

Impacts of Urbanization on Vegetation Phenology in Hohhot City over the Past Two Decades: Postprint

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Abstract

Understanding the relationship between vegetation phenology and urbanization is crucial for recognizing the impacts of human activities on ecosystems. Based on two types of MODIS vegetation index data for Hohhot City over the past 20 years, vegetation phenology was extracted using the dynamic threshold method, and combined with urbanization indicators, the response of vegetation phenology to urbanization in Hohhot City from 2001 to 2020 was studied. The study shows that forests and shrublands have an earlier start of growing season (SOS) (average day 132), but also an earlier end of growing season (EOS) (day 265). Cropland has a later SOS (day 168), while grassland has a later EOS (day 275), indicating that in the study area, both SOS and EOS of woody plants are earlier than those of herbaceous plants. Vegetation phenology on artificial surfaces shows large interannual variations, with phenological change rates of 4.1 days earlier per decade for SOS and 0.7 days later per decade for EOS. Additionally, using artificial surface ratio and urban-rural gradient information (i.e., concentric rings from urban core to surrounding rural areas) as urbanization indicators, the response of vegetation phenology in downtown Hohhot to urbanization was explored. The study found that SOS advances with increasing artificial surface ratio, while EOS shows the opposite trend. From the perspective of urban-rural gradient, within a specific range, SOS fluctuates and increases with distance from the city center, meaning the farther from the city center, the later the vegetation SOS, while EOS gradually decreases, meaning the farther from the city center, the earlier the vegetation EOS. In summary, different urbanization indicators demonstrate a nonlinear response of vegetation phenology to urbanization.

Full Text

Effects of Urbanization on Vegetation Phenology in Hohhot City in the Recent 20 Years

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Abstract

Understanding the relationship between vegetation phenology and urbanization is crucial for recognizing the impacts of human activities on ecosystems. Based on two MODIS vegetation index datasets for Hohhot City over the past 20 years, we extracted vegetation phenology using a dynamic threshold method and investigated the response of vegetation phenology to urbanization from 2001 to 2020 using urbanization indicators. The results show that the start of growing season (SOS) for forests and shrublands occurred earlier (mean day 132), and their end of growing season (EOS) also occurred earlier (day 265). In contrast, SOS occurred later in croplands (day 168), and EOS occurred later in grasslands (day 275), indicating that both SOS and EOS of woody plants were earlier than those of herbaceous plants in the study area. The interannual variation of urban land surface phenology was substantial, with SOS advancing by 4.1 days and EOS delaying by 0.7 days per decade. Furthermore, using the urban land surface ratio and urban-rural gradient information (concentric rings from the urban core to surrounding rural areas) as urbanization indicators, we explored the response of vegetation phenology to urbanization in Hohhot's central urban area. SOS advanced with increasing urban land surface ratio, whereas EOS showed the opposite trend. From the perspective of the urban-rural gradient, SOS fluctuated while EOS decreased within a certain distance from the urban center; that is, the farther from the city center, the later the SOS and the earlier the EOS. In conclusion, different urbanization indicators reveal a nonlinear response of vegetation phenology to urbanization.

Keywords: vegetation phenology; urbanization; Hohhot City

Introduction

Vegetation phenology is a critical indicator of vegetation growth and plays a key role in water and carbon cycling in terrestrial ecosystems. The start of growing season (SOS) represents the time when vegetation begins to sprout and grow, significantly influencing subsequent vegetation development. The end of growing season (EOS) is another representative phenological parameter marking the

onset of vegetation dormancy or the end of senescence (or leaf fall). These two parameters jointly determine the annual growing season length. While relationships between phenology and climatic factors have been extensively studied at large scales and have become important for understanding global change impacts on terrestrial ecosystems, in-depth quantitative research on the effects of human activities, particularly small-scale urbanization, remains relatively limited. Understanding urbanization's impact on phenology is essential not only for comprehending phenological responses to climate warming but also for informing urban planning decisions related to pollen allergy mitigation and ornamental plant cultivation layout.

This study selected Hohhot City, the capital of Inner Mongolia Autonomous Region and a major core city in the arid region of northern China, as the research area. Located on the southern side of Daqing Mountain in central-western Inner Mongolia [Figure 2: see original paper], Hohhot has jurisdiction over 4 districts and 5 counties, with a permanent population increasing from 2.39 million in the Fifth Census to 3.44 million in the Seventh Census, and a central urban area of 210 km². The study area features Daqing Mountain in the north and Tumochuan Plain in the south, with terrain gradually sloping from northeast to southwest at elevations ranging from 940 to 2280 m. The region experiences a mid-temperate semi-arid continental monsoon climate, with annual mean temperatures of 2.0–6.7°C, frost-free periods of 75–134 days, and average precipitation of 335.2–534.6 mm. From north to south, natural vegetation transitions from forest to mountain grassland, dry steppe, meadow steppe, halophytic vegetation, and psammophytic vegetation. Distributed greening plants are dominated by broadleaf deciduous trees such as willow (*Salix babylonica*), Xinjiang poplar (*Populus alba*), black locust (*Robinia pseudoacacia*), mountain peach (*Prunus davidiana*), and Simon poplar (*Populus simonii*); shrubs including lilac (*Syringa oblata*), flowering almond (*Amygdalus triloba*), rose (*Rosa rugosa*), pearl bush (*Sorbaria kirilowii*), and forsythia (*Forsythia suspensa*); and coniferous species such as Chinese pine (*Pinus tabulaeformis*), Chinese juniper (*Sabina chinensis*), spruce (*Picea asperata*), and Scots pine (*Pinus sylvestris*). Like most rapidly developing Chinese cities, Hohhot has experienced tremendous urbanization in recent decades, making it an ideal case for studying urbanization effects on surrounding vegetation phenology.

Data and Methods

1.1 Data Sources

Remote sensing data for calculating phenological parameters were obtained from the MOD13Q1 product, which provides 250 m resolution NDVI and EVI data for Hohhot. We used data from 2001 to 2020. NDVI and EVI are widely used to infer vegetation phenology as they indicate changes in canopy biophysical parameters such as aboveground biomass and leaf area index. EVI is particularly valuable for monitoring sparse or dense vegetation growth and decline without saturation issues that affect NDVI. Land cover data were derived from

the GlobeLand30 dataset, China' s 30 m global land cover product covering terrestrial areas between 80°N and 80°S, including categories such as cropland, forest, grassland, shrubland, wetland, water bodies, tundra, artificial surfaces, bare land, and glaciers. The time series was resampled to 250 m resolution to match the vegetation index data. Administrative boundaries for Hohhot were obtained from the standard map (Approval No. GS(2019)1822) downloaded from the Ministry of Natural Resources Standard Map Service website.

1.2 Methods

1.2.1 Phenology Extraction We employed two vegetation indices and two methods (summarized in) and averaged their results to improve phenology extraction accuracy. The dynamic threshold method was used to extract phenological values from remote sensing data. For each pixel' s annual time series curve, we defined SOS as the date when the vegetation index first crossed 20% of its amplitude, and EOS as the date when it last exceeded 80% of its amplitude. These dynamic thresholds have been widely applied in remote sensing phenology extraction. We applied this method to both NDVI and EVI time series and used the average of the two indices as our final phenological parameter [Figure 2: see original paper].

1.2.2 Trend Analysis Linear regression analysis was used to examine overall phenology trends in Hohhot. The slope of the regression line for individual pixels across years represents the interannual change rate. A positive slope indicates delayed phenology, while a negative slope indicates advanced phenology.

1.2.3 Urbanization Indicators Two urbanization indicators were established. The first is the artificial surface ratio: we created a 250 m fishnet across Hohhot' s entire area, calculated the proportion of artificial surfaces within each grid cell, and assigned values across 10 levels from 10% to 100% to represent urbanization intensity. The second indicator is the urban-rural gradient: we established 5 km interval buffer zones from the city center (Xinhua Plaza), creating nine concentric rings covering the central urban area and extending to 45 km to represent urban-rural transition zones or rural areas. This gradient approach follows methods representative of urbanization changes in previous studies.

Results

2.1 Spatial Patterns and Overall Trends

Statistical analysis of vegetation phenology across different land cover types from 2001 to 2020 reveals distinct patterns [Figure 3: see original paper]. Forests and shrublands in the Hohhot region showed the earliest SOS, occurring in late April with mean values around day 132, while other vegetation types emerged after day 132, indicating woody plants greened up earlier than herbaceous

plants. Croplands showed the latest SOS (mean day 168), followed by grasslands (around day 150). For EOS, forests and shrublands ended earliest (mean day 265), while grasslands ended latest (around day 275), demonstrating that woody plants had both earlier SOS and earlier EOS than herbaceous plants.

Spatial distribution of phenology trends across Hohhot shows concentrated patterns of advancement and delay [Figure 4: see original paper]. Advancing trends were mainly located within the central urban area's artificial surface coverage, while delaying trends occurred primarily in high-altitude grasslands and forest areas in the northeast. Artificial surfaces exhibited the most significant change rates, with SOS advancing by 4.1 days per decade and EOS delaying by 0.7 days per decade. Other land cover types also showed overall advancement in SOS, except for grasslands which exhibited slight delays. EOS trends varied: forests and shrublands advanced by 3.4 and 4.1 days per decade respectively, while artificial surfaces delayed by 1.9 days per decade. Consequently, growing season length shortened by 0.5 days per decade for artificial surfaces but showed minimal change for other cover types, likely due to urban heat island effects advancing SOS and delaying EOS for urban vegetation.

To ensure land cover consistency and exclude effects of land use change, we selected areas with stable land cover from 2000 to 2020. Notably, the interannual variation of phenology for artificial surfaces was more pronounced than spatial variation, indicating unstable phenological changes in the central urban area that warrant further investigation.

2.2 Response of Vegetation Phenology to Urbanization

Analysis of phenological responses to different artificial surface ratios shows that SOS gradually decreased (advanced) with increasing urban ratio, dropping sharply when the ratio exceeded 80% [Figure 6: see original paper]. EOS showed nearly the opposite pattern, increasing (delaying) with urbanization. In areas with the highest urbanization levels (artificial surface ratio >80%), phenological indicators changed dramatically, suggesting dominant influence of urban heat island effects. Areas with lower urban ratios (<20%) represent non-urban dominated pixels where phenology is primarily influenced by other land cover types.

Examining phenological changes along the urban-rural gradient reveals more complex patterns [Figure 7: see original paper]. With increasing distance from the city center, SOS showed fluctuating advancement while EOS decreased overall, with extreme values occurring at approximately 35 km from the center. The latest SOS and earliest EOS both occurred around 35 km, a range that generally follows urban heat island patterns but is also influenced by vegetation type composition. This non-linear relationship indicates that as impervious surfaces decrease and cropland/grassland proportions increase with distance, land cover changes become a major driver of phenological variation alongside heat island effects.

Discussion

Due to the lack of ground observation data, we validated our results indirectly by comparing our averaged phenology values from two vegetation indices with observed phenology values from other studies. The comparison shows that our remotely sensed phenology values are generally consistent with local observations, though slight differences exist due to: (1) inconsistent time series periods, (2) differences between single-species ground observations and mixed-pixel vegetation indices, and (3) variations between ground-observed phenological stages and remote sensing-identified phenological periods. The earlier SOS and later EOS for artificial surfaces compared to herbaceous plants may result from mechanisms underlying vegetation index data acquisition. Future work should incorporate more ground observation data or higher-resolution remote sensing for local phenology determination.

Overall, vegetation in the study area showed advancement in SOS, though trends varied significantly among land cover types, while EOS changes were minimal across different covers. This suggests that global warming and ongoing urbanization have substantially impacted SOS in Hohhot, particularly for artificial surfaces and shrublands. The advancement of SOS and delay of EOS with increasing urban ratio aligns with urban heat island expectations. The non-linear response along the urban-rural gradient, where SOS fluctuates and EOS shows delayed then accelerated trends, indicates that beyond a certain distance, urban heat island effects weaken while land cover change impacts become more pronounced.

The earlier SOS for forests and shrublands compared to herbaceous plants may be attributed to deeper root systems enabling water uptake from deeper soil layers and rapid responses to temperature warming. The earlier EOS for woody plants may result from limited water and low temperatures in autumn inhibiting growth and photosynthesis, increasing chlorophyll degradation and mortality risk. Taller woody plants also have longer water transport pathways and lower canopy temperatures, leading to earlier EOS. The later SOS for croplands reflects strong human management, as major crops like corn and potatoes have later emergence dates than natural vegetation.

Several uncertainties remain. First, besides urban heat island effects, other urbanization-related factors such as species composition, hydrological conditions, photoperiod, artificial irrigation, and CO₂ concentration may influence phenology. Second, we did not exclude croplands, whose phenology heavily depends on crop type and human management. Overall, this study demonstrates the value of urban environments for studying phenological responses to global change, though urbanization's complex effects require more direct observations, experimental manipulations, and cross-regional comparative studies.

Conclusion

This study examined vegetation phenology changes across different land cover types and urbanization levels in Hohhot from three perspectives:

- 1) Phenological responses varied among land cover types. Forests and shrublands showed earlier SOS (day 132) and EOS (day 265), while croplands showed later SOS (day 168) and grasslands showed later EOS (day 275).
- 2) Artificial surfaces exhibited the most significant phenological change rates, with SOS advancing by 4.1 days and EOS delaying by 0.7 days per decade, resulting in a shortened growing season length of 0.5 days per decade.
- 3) Different artificial surface ratios produced distinct phenological patterns: SOS advanced while EOS delayed with increasing urban ratio.
- 4) Along the urban-rural gradient, SOS fluctuated while EOS decreased from urban center to periphery, with extreme values occurring at approximately 35 km from the city center.

These findings reveal the nonlinear response of vegetation phenology to urbanization and highlight the complex interactions between urban heat island effects and land cover changes in shaping phenological patterns.

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