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Research Article

Response Patterns of Vegetation Phenology along Urban-Rural Gradients in Urban Areas of Different Sizes

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On the basis of MODIS Enhanced Vegetation Index time series data and multisource data, such as nighttime light data and China City Statistical Yearbook data, we investigated the differences in vegetation phenology along urban-rural gradients in urban areas of different sizes between coastal and inland cities in Liaoning Province, China. The results showed that the following: (1) the iterative extraction of urban built-up areas using the threshold method based on nighttime light data combined with the definition of urban built-up areas had high accuracy. (2) Additionally, we found that the start of the growing season (SOS) in Liaoning Province occurred between day 100 and day 180, while the end of the growing season (EOS) occurred between days 260 and 330. The difference in the SOS between coastal cities (i.e., Dalian, Yingkou, Panjin, Jinzhou, Huludao, and Dandong) and inland cities (i.e., Chaoyang, Fuxin, Tieling, Shenyang, Fushun, Liaoyang, Benxi, and Anshan) was 1.70 days. However, the difference in the EOS was more significant, i.e., the EOS in coastal cities occurred 4.47 days later than that in the inland cities. (3) In urban areas of different sizes, the ΔSOS and ΔEOS of inland cities had negative correlations with urban size. Specifically, when the urban size increased 10-fold, the ΔSOS and ΔEOS advanced by 10.03 and 5.71 days, respectively. In contrast, the ΔSOS and ΔEOS of coastal cities had positive and negative correlations with the urban size, respectively. Specifically, when urban size increased 10-fold, ΔSOS was delayed by 11.29 days while EOS was advanced by 8.83 days.

1. Introduction

Vegetation phenology refers to cyclic seasonal phenomena such as vegetation growth and other seasonal changes. Phenology can serve as a significant indicator of change in the climate and in ecological environments as well as an important parameter with respect to global changes [1–3]. The city is an open, large-scale, and complex system [4–6]. Urbanization involves the transformation of human production and lifestyle activities from a rural to an urban setting, which can lead to changes in species richness, biological homogenization characteristics, climatic environments, land surface temperatures, water quality, urban ventilation, and CO_2 emissions [7–15]. Recently, with the progression of global urbanization, problems associated with the urban ecological environment have become particularly important. Therefore, examinations of the influence that urbanization has on vegetation phenology are crucial when attempting to understand the changes in ecological environments caused by urbanization.

With rapid advances in remote sensing technology, remote sensing data have become a vital tool for large-scale vegetation phenology extractions due to characteristics such as wide coverage extents and extended time series [16]. Current studies on vegetation phenology based on remote sensing technology have focused on changes in vegetation indicated by changes in vegetation indices (Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), and Leaf Area Index (LAI)); such studies have examined the patterns of spatiotemporal change during the vegetation growth season, their relationships with climate change and urbanization, differences in vegetation phenology among various vegetation types, and vegetation productivity trends [17–22]. Studies on the influence of urbanization on vegetation phenology have been predominantly based at the city scale. We used a city or several cities in a region as the research subjects to examine the differences in vegetation phenology along urban-rural gradients. Typically, urban areas have an earlier start of the growing season (SOS) and later end of the growing season (EOS) than rural areas. Earlier work [23] investigated large cities in the United States where the growing season in urban areas lasted significantly longer than in rural areas. Urbanization causes the urban land surface temperature to be higher than the rural land surface temperature, and the urban heat island effect influences vegetation phenology with an exponential function. Zhou et al. [24] also found that an increase in the land surface temperatures in 32 major Chinese cities has led to an earlier SOS and delayed EOS. Other factors such as precipitation, sunshine, vegetation types, climate zone, and topography can affect the vegetation phenology as well [25–29].

The phrase "built-up area" refers to urban areas that are composed of developed land and land under construction within administrative divisions of a city; these areas typically contain municipal utilities and public facilities. The Notice on Adjusting Classification Standards of Urban Size (http://www.gov.cn/) clearly stipulates that cities be classified into five categories and seven grades in line with urban size classification standards, which are based on the statistical caliber of the resident population in urban areas. However, due to factors such as population mobility, classifying urban sizes according to the population standard is somewhat inaccurate [30]. The extent of built-up areas, as a representation of urban size, has been widely applied to classifications [31, 32]. Different urban sizes can have varying effects on vegetation phenology. For example, a previous study [33] investigated more than 4,500 city clusters of different sizes in the U.S.A., and the results revealed that the SOS advanced by 1.3 days and the EOS was delayed by 2.4 days with a 10-fold increase in urban size.

The city is the primary target of current research into differences in vegetation phenology along urban-rural gradients, for which there is a lack of comparative studies on coastal and inland cities that have different urban sizes. In this study, we used the Liaoning Province in China as the research subject. On the basis of MODIS EVI time series data and multisource data such as nighttime light data, China City Statistical Yearbook data, and land use data, we investigated the regularity of variations in the vegetation phenology along urban-rural gradients in urban areas of different sizes between coastal and inland cities, so as to quantify the response patterns of vegetation phenology to urbanization. We performed the following analyses: first, we obtained the range of urban built-up areas by using nighttime light data and verified the accuracy of the results; next, we examined the spatial distribution characteristics of vegetation phenology in Liaoning Province; and lastly, we explored the differences in vegetation phenology along urban-rural gradients in differently sized urban areas between coastal and inland cities to reveal the response patterns that vegetation phenology has to urbanization.

2. Data and Methods

2.1. Study Area. Liaoning Province (Figure 1) is located in the southern area of Northeast China (38°43′–43°26′N and 118°53′–125°46′E). Liaoning is the northernmost coastal province in China, and it includes two subprovincial cities (Shenyang and Dalian) and 12 prefecture-level cities (i.e., Yingkou, Panjin, Jinzhou, Huludao, Dandong, Chaoyang, Fuxin, Tieling, Fushun, Liaoyang, Benxi, and Anshan). Liaoning Province has a temperate monsoon climate, with long winters, short summers, and four distinct seasons. Since the 2003 proposal in the national strategy to revitalize old industrial bases in Northeast China, urbanization in Liaoning Province has progressed rapidly. Therefore, this is a representative area for the examination of spatiotemporal changes in vegetation phenology along urban-rural gradients in different urban areas.

2.2. Data Processing. In consideration of the research requirements and data availability, the data included in the present study were remote sensing imagery data and China City Statistical Yearbook data, as detailed in Table 1. Data processing consisted of the following methods: (1) batch processing of remote sensing data, i.e., splicing, projection, resampling, and cropping by administrative division and (2) summary and analysis of statistical data using the built-up area data in the China City Statistical Yearbook.

2.3. Research Methods

2.3.1. Extraction of Urban Built-Up Areas Using the Threshold Method. To cover the time range of this study (2001–2018), Defense Meteorological Satellite Program Operational Linescan System (DMSP/OLS) and National Polar Orbiting Partnership-Visible Infrared Imaging Radiometer Suite (NPP-VIIRS) images were used as the data sources for the built-up areas. Considering the continuity of nighttime light data and the differences in the sensors between the DMSP/OLS and NPP-VIIRS images, we integrated these two data types and extracted the boundaries of the urban built-up areas with reference to the built-up areas reported in the China City Statistical Yearbook [34–36]. The specific method was as follows:

(1) The DMSP/OLS and NPP-VIIRS data were preprocessed using techniques such as splicing, projection, resampling, and cropping.

(2) The NPP-VIIRS data were processed via negative elimination and average annual synthesis to obtain the annual NPP-VIIRS nighttime light data in 2013, 2015, and 2018.

(3) With the DMSP/OLS and NPP-VIIRS data for 2013, DMSP data with a digital number (DN) value between 0 and 50 were used as a mask to calculate the mean of the corresponding areas in the NPP-VIIRS data. These areas were used as constant target areas to fit the NPP-VIIRS data in 2013. The fitted results were used to correct the NPP-VIIRS data in 2015 and 2018.

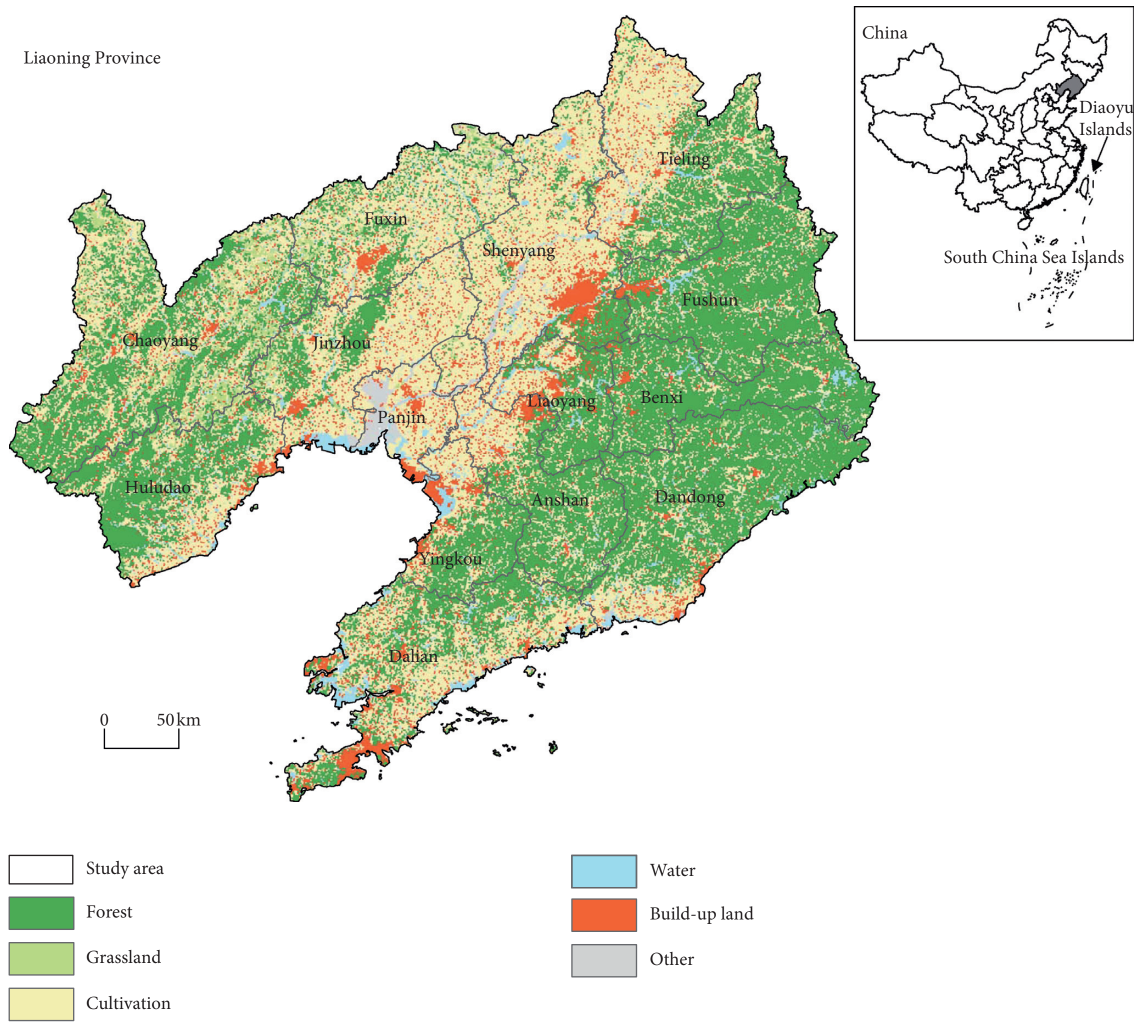

Figure 1: The location of the study area and land use types in 2018.

Table 1: Data sources and descriptions.

Data type	Data features	Data sources	Year	Data processing
MOD13Q1	250 m/16 d	https://lpdaac.usgs.gov/	2001, 2005, 2010, 2015, 2018	Batch processing
DMSP	1000 m	https://ngdc.noaa.gov/	2001, 2005, 2010, 2013	Batch processing
VIIRS-NPP	500 m	https://ngdc.noaa.gov/	2013, 2015, 2018	Batch processing and correction
China's land use/cover datasets	100 m	http://www.resdc.cn/	2001, 2005, 2010, 2015, 2018	Differentiate land use types
Administrative divisions data	Regional boundaries	National Catalogue Service for Geographic Information	2017	Extract administrative divisions
China City Statistical Yearbook	Text format	National Bureau of Statistics of China	2001, 2005, 2010, 2015, 2018	Summary and analysis

(4) Extremely high and unstable values were removed from the corrected NPP-VIIRS data to obtain a continuous sequence of nighttime light remote sensing images.

(5) With reference to the statistical area of urban built-up areas in Liaoning Province, the threshold method was applied to iteratively extract the urban built-up areas.

2.3.2. Extraction of Vegetation Phenology Using the Amplitude Method. The Savitzky–Golay (S-G) filter can describe complex and small changes in NDVI time series data and suppress noise such as that due to cloud pollution and atmospheric changes [37, 38]. MODIS EVI is the development and continuation of MODIS NDVI, and we used the S-G filter to smooth the MODIS EVI time series data. The methods to obtain vegetation phenology through TIMESAT included the threshold and amplitude methods. We used the amplitude method to extract the vegetation phenology with an amplitude of 30%. As human activity results in abnormal values for vegetation phenology, we set the effective range of the SOS and EOS to days 50–180 and days 240–330, respectively, to ensure data accuracy [39, 40].

2.3.3. Differences in Vegetation Phenology along Urban-Rural Gradients. We calculated the mean SOS and EOS in urban and rural areas and compared, step by step, the differences in vegetation phenology along urban-rural gradients by using the following expression:

$$\Delta \mathrm{SOS}i = \mathrm{SOS}ub - \mathrm{SOS}ri, \tag{1}$$

where SOS*ub* and SOS*ri* represent the mean SOS of the urban areas and i^{th} buffer zones, respectively, and ΔSOS*i* represents the differences in the SOS along the urban-rural gradients [24]. When negative, the SOS of a rural area is later than that of an urban area. When positive, the SOS of a rural area is earlier than that of an urban area. The method to calculate the differences in the EOS along urban-rural gradients is identical to that of the SOS.

3. Results

3.1. Extraction Results for Built-Up Areas. The threshold method was applied to iteratively extract the built-up areas of 14 cities in Liaoning Province in 2001, 2005, 2010, 2015, and 2018. In addition, the intersection of built-up areas in each year was used as the urban area. With the urban area as the center, 10 buffer zones with a diameter of 1 km were established as the rural areas surrounding the urban centers (Figure 2). For the spatial distribution characteristics, the built-up area in Shenyang was the largest. Built-up areas included a variety of land use types, such as urban construction land, water bodies, and parks, which demonstrated evident continuity and, therefore, were consistent with the definition of an urban built-up area. Table 2 lists the error rates associated with the extraction of urban built-up areas in 2001, 2005, 2010, 2015, and 2018, which were below 7%. Referring to previous results and research needs [41, 42], these data conform to the accuracy requirements of our study.

3.2. Extraction Results for Vegetation Phenology. We examined the spatial distribution characteristics of the vegetation phenology in Liaoning Province by calculating the mean SOS and EOS in 2001, 2005, 2010, 2015, and 2018 (Figure 3). In Liaoning, the SOS occurred during days 100–180, with a mean of 147.28 days, while the EOS occurred during days 260–330, with a mean of 290.12 days. Based on the heterogeneity of the spatial patterns, the SOS in eastern and part of western Liaoning was earlier, i.e., it occurred during days 110–130; in contrast, the SOS in central and part of western Liaoning, as well as northern Dalian was later than that in eastern Liaoning, i.e., it mainly occurred during days 150–180. The distribution difference in the EOS was smaller than that in the SOS. The EOS in eastern and central Liaoning as well as part of Dalian occurred during days 300–330, later than that in western and part of central Liaoning, which mainly occurred during days 270–290. The difference in the SOS was minor between coastal cities and inland cities, as the mean SOS of the former was 146.22 days and 147.92 days for the latter. In contrast, the difference in the EOS was significant between coastal and inland cities, where the mean EOS of the former was 292.89 days while that of the latter was 288.42 days.

3.3. Differences in Vegetation Phenology along Urban-Rural Gradients in Variously Sized Urban Areas. In contrast with rural areas, urban areas had an earlier SOS and later EOS (Figure 4). With an increase in distance from an urban area, the SOS of all cities showed a gradually delaying trend, especially in Shenyang and Yingkou, in which the SOS was delayed by 36.53 days and 35.55 days, respectively. The EOS exhibited a gradually advancing trend with an increasing distance from the urban area, especially in Jinzhou, Chaoyang, and Fuxin, in which the EOS advanced by 18.65, 17.99, and 17.35 days, respectively. The degree of difference in the SOS and EOS along the urban-rural gradients varied appreciably between the coastal and inland cities. The difference in the SOS along urban-rural gradients of coastal cities was slightly smaller than that of inland cities. Specifically, with the increase in distance from an urban area, the mean delay of the SOS in coastal cities was 20.40 days while that in inland cities was 21.25 days. The difference in the EOS along urban-rural gradients between the coastal and inland cities was significantly smaller than the difference in the SOS. The difference in the EOS along the urban-rural gradients of the coastal cities was smaller than that of the inland cities. With the increase in the distance from the urban area, the mean advance in the EOS for the coastal cities was 10.48 days while that in the inland cities was 13.33 days.

The difference in vegetation phenology along urban-rural gradients in various sized urban areas changed significantly between the coastal and inland cities. The built-up areas, representing various urban sizes, are plotted on the *x*-axis, whereas the difference in phenology between the urban and rural areas is plotted on the *y*-axis in Figure 5. Correlation models between urban size and difference in phenology were established to represent the influence that different urbanization processes have on the vegetation phenology in coastal and inland cities. There was a significant negative correlation between the ΔSOS and urban size in inland cities, i.e., a larger urban size was associated with a larger ΔSOS. When the urban size increased 10-fold, the ΔSOS advanced by 10.03 days. In contrast, there was a negative correlation between the ΔEOS and urban size. When the urban size increased 10-fold, the ΔEOS advanced by 5.71 days. Correlations between the difference in the vegetation phenology along urban-rural gradients and urban size in coastal cities differed from those in the inland cities. In coastal cities, there was a positive correlation

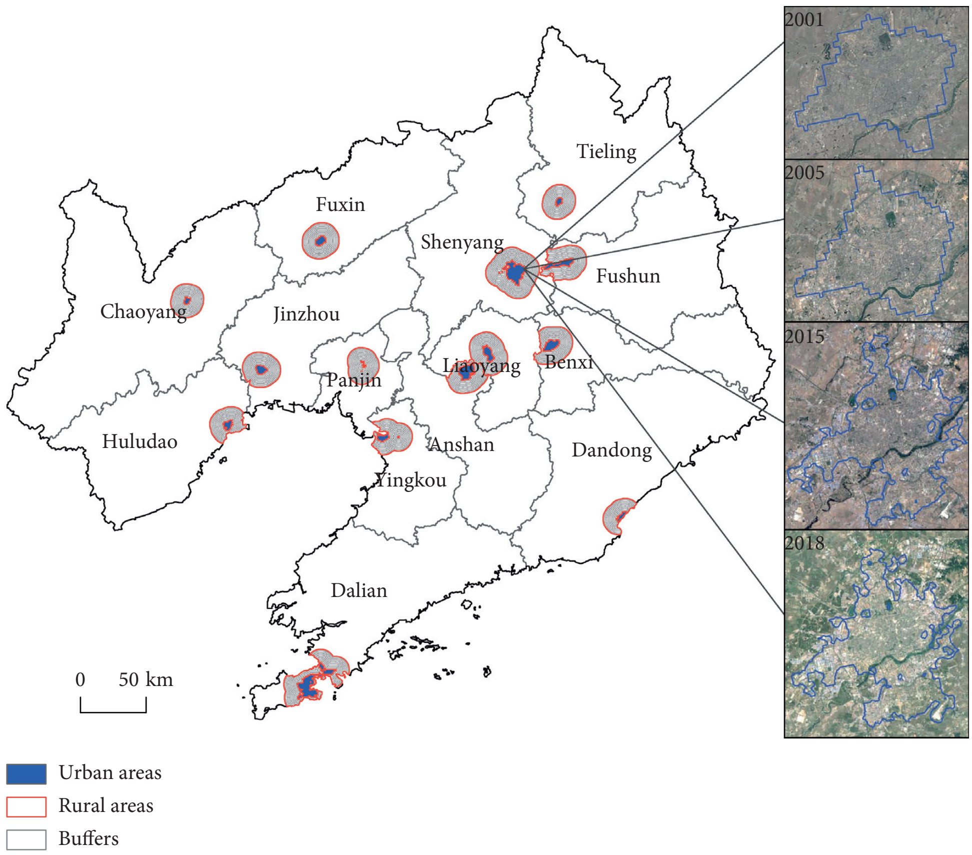

Figure 2: Results for urban areas and rural areas (example of Shenyang to show the extraction results for urban built-up areas year by year).

Table 2: Accuracy validation results for the built-up areas.

	2001	2005	2010	2015	2018
Nighttime light data (km^2)	1298.51	1415.00	1646.00	1953.00	2219.00
China City Statistical Yearbook (km^2)	1270.28	1473.62	1542.91	1935.91	2192.94
Error (km^2)	28.23	−58.62	103.09	17.09	26.06
Error rate (%)	2.17	−4.14	6.26	0.88	1.17

between the ΔSOS and urban size, i.e., a larger urban size was associated with a smaller ΔSOS. When the urban size increased by 10-fold, the ΔSOS was delayed by 11.29 days. In contrast, there was a negative correlation between ΔEOS and urban size. When the urban size increased by 10-fold, the ΔEOS advanced by 8.83 days.

4. Discussion

4.1. Reasons for the Differences in Vegetation Phenology between Coastal Cities and Inland Cities. Differences in climate zones and vegetation types can affect vegetation phenology [43–47]. According to climate zone results from the Data Center for Resources and Environmental Sciences of the Chinese Academy of Sciences, 14 of the cities in Liaoning Province are located within five different climate zones. Based on the statistical results, different climate zones have different SOS and EOS times (Figure 6(a)). As the Sanjiang-Changbai region contains more forests, it had an earlier SOS and later EOS. Different climate zones led to differences in urban vegetation phenology (Figure 6(b)). As vegetation types varied in different regions, the mean phenology of agricultural land (paddy fields and dry land), forestland (woodland, shrub land, sparse woodland, and other woodlands), and grassland (high-cover, midcover, and low-cover grassland) were calculated using classification criteria based on remote sensing data for land use (Table 3). The results showed that the SOS of forestland was earlier than that of agricultural land and grassland while the EOS was later, which was a result closely related to the comprehensive influence that human and climatic factors have on agricultural land [48].

These differences in climate led to differences in the vegetation phenology between the coastal and inland cities. Differences in temperature and precipitation between coastal and inland cities are crucial factors that affect vegetation phenology [26, 49, 50]. Based on previous research, an increase in temperature in spring can lead to an earlier SOS, whereas an increase in temperature in autumn

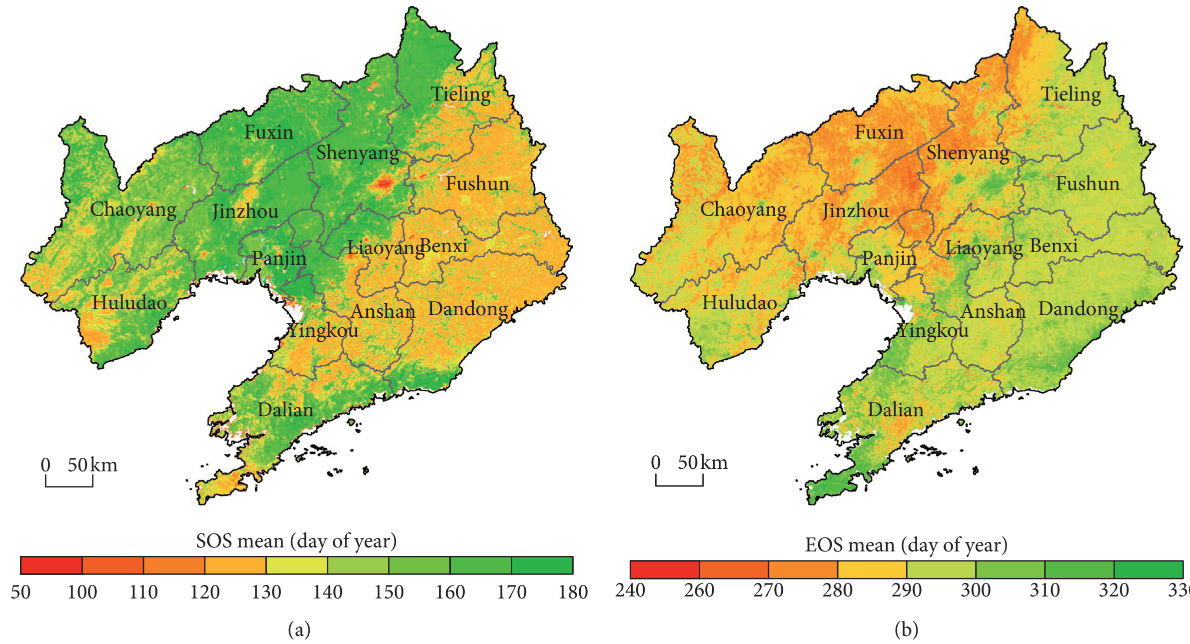

FIGURE 3: Spatial patterns of the average vegetation phenology in Liaoning Province for 2001, 2005, 2010, 2015, and 2018. (a) Average SOS in Liaonian Province between 2001 and 2018. (b) Average EOS in Liaonian Province between 2001 and 2018.

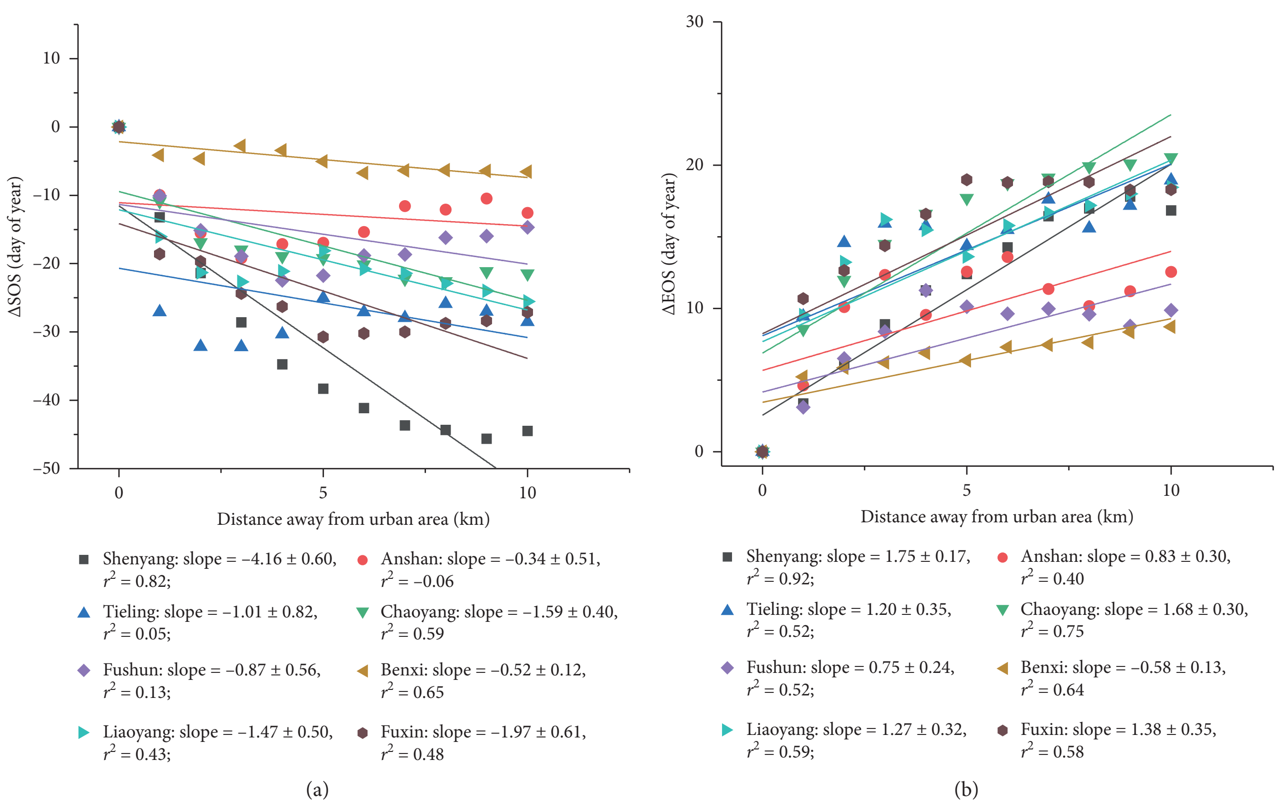

FIGURE 4: Continued.

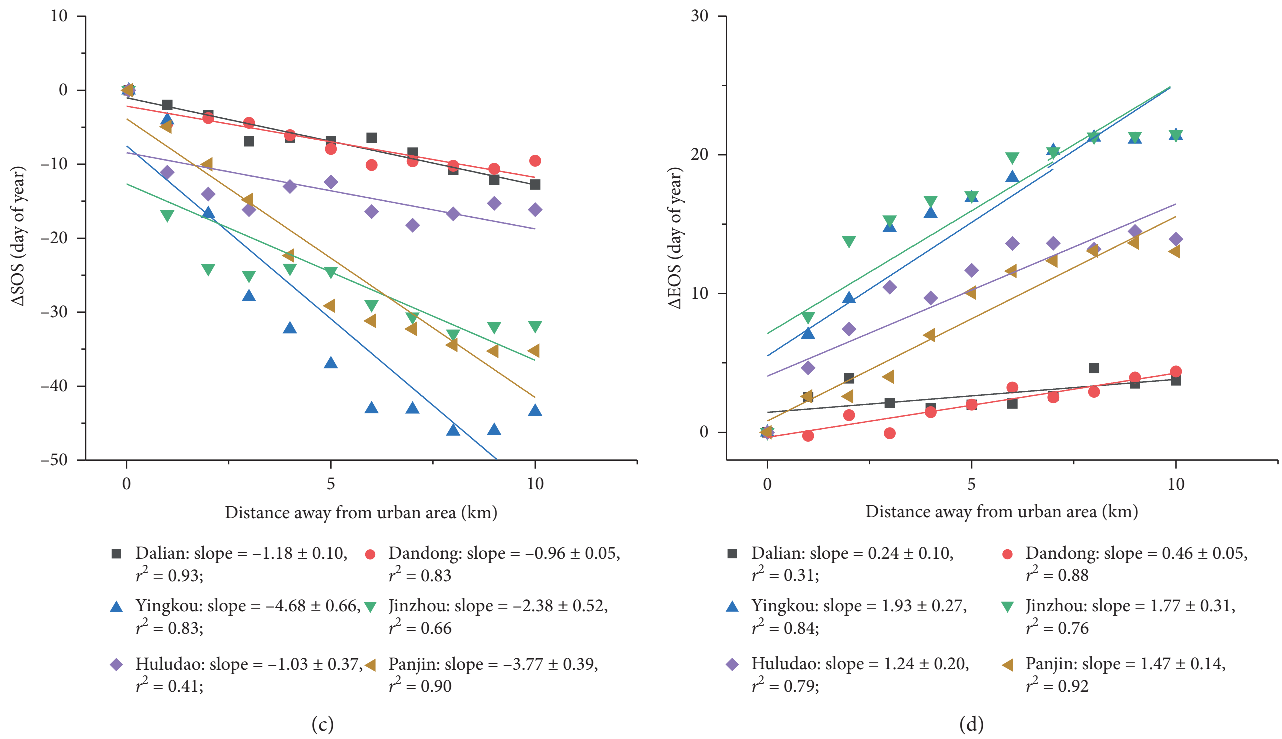

Figure 4: Differences in vegetation phenology along the urban-rural gradients. (a) ΔSOS in inland cities. (b) ΔEOS in inland cities. (c) ΔSOS in coastal cities. (d) ΔEOS in coastal cities.

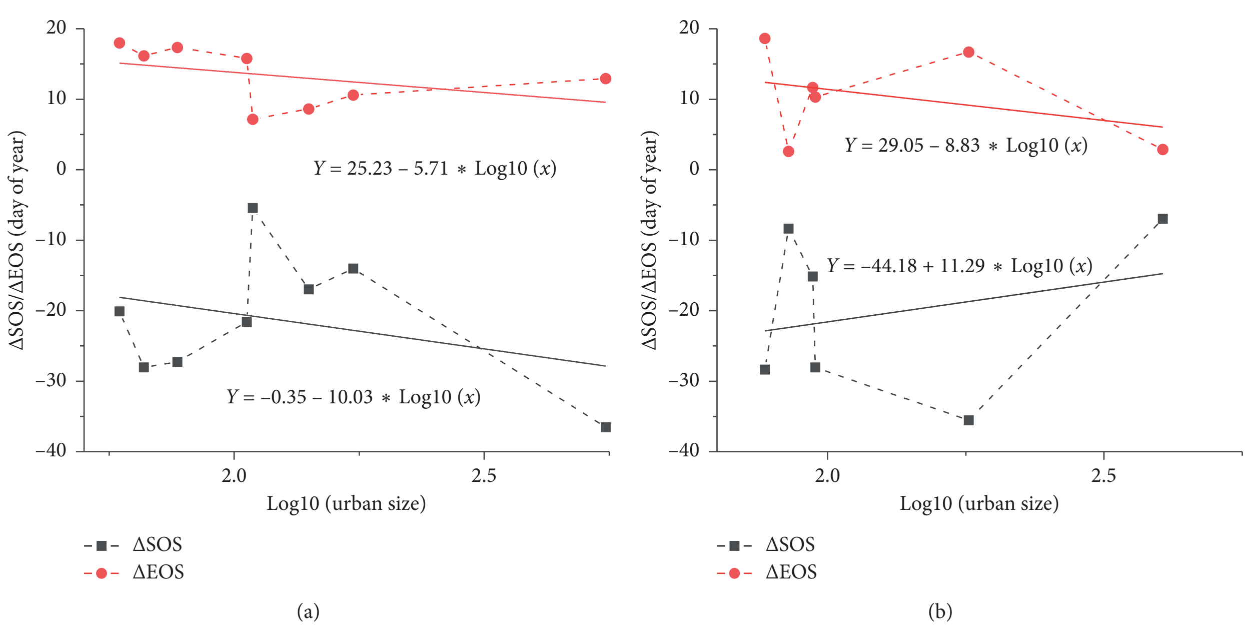

Figure 5: The relationship between vegetation phenology and urban size. (a) Inland cities. (b) Coastal cities.

can lead to a later EOS. The precipitation gradient also affects the vegetation phenology, but there is an evident lag effect [45, 51, 52]. Compared with inland cities, coastal cities had higher temperatures and more precipitation, which could have led to the differences in vegetation phenology. With continued urbanization, the types of urban land use have changed appreciably, thus resulting in an increase in the area of impervious surfaces [53]. Other studies have found that there is an evident correlation between vegetation phenology and urbanization (i.e., urbanization leads to an earlier SOS and later EOS), and the magnitude of urbanization (i.e., the area of impervious

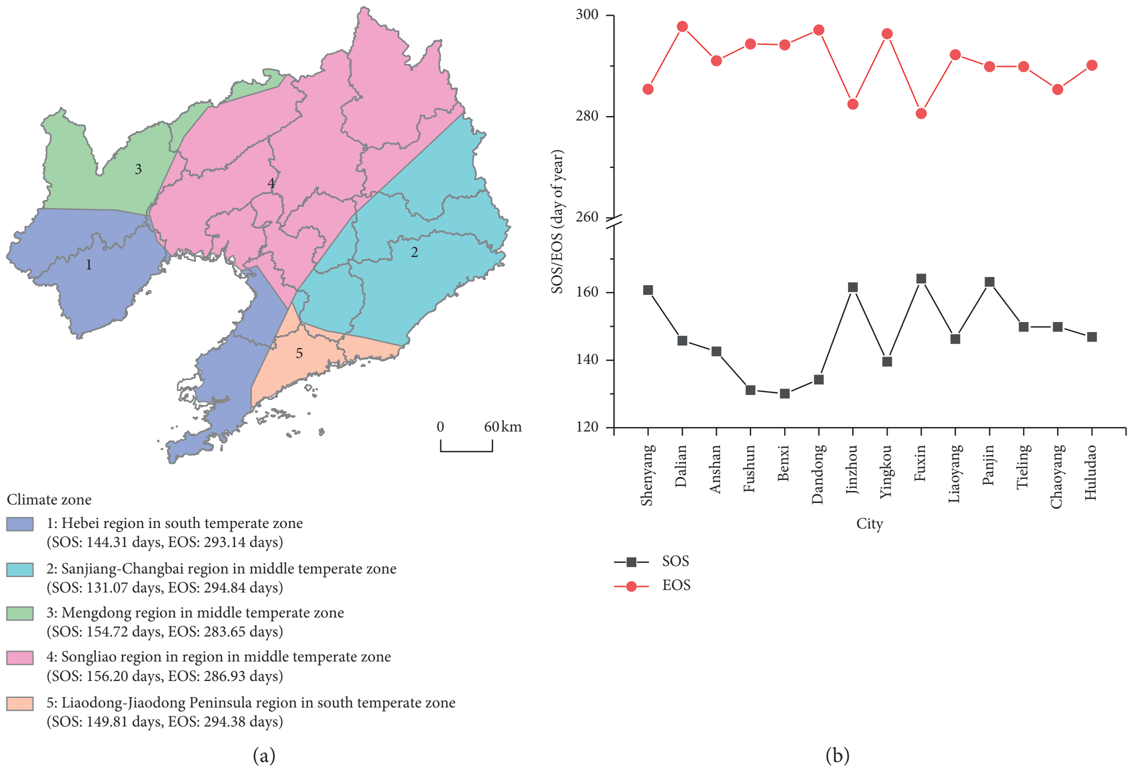

FIGURE 6: (a) Climate zone of Liaoning Province and (b) Vegetation phenology of 14 cities in Liaoning Province.

TABLE 3: Phenology of different land use types.

Land use types	Agricultural land		Forestland				Grassland		
Name	Paddy field	Dry land	Woodland	Shrub land	Sparse woodland	Other woodlands	High-cover grassland	Midcover grassland	Low-cover grassland
SOS (day of year)	165.63	156.03	134.22	146.54	147.62	152.65	152.07	152.09	153.71
EOS (day of year)	288.89	286.52	293.93	289.11	288.74	293.44	286.36	285.24	284.22

surfaces) has a significant relationship with the advanced SOS and delayed EOS [54–56]; this is consistent with the results of this study. Considering the differences in climate between the coastal and inland cities, we used the urban built-up areas to represent urban size and investigated the difference in vegetation phenology between urban and rural areas with respect to various urban sizes. The results differed, to a certain extent, from those reported in [33], and the data were closely related to the study area, data, methods, and period [57, 58].

4.2. Uncertainties. This study explored the response patterns of vegetation phenology along urban-rural gradients for different sized urban areas in coastal and inland cities, and the results provide a basis for forecasting the influence that urbanization has on the ecological environment. Nevertheless, this study had the following limitations: (1) use of MOD13Q1 to obtain the vegetation phenology affected the accuracy of vegetation phenology results due to the occurrence of mixed pixels in the data product [59] and (2) because of the abnormal fluctuations and discontinuity of the DN pixel values, there was a certain subjectivity when using nighttime light data to obtain the range of urban built-up areas based on the threshold iterative method, which affected the accuracy [41, 60].

Future studies should consider the comprehensive effects of climate background, geographical location, and urbanization on vegetation phenology. Furthermore, higher-resolution remote sensing data products should be applied in order to more realistically reflect the response of vegetation phenology to urbanization, so that the impact of urbanization on the ecological environment can be quantified.

5. Conclusions

This study used Liaoning Province in China as the research subject. With MODIS EVI time series data from 2001, 2005, 2010, 2015, and 2018, as well as multisource data such as nighttime light data and China City Statistical Yearbook data, we classified urban built-up areas into different urban sizes and investigated the differences in the vegetation phenology along urban-rural gradients in variously sized urban areas between coastal and inland cities. Based on these analyses, our conclusions indicate the following:

(1) The urban built-up areas iteratively extracted by using the threshold method based on the nighttime light data included various land use types. There was apparent continuity among the various types, with an error rate below 7%.

(2) The SOS of Liaoning Province occurred during days 100–180, while the EOS occurred during days 260–330. The difference in the SOS between the coastal and inland cities was insignificant (1.70 days), but that for the EOS was significant (4.47 days).

(3) In contrast with rural areas, urban areas had an earlier SOS and later EOS. Differences in the SOS and EOS along the urban-rural gradients of coastal cities were smaller than those of the inland cities, with a difference of 0.85 and 2.85 days, respectively. In the differently sized urban areas, the ΔSOS and ΔEOS of inland cities had negative correlations with the urban size. The ΔSOS and ΔEOS of coastal cities showed a positive and negative correlation with the urban size, respectively.

Our study provides a reference for quantifying the influence that urbanization has on vegetation phenology. Moreover, a comparative study on the differences in vegetation phenology along urban-rural gradients between coastal and inland cities facilitates our understanding of different urbanization processes in coastal and inland cities, which is vital for improvements to the ecological environment.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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