The divergent response of vegetation phenology to urbanization: A case study of Beijing city, China

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HIGHLIGHTS

• We firstly characterized the response of vegetation phenology to urbanization using quantitative indicators.
• A distinct divergent response of vegetation phenology to urbanization was observed.
• Suburban with a medium urbanization level has the earliest date of start of season.
• Process-based phenology models are encouraged to explain this divergent pattern.

ABSTRACT

Characterizing the relationship between vegetation phenology and urbanization indicators is essential to understand the impacts of human activities on urban ecosystems. In this study, we explored the response of vegetation phenology to urbanization in Beijing (China) during 2001-2018, using impervious surface area (ISA) and the information of urban-rural gradients (i.e., concentric rings from the urban core to surrounding rural areas) as the urbanization indicators. We found the change rates of vegetation phenology in urban areas are 1.3 and 1.1 days per year for start of season (SOS) and end of season (EOS), respectively, about three times faster than that in forest. Moreover, we found a divergent response of SOS with the increase of ISA, which differs from previous results with advanced SOS in the urban environment than surrounding rural areas. This might be attributed to the mixed land cover types and the thermal environment caused by the urban heat island in the urban environment. Similarly, a divergent pattern of phenological indicators along the urban-rural gradient shows a nonlinear response of vegetation phenology to urbanization. These findings provide new insights into the complicated interactions between vegetation phenology and urban environments. High-resolution weather data are required to support process-based vegetation phenology models in the future, particularly under different global urbanization and climate change scenarios.

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1. Introduction

Phenology studies are a branch of science investigating the periodic life cycle events of plants and their relations with the environmental and climatic conditions. The dynamics of land surface phenology is a kind of sensitive biological response to the changing environment and climate (Khaduri et al., 2008; Tao et al., 2008). In particular, changes in temperature and precipitation have profound impacts on the dynamics of interannual phenophase (Shen et al., 2011), affecting the land surface processes such as terrestrial carbon cycle (Chmielewski and Rötzer, 2001; Richardson et al., 2009), vegetation dynamics (Zhao et al., 2016), and public health (Li et al., 2019). In contrast, vegetation phenology can also adapt to changing environments by shifting their phenology for resilience (Ford et al., 2016; Parmesan and Yohe, 2003) and further affect the terrestrial carbon cycle (Ponce-Campos et al., 2013). Besides, spring phenology events such as flowering were occurring earlier globally, resulting in extended duration for pollen production and increasing risks of pollen-induced allergy (Jochner and Menzel, 2015).

The urban environment is a natural laboratory to explore the response of vegetation phenology to global warming and urbanization in the future (Wang et al., 2019). Different from the natural ecosystem, plants in the urban ecosystem are simultaneously experiencing global warming and urban heat island (UHI). Thus, understanding the response of vegetation phenology to urbanization is essential to adaptation and mitigation for future climate change and urbanization. Besides, vegetation phenology is spatiotemporally heterogeneous in different urban ecosystems, depending on diverse vegetation types, thermal environments, and climate zones (Li et al., 2017b; Wang et al., 2017). For instance, the UHI effects vary across different cities, resulting in diverse phenology responses to urbanization across different climate zones and the urban-rural gradients. Accordingly, the interactions between weather conditions (e.g., raising temperature) and vegetation phenology are fundamental to understanding the phenology change to future global warming (Youngsteadt et al., 2015).

Urbanization is gradually shaping the urban landscape and ecosystem in multiple ways, including the UHI effect (Zhang et al., 2009), the heterogeneous surface climate conditions (Bounoua et al., 2015), the diverse vegetation structure (Kaye et al., 2006) and species (Pickett et al., 2011). The urban sprawl process can indirectly influence the greenness and rhythms of plants by changing the urban environment (Zhao et al., 2016). The date of leaf unfolding in spring advances, and the growing season length extends in urban regions compared to surrounding rural areas (Li et al., 2017a; Zhang et al., 2004). Studies have been conducted to explore the reasons behind the vegetation phenology dynamics under different environments, using empirical analyses approaches and process-based models (Buyantuyev and Wu, 2012a; Jia et al., 2018; Jia et al., 2021; Qiu et al., 2017; White et al., 2002; Zhou et al., 2016). These studies have shown that the spatial patterns and temporal trends of vegetation phenology were positively correlated to the land surface temperature. In general, the rising air temperature induced by the intensified UHI effect would likely result in extended growing seasons (Briber et al., 2013; Zhang et al., 2004), and it has been a consensus in urban vegetation phenology studies.

Limited efforts have been made on long-term and quantitative analyses of the vegetation phenology response to different urbanization levels. Comparisons of phenological indicators between urban and rural areas were commonly used in previous studies (Jia et al., 2021; Studer et al., 2007; Zhao et al., 2016; Zhou et al., 2016). However, these studies were primarily conducted either focusing on the spatial dimension (e.g., urban and rural areas) (Roetzer et al., 2000; Zhang et al., 2004; Zhao et al., 2016; Zhou et al., 2016) or specific years without full consideration of phenology changes over a relatively long period (Jia et al., 2021). Thus, the spatiotemporal dynamics of vegetation phenology to urbanization were not thoroughly and quantitatively investigated. Besides, due to the lack of fine-resolution urban extent time series data, the urbanization level was commonly indicated by the urban size (Li et al., 2017a), whereas the spatial heterogeneity of urban development in the domain was ignored in previous studies. To the best of our knowledge, within the urban domain, the response of vegetation phenology to diverse urbanization levels at a fine-scale has not been comprehensively investigated.

Therefore, we explored the response of vegetation phenology to urbanization using long-term (2001-2018) land cover, phenology, and urban extent data, taking the Beijing city in China as a case study. We hypothesized the impacts of urbanization on vegetation phenology might be different to diverse urbanization levels (e.g., city core, suburban, and rural areas) in urban ecosystems. Therefore, compared to previous studies, in this study, we focused on the phenology responses to urbanization using quantitative indicators at a fine resolution and a long temporal span. The objectives of our study were to explore: (1) the phenological difference between the urban and surrounding natural ecosystems; and (2) the response of vegetation phenology to urbanization using quantitative indicators.

2. Study area

As the capital city of China, Beijing is one of the fastest-growing cities with high economic production in the world. Beijing is also one of China’s most densely populated cities, with more than 21 million populations in 2020. Latitudinally located between 39° and 41°, Beijing exhibits pronounced seasonal temperature differences. As a megacity with rapid urbanization in the northern plain of China, Beijing experienced a noticeable expansion of urban areas over the past decades (Wu et al., 2006). The significant urban expansion has considerably affected the thermal environment, resulting in higher temperatures in central urban areas than surrounding rural areas (Li et al., 2015). Hence, it is an ideal choice to explore the response of vegetation phenology to urbanization (Fig. 1).

3. Methodology

We explored the response of vegetation phenology to urbanization using the proposed framework in Fig. 2. First, we collected and preprocessed different datasets across years, including the time series data of land cover, phenology, and urban extent. Then, we extracted the phenological indicators from the raw data. Third, by combing these datasets with time series information, we quantitatively analyzed the vegetation phenology difference between urban and other land cover types, phenology dynamics across years, and the response of vegetation phenology to urbanization. Details of these steps can be found in the following sections.
3.1. Data collection and preprocessing

We adopted three main datasets in this study, including the Moderate Resolution Imaging Spectroradiometer (MODIS) vegetation phenology data (MCD12Q2), the land cover data (MCD12Q1), and the global annual impervious area (GAIA). First, we derived the vegetation phenology data MCD12Q2 with a spatial resolution of 500 m from the U.S. Geological Survey (https://lpdaac.usgs.gov/) (Friedl et al., 2019). Multiple phenological indicators are recorded in the MCD12Q2 dataset, including the onset of greenness, greenup midpoint, peak greenness, and senescence. We excluded those pixels with poor quality and converted the raw record (i.e., days since January 1, 1970) to the day of year (DOY). Similarly, we also downloaded the land cover data MCD12Q1 from the same archive. We selected the land cover results with the International Geosphere-Biosphere Programme (IGBP) classification. We aggregated the IGBP classification into five types in our study, i.e., forest, shrub, grass, cropland, and urban. To quantitatively characterize the responses of vegetation phenology to urbanization, we also included the GAIA data in this study (Gong et al., 2020; Li et al., 2020). The GAIA data were produced using the full archive of Landsat images globally at a spatial resolution of 30 m with an annual interval from 1985 to 2018. The mean overall accuracy of GAIA is above 90%, and the urban expansion in GAIA is temporally consistent (i.e., from nonurban to urban in a monotonous manner). We aggregated the raw GAIA data to the same resolution (500 m) as MODIS products, in the form of the fraction of impervious surface area (ISA). In addition, the period of this study is from 2001 to 2018, during which period these three datasets are all available.

3.2. Phenological Indicators

We derived annual phenological indicators (2000-2018) from the MCD12Q2 product to characterize the spatiotemporal patterns of urban vegetation phenology. These phenological indicators were mainly derived from the fitted curve of the two-band Enhanced Vegetation Index (EVI2) (Jiang et al., 2008). To comprehensively characterize the seasonal cycle of vegetation phenology, we derived four phenological indicators from the MCD12Q2 product (Fig. 2). The start of the growing season (SOS) was defined as the date when EVI2 first crossed 15% of the segment EVI2 amplitude; the start of peak (SOP) was defined as the date when EVI2 first crossed 90% of the segment EVI2 amplitude; the end of peak (EOP) was defined as the date when EVI2 last crossed 90% of the segment EVI2 amplitude; the end of the growing season (EOS) was defined as the date when EVI2 last crossed 15% of the segment EVI2 amplitude. The quality of the MODIS phenology product has a good agreement with field observations in terms of the absolute errors and the temporal trends (Ganguly et al., 2010; Li et al., 2017a; Liang et al., 2011; Zhang et al., 2006). We also included the indicator of growing season length (GSL), which was defined as the length between the SOS and EOS.

3.3. Analysis of vegetation phenology in the urban environment

We analyzed vegetation phenology in the urban domain from three aspects. First, we explored the vegetation phenology difference between urban and other land cover types (i.e., forest, shrubland, grassland, and cropland) and the dynamics of phenological indicators from 2001 to 2018. We only kept those persistent pixels for analyses to exclude the influence caused by land use cover change. Also, a linear regression model was used to characterize the long term (i.e., almost 20 years) change of phenological indicators. Then, we analyzed the response of vegetation phenology to urbanization using ISA as the urbanization indicator, which can represent the urbanization level at the local scale (i.e., circa 500 m grid) (Fig. S1). Thus, pixels within different ISA bins were pulled together for analyzing their phenological indicators. Finally, we explored the phenology change along the urban-rural gradient, expressed as multiple concentric rings seeded upon Tiananmen Square (i.e., the center of Beijing city). In total, there are 11 rings in our study with a step of 5 km (Fig. 3a). Each ring was used as a basic unit within which we calculated the mean values of different phenological indicators. Although there is a mixture of different land cover types in each ring, the gradient of urban development from the city center to rural areas can be well reflected, as illustrated in Fig. 3b. Specifically, we can see a clear distance-decay pattern of ISA change with the increasing distance to Tiananmen Square. Also, there is a noticeable increase of ISA in different rings over past decades, especially in the suburban region (i.e., around 20-30 km).

4. Results and discussion

4.1. Phenology difference in the urban ecosystem

There is a distinct phenological difference across different land cover types in Beijing (Fig. 4). In terms of the mean value of each indicator (Table S1), the SOS of cropland is the earliest, with an average DOY of 103, followed by forest (108), shrub (109), grass (111), and urban (112) (Fig. 4a). Overall, SOS in the urban domain is slightly later than surrounding natural land cover types, and there is a wider range of SOS in urban domains than other types, suggesting that pixels with
advanced and delayed SOS are widely and co-existing in urban domains. The SOP follows a general increasing trend in forest, shrub, grass, cropland, and urban (Fig. 4b). Combing the information from SOS and SOP, we can infer that the forest has a rapid growth of greenness during the growing season (i.e., the difference between indicators of SOS and SOP is slight). While for the senescence season, the greenness in grassland declines rapidly when referring to phenological indicators of EOP and EOS, which is almost 20 days shorter than the forest (Fig. 4c&d and Table S1). In addition, compared with the land cover data in two representative years (i.e., the start year of 2001 and the end year of 2018) (Fig. S3), we can find phenological indicators are notably different in different cover types such as cropland and grass (Fig. 5).

Vegetation phenology (i.e., SOS and EOS) in the urban domain is more sensitive than other cover types in the rapidly changing urban environment (Fig. 6). In general, the SOS becomes earlier, and the EOS becomes later over the past two decades. However, the responses of vegetation phenology to the surrounding environment vary across different cover types, i.e., forest and shrub are less sensitive than urban and cropland. The mean rates of SOS advance and EOS delay in urban areas are 1.27 and 1.06 days per year, respectively, about triple faster than forest. Meanwhile, the changing rate of phenological indicator SOS is larger than EOS, suggesting the changing urban environment profoundly impacts plants during the growing season. Besides, among these types, changes of phenological indicators (SOS and EOS) in urban and cropland are more distinctive than other types, i.e., the SOSs in urban and cropland have advanced about 30 and 20 days, respectively.
respectively. This phenomenon is likely attributed to the changing urban environment (e.g., UHI) and human activities. For instance, the UHI-induced thermal environment can advance the date of leaf unfolding in the growing season (Li et al., 2017a), and farmers would postpone the seeding and planting dates in cropland due to global warming and urbanization (Luo et al., 2020; Zuo et al., 2014).

4.2. Response of vegetation phenology to ISA

Vegetation phenology in urban domains exhibits a divergent response to urbanization levels indicated by ISA. Fig. 7 shows the response of phenological indicators (i.e., SOS, SOP, EOP, and EOS) to different ISA levels. We divided the whole range of ISA (0−100) into different intervals to reflect the urbanization levels. Overall, the SOS slightly decreases at first and then noticeably increases with the increase of ISA. An opposite response to ISA is found in EOS. For the other two phenological indicators (i.e., SOP and EOP), they decline with the increase of ISA, while their change magnitudes are not so considerable as SOS and EOS. These phenomena are robust and observed across the other years (Figs. S4-S5).

Such a divergent response of phenological indicators to urbanization levels is related to multiple factors. On the one hand, pixels with relatively low ISA values (e.g., less than 20%) (Fry et al., 2011) are nonurban dominated. Phenological indicators in these regions are mainly attributed to other natural cover types (e.g., forest, shrub, grass, and cropland). On the other hand, for regions with relatively high urbanization levels (e.g., ISA is above 50%), phenological indicators mainly reflect the vegetation in the urban domain which is influenced by the thermal environment induced by the UHI. Taking the example of SOS, we found a delayed SOS with the increase of urbanization level. This finding is different from our common sense that UHI advances the SOS in urban regions compared to surrounding rural areas (Zhou et al., 2016; Zipper et al., 2016). This non-linear response mechanism of plants can be partially due to the warming environment, which has been convinced in natural (Fu et al., 2015) and urban ecosystems (Meng et al., 2020a). The process of leaf unfolding is mainly controlled by chilling (e.g., cold days) and forcing (e.g., warm days) simultaneously. The UHI can accelerate forcing unit accumulation and thus advance the SOS in suburban and rural areas. However, the leaf unfolding process may be hindered by the chilling unit accumulation in the urban core region, where the UHI effect is stronger than surrounding areas, resulting in a delayed SOS with the increase of ISA due to the high correlation between ISA and land surface temperature (Yang et al., 2021). These physiological processes can be modeled using existing spring phenology models that consider the chilling and forcing effects (Fu et al., 2015; Meng et al., 2020b), using the daily air temperature data over past years. However, it is still a challenging task to collect and generate gridded daily air temperature datasets in our study area, given the fact that most existing products either have relatively coarse spatial (e.g., >10 km) (He et al., 2020; Hersbach et al., 2020) and temporal (e.g., monthly) resolutions (Peng et al., 2019), or are limited in reflecting the temperature difference between urban and rural areas caused by the UHI effect (Meng et al., 2020b; Oyler et al., 2016). Considering the availability of input data for process-based phenology models, future analyses using existing chilling models to explain the response of vegetation phenology to urbanization are required, which is beyond our scope in this paper.

Fig. 5. Map of phenological indicators in the start (2001) and end (2018) years in Beijing. Data with poor quality were masked in this study.
Fig. 6. Long term change of phenological indicators across different land cover types.

Fig. 7. Response of phenological indicators to ISA (2015). The central mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively.
Various weather and physiological factors could explain the response of vegetation phenological indicators to urbanization. Although other environmental factors such as precipitation and photoperiod may alter the rhythm of vegetation growth, the temperature has been widely regarded as a crucial driver to explain vegetation phenology dynamics, especially for the indicator of SOS. Many phenology models primarily driven by temperature have been developed (Meng et al., 2020c; Piao et al., 2019), such as the growing degree day model and the chilling model. In these spring phenology models, vegetation response to temperature is different according to diverse climate zones and vegetation types (Li et al., 2017a), and they have been widely used in ecology studies and Earth system models. However, unlike the spring phenology models, there is no consensus on the formulation of leaf coloring (e.g., EOS) using the autumn phenology models (Jeong and Medvigy, 2014). Field experiments suggest both the photoperiod and temperature are regarded as two primary factors that may contribute to the leaf coloring of trees (Lim et al., 2007). In contrast, their interactions are still unclear, with critical parameters in the autumn phenology models to be calibrated using field observations. Considering the impact of artificial nighttime light in cities, the photoperiod effect on plant phenology becomes more complicated than in surrounding rural areas (Zheng et al., 2021). Therefore, field experiments with an improved understanding of phenology response to the environment are highly required in future works (Meng et al., 2021).

4.3. Phenology difference along the urban-rural gradient

Phenological indicators in the middle of the urban-rural gradient differ from those closest to the urban center and rural areas (Fig. 8). Overall, we observed an advancement of SOS and SOP, and a delay of EOP and EOS from 2001 to 2018, which is consistent with Fig. 6 in terms of the temporal trends. Also, the largest SOS occurs in the ring with around 20 km to the urban center, later than the regions closest to the urban core or rural areas. A similar pattern is found in other indicators such as SOP, EOP, and EOS, and peaks of these indicators are in the middle of the urban-rural gradient. Specifically, there is a distinct inverted “U-shape” pattern of SOP from the urban core to rural areas, suggesting a divergent vegetation phenology response to urbanization. The phenological indicators in these rings represent the mean status of mixed land cover types (Table S2). There is a rapid decline of urban fractions in each ring from 5 km to 55 km, whereas cropland and grass exhibit rapid growth from the urban core to rural areas. Change of land cover fractions in these rings is a primary reason for this difference in the urban-rural gradient. In addition, it is worthy to note that phenological change over different years (Fig. 6) is more significant than that along the urban-rural gradient (Fig. 8).

This non-linear response of vegetation phenology along the urban-rural gradient partially attributes to diverse factors unique in the urban ecosystem. In addition to the influence of land cover and UHI, other abiotic and biotic factors such as irrigation, nighttime light, and plant species may also impact the response of vegetation phenology to urbanization, although their roles are not so significant (Meng et al., 2020a; Meng et al., 2020b). Although different plant species have various phenological dates, the derived vegetation phenology is still valid due to the following two reasons. On the one hand, previous studies confirmed that the wide variety of tree species does not change significantly along with the urbanization gradient (Ortega-Álvarez et al., 2011). On the other hand, given that the spatial resolution of the vegetation phenology dataset is 500 m, signals of different species were reflected as mixed phenological characteristics (Blood et al., 2016). Besides, the irrigation of trees in cities and the precipitation may alter the vegetation phenology, such impact is more evident in arid regions than cities in humid zones (e.g., Beijing) (Buyantuyev and Wu, 2012b). Additionally, plants in the urban domain are affected by artificial nighttime light, which would affect the photoperiod and further alter the vegetation phenology (Li and Zhou, 2017; Zhao et al., 2019). Overall, the response of phenological impacts from nighttime light is weak compared to other factors such as temperature, precipitation,
and photoperiod, although empirical studies have reported the night-time light can advance the SOS in cities (Zheng et al., 2021).

5. Conclusions

In this study, we used the time-series data of land cover, phenology, and urban extent from remotely sensed observations to explore the vegetation phenology difference in Beijing (China). First, we investigated the phenological difference across multiple land cover types from 2001 to 2018. Then, we investigated the response of vegetation phenology to urbanization using the indicator of ISA at the grid-scale and the urban-rural gradient from the urban core to rural areas, respectively.

In general, we found a divergent response of vegetation phenology to urbanization. The change rate of phenological indicators in the urban domain is the most significant over the past two decades, with the advanced SOS (1.3 days per year), delayed EOS (1.1 days per year), and extended GSL (2.4 days per year). These changing phenological indicators are more than three times relative to those in the forest, and the UHI effect is a primary cause for this phenomenon. Furthermore, we discovered a divergent response of vegetation phenology to urbanization using indicators including ISA and the urban-rural gradient. Taking the example of SOS, there is a slightly decreasing trend when the ISA increases from 10% to 30%, after which an opposite trend is observed, i.e., the SOS becomes later with the increase of ISA. From the aspect of urban-rural gradient, we found that phenological indicators in suburban regions are notably different from those in the urban core and rural areas, showing a similar divergent pattern. The UHI effect and the composition of land cover types in each grid and ring can explain the observed phenomenon.

Our study provides quantitative evidence on vegetation phenology response to urbanization, which is notably different from previous comparisons of phenology between urban and rural areas. The divergent response of vegetation phenology to urbanization is robust regarding the long time series of urban and phenology products. It is worthy to note that the resolution of MODIS products (500 m) is relatively coarse, resulting in the detected phenology containing multiple vegetation types and fractions. This issue can be addressed using fine-resolution satellite observations such as harmonized Earth observations from Landsat and Sentinel (Claverie et al., 2018). In addition, a process-based phenology model is promising to simulate the vegetation phenology response under future global warming and urbanization (Meng et al., 2020a).

CRediT authorship contribution statement

Yehua Zhang: Formal analysis, Investigation, Visualization, Writing – original draft. Peiyi Yin: Formal analysis, Investigation, Writing – original draft. Xuecao Li: Conceptualization, Methodology. Formal analysis, Investigation, Writing – review & editing, Supervision, Project administration. Quandi Niu: Writing – review & editing. Xiyuan Wang: Writing – review & editing. Wenting Cao: Writing – review & editing. Jianxiu Huang: Writing – review & editing. Han Chen: Writing – review & editing. Xiaochuang Yao: Writing – review & editing. Le Yu: Writing – review & editing. Baoguo Li: Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This study was supported by the Chinese University Scientific Fund (1191-15051001).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.150079.

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