

Here, we choose 117 cities, each of which had over one million residents by the end of 2006, in mainland China (Fig. 1) for our study. These cities are well distributed in China's populous regions and their total population sums to 260 million (National Bureau of Statistics 2007). The moderate-resolution imaging spectroradiometer (MODIS) Global Land Cover Map at 500 m spatial resolution (Friedl et al. 2002) and a vectorized China's city distribution map (China's State Bureau of Surveying and Mapping 1999) were used to delimit urban areas for each of the selected cities. In order to explore regional patterns of China's urbanization and its impacts on urban vegetation, we divided these cities into three different regions: East, Central, and West (Fig. 1). In addition, we also highlighted the Yangtze River Delta and the Pearl River Delta where the most rapid urbanization in China has been observed (Zhou and Cao 1999).

Vegetation cover dynamics in China's urban areas were interpreted through analyzing NDVI changes. NDVI data used in this study were

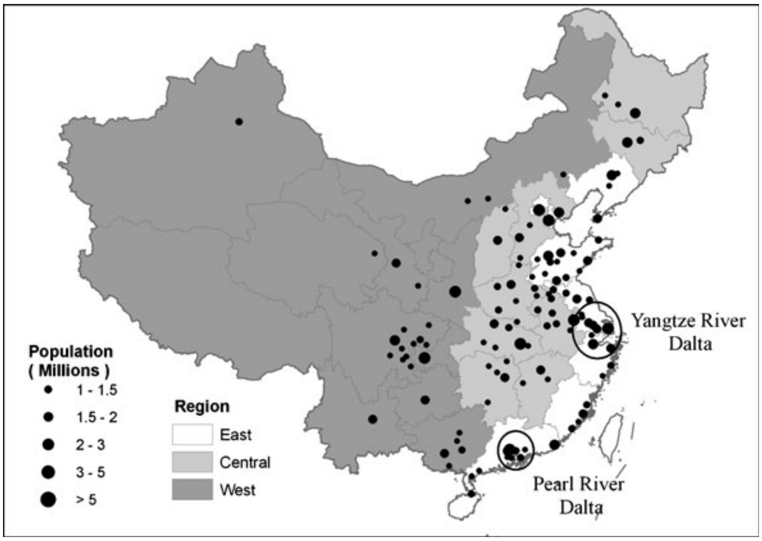

Fig. 1 Distribution of cities with over one million residents by the end of 2006 in mainland China

produced by the Global Inventory Monitoring and Modeling Studies group using the NOAA/AVHRR series satellites at a spatial resolution of 8 × 8 km^2 and 15-day interval, for the period from 1982 to 2006 (Tucker et al. 2005). The processing of this dataset included, calibration for sensor degradation, and correction for stratospheric volcanic aerosols (Zhou et al. 2001; Slayback et al. 2003). Maximum value composite was applied to obtain monthly NDVI value (Holben 1986).

A socioeconomic dataset, including urban population, gross domestic product (GDP) per capita and city built-up areas, was compiled from the annual Statistical Yearbooks of China's Cities, 1984–2006 (National Bureau of Statistics 2007). For each city, these indexes only cover municipal administrative area, not including subordinated towns and villages. The survey methods are consistent across the country following the socioeconomic survey protocol of the National Bureau of Statistics.

Analyses

Average growing season NDVI is an often used indicator of vegetation greenness (e.g., Zhou et al. 2001; Tucker et al. 2005; Slayback et al. 2003). In order to estimate average vegetation cover for the urban area of each city ($NDVI_u$), we first averaged monthly NDVI data during the growing season (from April to October). Then, the urban area of each city was obtained based on the MODIS Global Land Cover Map and the vectorized map of China's city distribution. Finally, we overlaid the growing season NDVI image over the urban area map to calculate the urban area weighted average of growing season NDVI ($NDVI_u$) for each city (Eq. 1).

$$NDVI_u = \frac{\sum NDVI_i \times p_i}{\sum p_i} \tag{1}$$

where p_i is the percentage of urban area for pixel i of the NDVI map, and $NDVI_i$ is the growing season NDVI for the pixel i. In addition, we also estimated the vegetation cover of the surrounding rural area for each city ($NDVI_b$). Here, $NDVI_b$ was calculated by averaging growing season NDVI for pixels within 40 km (five pixels) outside the edge of urban pixels.

Trend of vegetation cover during the study period was estimated using the least square linear regression. As cities in different regions may have different fast urbanization periods, a piecewise regression model (Toms and Lesperance 2003) was applied to detect the year when significant trend in vegetation cover starts or ends. In this model (Eq. 2), two regression lines converge in the turning point (α). This point is optimized through fitting the model to data. β_1 is the slope before the turning point, and $\beta_1 + \beta_2$ is the slope after the turning point. To evaluate whether it is suitable to use the piecewise regression in trend analysis, a Student t test is applied to test the statistical significance of the trend change (β_2) between the trends before and after TP.

$$f(x) = \begin{cases} \beta_0 + \beta_1 x, & x \leq \alpha \\ \beta_0 + \beta_1 x + \beta_2 (x - \alpha), & x > \alpha \end{cases} \quad (2)$$

Results

Spatial patterns of $NDVI_u$ and the difference between $NDVI_u$ and $NDVI_b$

Figure 2 shows the spatial pattern of $NDVI_u$ and the difference between average $NDVI_u$ and $NDVI_b$ during the study period. As shown in Fig. 2a, large values of $NDVI_u$ are mainly found

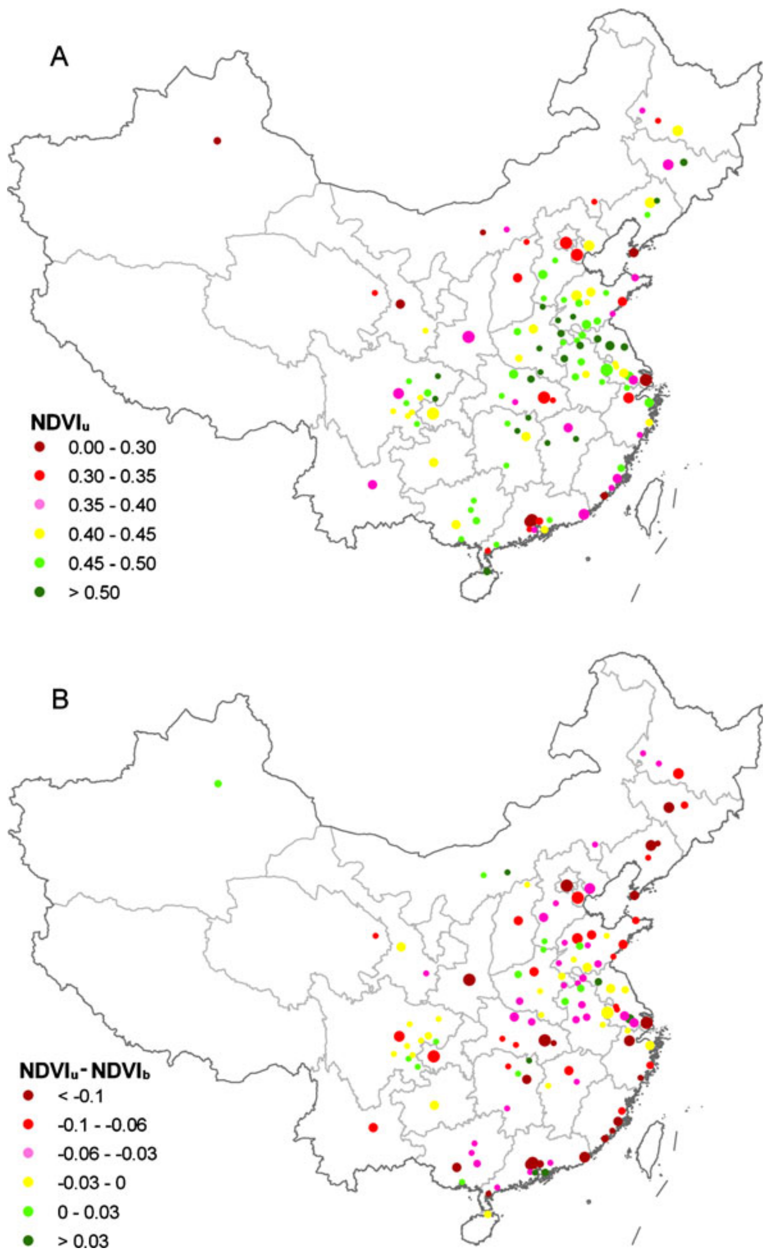

Fig. 2 Spatial patterns of average $NDVI_u$ (**a**) and average difference between $NDVI_u$ and $NDVI_b$ (**b**) during the period of 1982–2006. *Dot size* represents number of urban residents (see Fig. 1)

in Central China, while in northwestern cities, $NDVI_u$ is usually lower than 0.40. In addition, $NDVI_b$ values for cities in the Pearl River Delta generally (except Huizhou and Dongguan) are less than 0.40 (Fig. 2). At the regional scale, average $NDVI_u$ for the cities in Central China is about 0.46, while it is 0.42 and 0.41 in East and West China, respectively.

While it is a general phenomenon that most of the cities (84% or 98/117) show a lower vegetation cover in urban area than that in its surrounding areas, a regionally various pattern of the difference between $NDVI_u$ and $NDVI_b$ is also detected (Fig. 2b). Large (greater than −0.1) negative difference between $NDVI_u$ and $NDVI_b$ mainly appears in the coastal regions of East China. As a result, at the regional scale, East China showed the largest difference between $NDVI_u$ and $NDVI_b$ with the average of −0.07 ($P < 0.01$), while West China had lowest difference of −0.03 ($P < 0.01$). Differences between $NDVI_u$ and $NDVI_b$ in Central China is −0.05($P < 0.01$).

In order to explore the driving factors responsible for the observed spatial patterns of both vegetation cover in urban area and its difference with vegetation cover of surrounding area, $NDVI_u$ and the difference between $NDVI_u$ and $NDVI_b$ were plotted against log-transformed urbanization indexes (urban population, GDP per capita and urban built-up area) across all the sampled cities (Fig. 3). Both $NDVI_u$ and the difference between $NDVI_u$ and $NDVI_b$ are negatively correlated with urban built-up area, which accounts for largest variations among all the three urbanization indexes ($R^2 = 0.30$, $P < 0.01$; $R^2 = 0.16$, $P < 0.01$, respectively), suggesting lower urban $NDVI_u$ and the difference between $NDVI_u$ and $NDVI_b$ in larger cities.

Temporal trends in $NDVI_u$ and the difference between $NDVI_u$ and $NDVI_b$

Temporal trends in $NDVI_u$

Figure 4 displays the spatial distribution of the linear trends of $NDVI_u$, linear trends of $NDVI_b$, and linear trends of the difference between $NDVI_u$ and $NDVI_b$ from 1982 to 2006. The largest negative $NDVI_u$ trends (greater than −0.002 year^{-1}) is mainly observed in East China, particularly in the Pearl River Delta and Yangtze River Delta (Fig. 4a). Overall, in East China, 40 of the 54 (74%) cities show a negative $NDVI_u$ trend with an average slope of -1.32×10^{-3} year^{-1} ($P < 0.01$; Fig. 5), while declining $NDVI_u$ trends are less substantial in the other two regions (-0.2×10^{-3} year^{-1} in Central China ($P = 0.63$) and -0.04×10^{-3} year^{-1} in West China ($P = 0.91$).

At the national scale, although average $NDVI_u$ across all the sampled cities significantly decreased at a rate of 0.67×10^{-3} year^{-1} ($P < 0.01$; Fig. 5a and Table 1), urban NDVI dynamic trends along the time scale can be divided into two distinct periods with the year of 1990 as the turning point. $NDVI_u$ before 1990 does not show statistically significant trend; however, after 1990, it remarkably decreases (-1.28×10^{-3} year^{-1}, $P < 0.01$). A similar pattern of change in $NDVI_u$ is observed at the regional scale with different timing of turning points in different regions (Fig. 5b). In Central China and East China, $NDVI_u$ started to decline significantly in 1987 and 1990, respectively; while in West China, $NDVI_u$ remained relatively constant until 1998 when it started to decrease (Table 1). Significant decreases after the turning point year were observed in East China and West China, but not in the Central China region.

We then selected China's two most prosperous and industrialized regions, the Pearl River Delta and the Yangtze River Delta, for $NDVI_u$ temporal trend analysis (Fig. 5c). In the Pearl River Delta, $NDVI_u$ significantly declined at a rate of -5.72×10^{-3} year^{-1} before 1997 ($P < 0.01$), then remained relatively constant ($P = 0.58$). In contrast, in the Yangtze River Delta, significant decreasing trend of $NDVI_u$ was not observed until after 1990 (-3.06×10^{-3} year^{-1}, $P < 0.01$).

Temporal trends in the difference between $NDVI_u$ and $NDVI_b$

In comparison to the trends in $NDVI_u$, more cities in Central and West China show negative trends in the difference between $NDVI_u$ and $NDVI_b$ during the period of 1982–2006 (Fig. 4c). Together

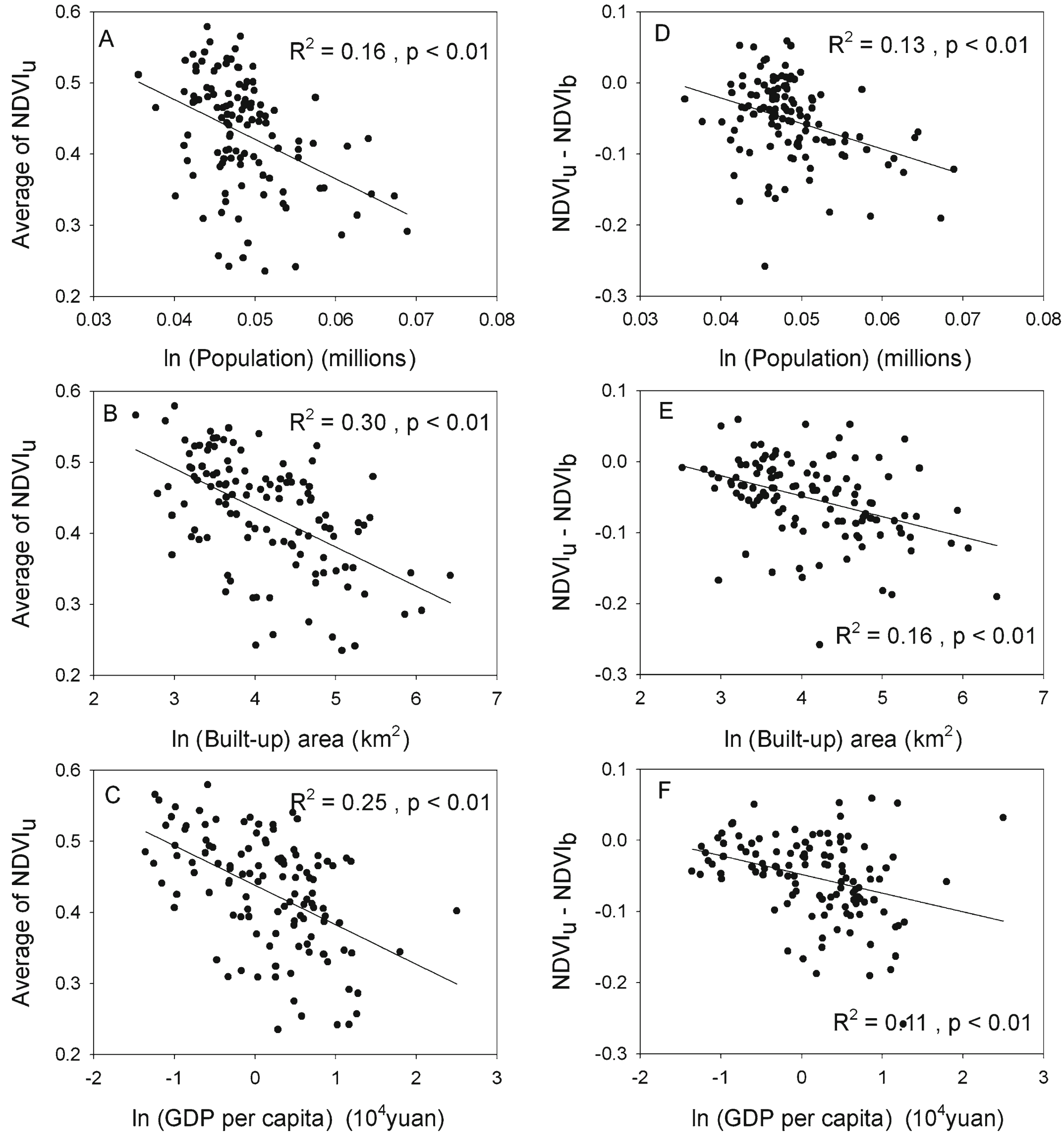

Fig. 3 Spatial relationships of $NDVI_u$ and the difference between $NDVI_u$ and $NDVI_b$ with indexes of urbanization (urban population, GDP per capita, and urban built-up area) across all cites. **a** Relationships between $NDVI_u$ and population; **b** Relationships between $NDVI_u$ and built-up area; **c** Relationships between $NDVI_u$ and GDP per capita; **d** Relationship of the difference between $NDVI_u$ and $NDVI_b$ with population; **e** Relationship of the difference between $NDVI_u$ and $NDVI_b$ with urban built-up area; **f** Relationship of the difference between $NDVI_u$ and $NDVI_b$ with GDP per capita. Urbanization indexes (urban population, GDP per capita and urban built-up area) are log transformed

with the observation that the decreasing trend of the difference between $NDVI_u$ and $NDVI_b$ is also more prominent than that of $NDVI_u$ in these two regions (Fig. 5e), it implies an increase in $NDVI_b$ during the study period. In addition, the decreasing trend in the difference between $NDVI_u$ and $NDVI_b$ appeared to increase from West China to East China (Fig. 5e and Table 2). Over the last 25 years, the difference between $NDVI_u$ and $NDVI_b$ for the Pearl River Delta and the Yangtze River Delta significantly decreased with annual rates of 1.58×10^{-3} year^{-1} ($P < 0.01$) and 0.99 ×

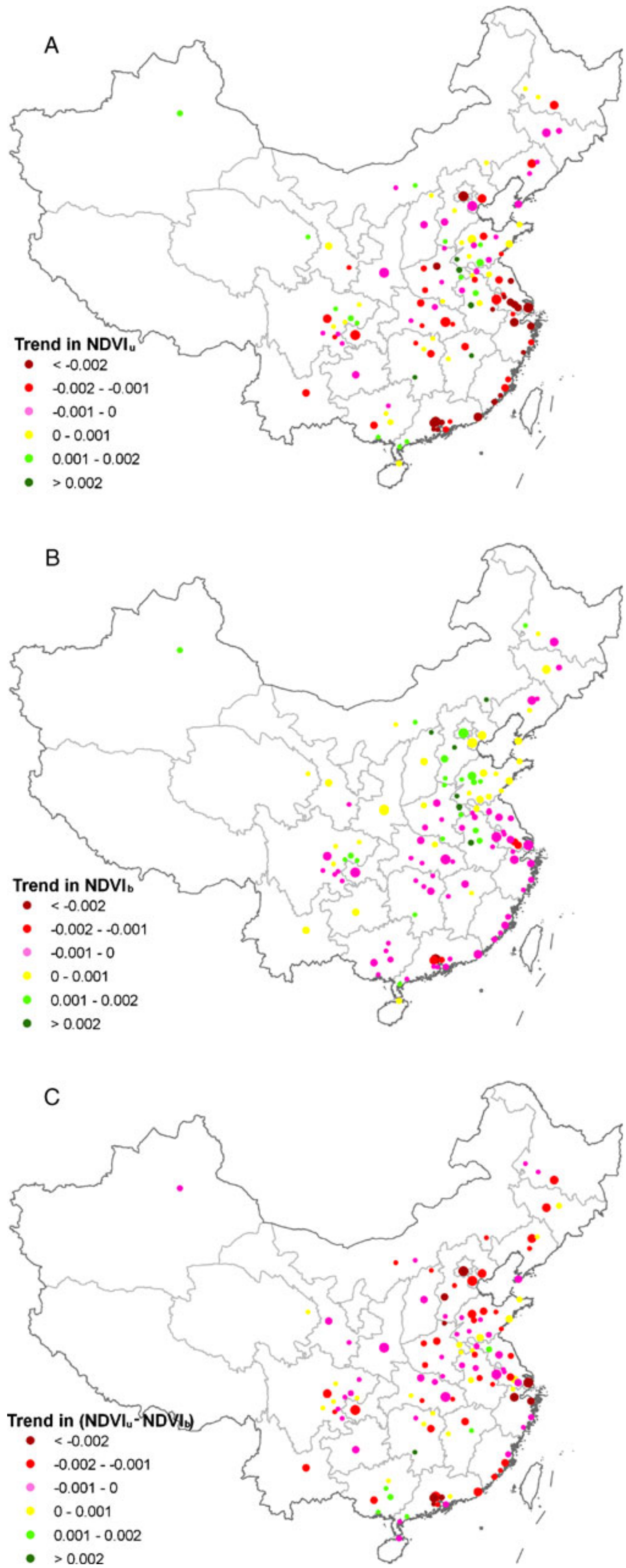

Fig. 4 Spatial patterns of trend in **a** $NDVI_u$, **b** $NDVI_b$, and **c** the difference between $NDVI_u$ and $NDVI_b$ during the period of 1982–2006. *Dot size* represents number of urban residents (see Fig. 1)

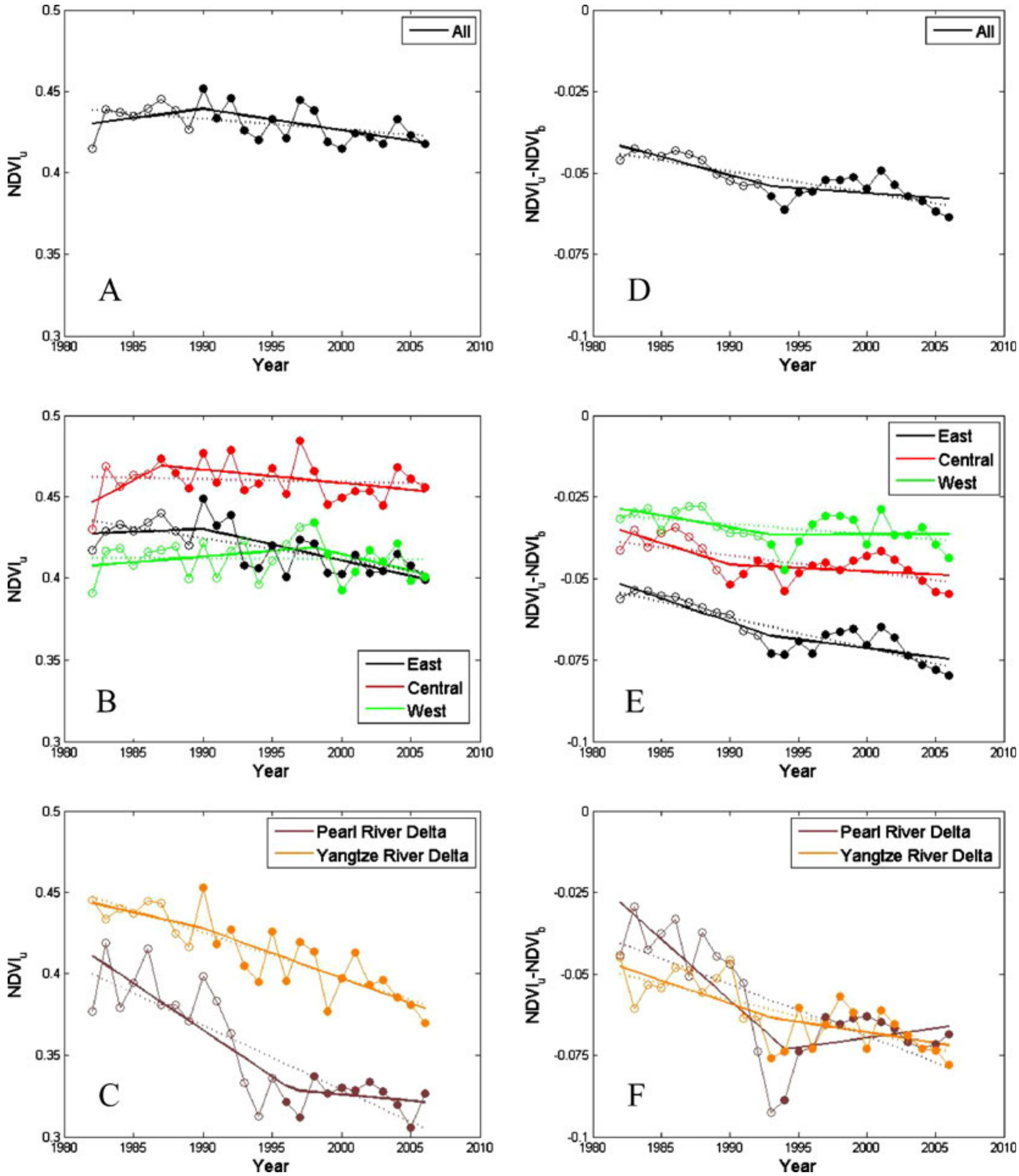

Fig. 5 Change in $NDVI_u$ and the difference between $NDVI_u$ and $NDVI_b$ for different regions from 1982 to 2006. **a** Change in average $NDVI_u$ for all cites used in this study; **b** change in average $NDVI_u$ for East, Central, and West China; **c** change in average NDVIu for the Pearl River Delta and the Yangtze River Delta; **d** change in the average of difference between $NDVI_u$ and $NDVI_b$ for all sampled cites; **e** change in the average of difference between $NDVI_u$ and $NDVI_b$ for East, Central, and West China; **f** change in the average of difference between $NDVI_u$ and $NDVI_b$ for the Pearl River Delta and the Yangtze River Delta

10^{-3} year^{-1} ($P < 0.01$; Fig. 5f and Table 2), respectively, while in West China, it is significantly decreased with a rate of 0.31×10^{-3} year^{-1} ($P = 0.02$). Furthermore, at the regional scale, such significant decreasing trend in the difference between $NDVI_u$ and $NDVI_b$ mainly occurred before the early 1990s across all the three regions, and then it turned to be statistically insignificant

Table 1 $NDVI_u$ trends in different regions by piecewise regressions and linear regressions

Region	TP	Before TP		After TP		1982–2006	
		Slope (10^{-3} year^{-1})	P	Slope (10^{-3} year^{-1})	P	Slope (10^{-3} year^{-1})	P
Pearl River delta	1997*	−5.72	<0.01	−0.77	0.58	−3.93	<0.01
Yangtze River delta	1990	−1.93	0.13	−3.06	<0.01	−2.71	<0.01
East	1990	0.57	0.62	−1.90	<0.01	−1.31	<0.01
Central	1987*	4.52	0.02	−0.82	0.05	−0.19	0.63
West	1998	0.72	0.17	−1.96	0.08	0.04	0.91
All	1990*	1.28	0.21	−1.28	<0.01	−0.67	0.02

Slope and significant level (P value) are shown for trends before TP, after TP, and of the whole period from 1982 to 2006
TP turning point
* $P < 0.05$ between the trend before TP and the trend after TP

except in East China (Fig. 5e). In East China, a significant decrease in the difference between $NDVI_u$ and $NDVI_b$ is also observed after 1993 ($P = 0.01$), although the magnitude of the trend (-0.55×10^{-3} year^{-1}) is only 39% of the trend before 1993 (Fig. 5e; Table 2).

Relationship between NDVI change and urbanization

Figure 6 shows the relationship between trends in $NDVI_u$, trends in the difference between $NDVI_u$ and $NDVI_b$ and the trends in urbanization indexes (urban population, GDP per capita and urban built-up area) across different cities. Trends in GDP per capita are best able to explain the variation in $NDVI_u$ trends ($R^2 = 0.31$). For trends in the difference between $NDVI_u$ and $NDVI_b$, trends in GDP per capita and trends in urban built-up area have similar explanation powers ($R^2 = 0.17$ and 0.20, respectively). The trend of urban population is also significantly correlated with both trends in $NDVI_u$ and in the difference between $NDVI_u$ and $NDVI_b$ (Fig. 6).

Discussion

Spatial patterns of $NDVI_u$

Our results suggest that the cities in Central China have higher average NDVI than those in the West or East, which may be partly explained by the environmental differences between central and west, and between central and east. Differences in historical development may also contribute this phenomenon. Comparing to West China, which usually has annual precipitation less than 400 mm and is dominated by arid or semi-arid vegetations, Central China is much moister and higher in plant productivity. On the other hand, for most of Central China cities, the city topography is usually

Table 2 Trends of difference between $NDVI_u$ and $NDVI_b$ in different regions by piecewise regressions and linear regressions

Region	TP	Before TP		After TP		1982–2006	
		Slope (10^{-3} year^{-1})	P	Slope (10^{-3} year^{-1})	P	Slope (10^{-3} year^{-1})	P
Pearl River delta	1994*	−3.75	<0.01	0.58	0.33	−1.58	<0.01
Yangtze River delta	1993	−1.42	<0.01	−0.64	0.12	−0.99	<0.01
East	1993*	−1.42	<0.01	−0.55	0.01	−0.93	<0.01
Central	1990*	−1.33	<0.01	−0.20	0.29	−0.51	<0.01
West	1993	−0.72	0.02	0.01	0.97	−0.31	0.02
All	1993*	−1.13	<0.01	−0.29	0.14	−0.66	<0.01

Slope and significant level (P value) are shown for trends before TP, after TP, and of the whole period from 1982 to 2006
TP turning point
* $P < 0.05$ between the trend before TP and the trend after TP

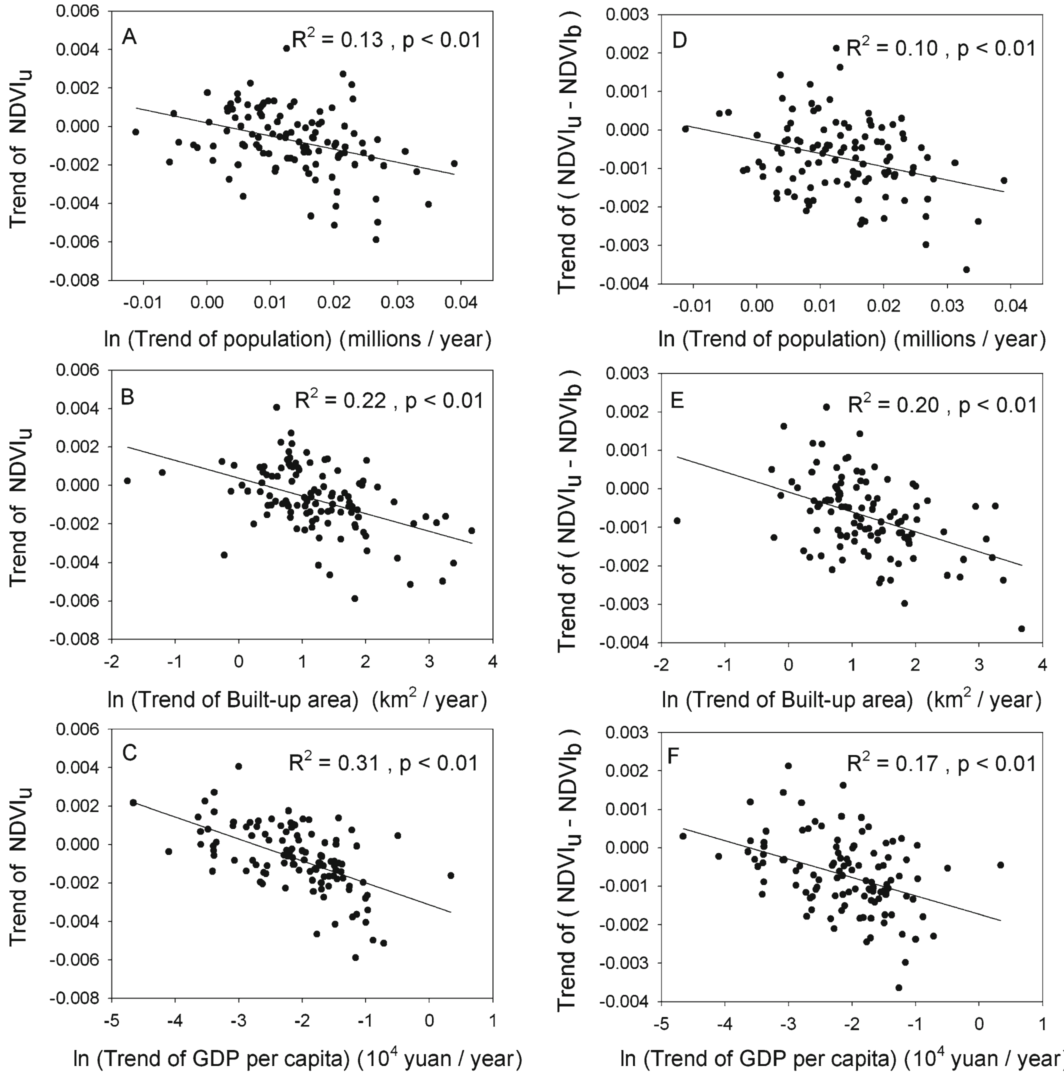

Fig. 6 Spatial relationships of trend in $NDVI_u$, trend in the difference between $NDVI_u$ and $NDVI_b$, and trend in urbanization indexes (urban population, GDP per capita and urban built-up area) across all sampled cites. **a** Relationships between trend in $NDVI_u$ and trend in population; **b** Relationships between trend in $NDVI_u$ and trend in urban built-up area; **c** Relationships between trend in $NDVI_u$ and trend in GDP per capita; **d** Relationship of trend in the difference between $NDVI_u$ and $NDVI_b$ and trend in population; **e** Relationship of trend in the difference between $NDVI_u$ and $NDVI_b$ and trend in built-up area; **f** Relationship of trend in the difference between $NDVI_u$ and $NDVI_b$ and trend in GDP per capita. Urbanization indexes (urban population, GDP per capita and urban built-up area) are log transformed

more diverse and contains more small hilly areas, which usually still remain all or partially forested, than those Eastern cities which are usually very flat lying on flooding plain. For example, densely forested Mt. Yuelu is in the Central city of Changsha, and forested Luojia is in the center of the Central city Wuhan. In addition, Eastern cities usually have an earlier and faster development and urbanization history than the Central China cities. Together, they may explain why cities in Central China has a higher average NDVI than those in the east. Further study is necessary to provide improved explanation for the higher urban NDVI in Central China.

Urban NDVI change from 1982 to 2006

Since urbanization intensity has a negative impact on urban vegetation (Masek et al. 2000), it is reasonable to speculate that faster urbanization rate will cause more $NDVI_u$ reduction. This speculation is supported by our results (Fig. 4). For example, in our results, we observed that the negative trend in $NDVI_u$ of cities in Northeast China over the last 25 years is much smaller than that in Southeast China (Fig. 4), although cities in both regions have relatively large negative differences between $NDVI_u$ and $NDVI_b$ (Fig. 2). This is related to the fact that urbanization since the 1980s has slowed down in Northeast China, while it is accelerating in Southeast China (Yang et al. 2004). Northeast China is China's earliest industrialized region and most of the large cities have been urbanized before the 1980s (Yang et al. 2004). Since 1980, the urbanization rate in Northeast China is only one third of the national average (Yang et al. 2004). On the other hand, coastal cities in Southeast China benefited most from China's open-and-reform policy since the 1980s and thus have a higher urbanization rate than the national average (Shen 2005).

Our results also suggested that in Central and West China, although several cities show an increasing trend in $NDVI_u$, the difference between $NDVI_u$ and $NDVI_b$ generally shows a declining trend, which implies a rapid increase of NDVI in surrounding rural areas ($NDVI_b$). Indeed, previous observational and modeling studies have suggested that vegetation activity has increased over the past two to three decades in central and western China (Cao et al. 2003; Fang et al. 2003). Aside from plausible explanations such as enhanced vegetation growth driven by current climate change (Piao et al. 2004, 2009), irrigation, and tree planting (Runnström 2000), one other possible reason for the increased NDVI in the surrounding rural areas may be the decreased human disturbance as a result of increased population emigration from rural areas into urban areas, one typical product of China's recent urbanization (Runnström 2000). Over the last three decades, urban population in China has increased by 202% (National Bureau of Statistics 2007) and most of such increase is credited to the population emigration from rural to urban areas. Such large-scale movement of rural population to cities has reduced the collection of fuel wood and accelerated the recovery of rural vegetation, which benefits carbon sequestration and at least partly offsets the direct negative effects of urbanization on carbon uptake through extending urban area. A previous study has also suggested that such indirect effects of urbanization on vegetation recovery may partly account for increased carbon sequestration in China (Piao et al. 2009). This result also highlights that the consequence of urbanization on vegetation and ecosystem dynamics may be far beyond the urban boundary. Therefore, the direct and indirect effects of urbanization should not be dismissed for evaluating current global carbon balance, and further studies are in demand.

Noticeably, a few cities, particularly in West and Central China, show positive differences between $NDVI_u$ and $NDVI_b$. This higher urban vegetation greenness may be related with management and geographical reasons. For some cities in arid and semiarid regions, like Urumqi of Xinjiang and Baotou of Inner Mongolia, surrounding areas are desert or desert-like grassland with a very small growing season $NDVI_b$, typically less than 0.3. Thus urban vegetation with irrigation and management practice shows higher greenness. Some other cities located in mountainous region, like Guang'an and Luzhou in Sichuan, may also have a positive urban-minus-non-urban NDVI values as those cities themselves usually are located in riverside basin with higher productivity than surrounding mountains.

Turning point of NDVI change

Over the last three decades, the most rapid urbanization in China occurred in the Yangtze River Delta and the Pearl River Delta (Zhou et al. 2004; Shen 2005; Jin et al. 2008). Consequently, the decreasing trend of $NDVI_u$ in these two delta areas is higher than that of other areas in China (Fig. 5). Moreover, our results also suggested that the changes in $NDVI_u$ for these two deltas show different characteristics (Fig. 5). The Pearl River Delta experienced a rapid decline in

$NDVI_u$ from the early 1980s to the mid-1990s; while in the Yangtze River Delta, $NDVI_u$ did not decline significantly until the early 1990s. This may be attributed to the policy-oriented difference in urbanization evolution in these two areas. In the Pearl River Delta, fast urbanization started in the early 1980s when China's "open-and-reform" experiment was first implemented here. By the mid-1990s, urbanization of most areas in the Pearl River Delta has been slowing down. For instance, a recent study reported that in Shenzhen, a major city in the Pearl River Delta, more intensive construction happened before 1996 (Wang et al. 2009). On the other hand, in the Yangtze River Delta, urbanization becomes more rapid after 1990 (Zhao et al. 2006a, b). For example, in Shanghai, the largest city in this region, annual increase of urban built-up area is about 39 km^2 $year^{-1}$ since 1990 which is about three times of that in the 1980s (12 km^2 $year^{-1}$) (National Bureau of Statistics 2007).

Urban development in West China is behind cities in other regions. In our data collection, 22 cities in West China have per capita GDP of RMB 2500 (~368 US $) in 1990, which is less than 70% of the national average for the 117 cities in this study. However, city development in West China accelerated following the central government's policy emphasizing regional balance in economic development and the western development initiative after the mid-1990s (Zhou and Cao 1999). The average annual increasing rate of per capita GDP for the 22 cities in West China after 1998 is about 2.4 times of that before 1998 (National Bureau of Statistics 2007). This corroborates our finding that a turning point of $NDVI_u$ in West China occurred in 1998. It should be noted that although $NDVI_u$ for West China decreased marginally since 1998 ($P = 0.08$), the magnitude of its trend (-1.96×10^{-3} $year^{-1}$) is larger than that for East China (-1.90×10^{-3} $year^{-1}$) and Central China (-0.82×10^{-3} $year^{-1}$) since their corresponding turning point (Fig. 5). With fast development in West China, how to achieve sustainable development by balancing urban development and urban vegetation and environment remains a big challenge for the policy makers.

Conclusions

Urbanization is a characteristic feature of China's recent fast economic development. It is evident that current urbanization has generally reduced vegetation greenness in China. Although large uncertainties remain about the rate and magnitude of future urban expansion in China, maintaining a balance between ecological sustainability and the continuous process of urbanization is one of the major issues faced by the Chinese government. In addition, urban vegetation deterioration from urbanization has been suggested to have a further influence on regional carbon balance and regional warming (Zhou et al. 2004). Though our studies suggested a strong influence that urbanization processes has exerted on urban vegetation dynamics, accurate accounting of the urbanization forcing on vegetation cover, climate, and thus carbon cycle are still needed in further studies. Incorporating the interaction between urbanization processes and vegetation and carbon cycle changes in climate and biosphere models will help us better quantify human footprint on the carbon cycle and the climate system.

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