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Response of Plant Phenology on Microclimate Change Depending on Land Use Intensity in Seoul, Central Korea

A-Reum Kim [1], Jaewon Seol [2], Bong-Soon Lim [3], Chi-Hong Lim [3], Gyung-Soon Kim [4] and Chang-Seok Lee [3,*]

1 Forest Ecology Division, National Institute of Forest Science, Seoul 02455, Republic of Korea; bgvib@korea.kr
2 Division of Forest Biodiversity, Korea National Arboretum, Pocheon 11186, Republic of Korea; seoljaewon@korea.kr
3 Department of Bio & Environmental Technology, Seoul Women's University, Seoul 01797, Republic of Korea; bs6238@swu.ac.kr (B.-S.L.); chlim@swu.ac.kr (C.-H.L.)
4 National Institute of Ecology, Seocheon 33657, Republic of Korea; ecokimgs@nie.re.kr
* Correspondence: leecs@swu.ac.kr; Tel.: +82-2-970-5666

Abstract: The difference in the leaf unfolding date of Mongolian oak obtained through MODIS image analysis between the urban center and the outskirts of Seoul was found to be seven days. The difference in the flowering date of cherry obtained through field observations was also found to be seven days between the urban center and the outskirts. The frequency of the abnormal shoot of Korean red pine differed by 71% between the urban center and the outskirts, and the length growth differed by 8.6 cm. There was a statistically significant correlation between the leaf unfolding date of Mongolian oak, the flowering date of the cherry, and the spatial difference in the frequency and length of the abnormal shoot of the Korean red pine. The temperature difference between the urban center and the outskirts of Seoul based on the mean temperature over the past 30 years was about 5 °C. The spatial difference in plant phenology showed a statistically significant negative relationship with the spatial difference in temperature. On the other hand, the spatial difference in temperature showed a statistically significant positive relationship with the spatial difference in the urbanization rate. These results are interpreted as the result of excessive land use during urbanization causing the heat island phenomenon, and the resulting temperature difference is reflected in the phenology of plants. These results are evidence that urbanization, which uses excessive land and energy, has a very significant impact on climate change. In addition, it is also evidence that sustainable land use could be an important means to achieve climate change adaptation and further solve climate change problems.

Keywords: climate change; MODIS; Mongolian oak; phenology; urbanization

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1. Introduction

The increase in CO_2 concentrations in the atmosphere due to the excessive use of land and fossil fuels is causing abnormalities in the carbon cycle of the Earth, which remained in equilibrium [1–5]. Urbanization is seriously affecting the terrestrial ecosystem [6–10] as one of the major social and scientific changes that have spread around the world [5,8]. Changes in land use due to urbanization are changing carbon storage patterns, releasing greenhouse gases into the atmosphere, and breaking the balance of the carbon budget [5,11–13]. The increase in development areas and population causes changes in meteorological factors [10,14,15], which accumulate and lead to climate change [16–18].

Urbanization has had a very significant impact on the terrestrial ecosystem as one of the important artificial factors affecting the climate [15,19]. Urbanization not only causes local climate change on daily, seasonal, and annual scales [20–23] but also increases extreme weather events [24–27]. Moreover, warming and extreme heat events due to urbanization and increased energy consumption are simulated to be as large as the impact of doubled

CO_2 in some regions [28]. In those respects, microclimate change due to urbanization could be regarded as climate change at a local level [29].

Local climate change in urban areas is known as urban heat island (UHI), which is increasing in intensity along with climate change. The urban heat island effect is characterized by higher air and surface temperatures in urban areas compared to surrounding rural areas [9,30,31]. The urban heat island phenomenon not only causes an increase in surface temperature but also increases energy and water consumption and environmental pollution, and greatly affects weather phenomena such as precipitation, frequency, and magnitude of flooding [18,21,32–34]. Increasing energy consumption due to urban heat island phenomena and increasing medical and social costs due to heat-related diseases such as heatstroke are also emerging serious problems [35,36].

Plant phenology is usually used as an indicator to monitor the response of ecosystems to climate change because they respond sensitively to meteorological factors such as temperature and precipitation [37–45]. The phenological characteristics of the plant are closely related to changes in weather factors [19,46,47]; the observation of long-term plant phenology conducted through many studies shows that climate change is affecting the development process of plants [48–52].

In the study of plant phenology, urban areas are important research areas because the potential effect of future climate change on plant development can be evaluated there [19,53]. Temperature increases due to the urban heat island effect can affect plant phenology, such as the start of growing season (SOS), end of growing season (EOS), and GSL (growing season length) [30,54–56]. It is very important to understand the effects of the urban heat island phenomena on plant phenology because urban heat island effects are similar to those of temperature changes expected in the near future [9].

The urban sprawl can influence the plant growth and timing of the developmental stage of plants by changing the environment [57]. Previous studies have showed that plant phenology events are influenced by urbanization [30,56,58,59]. Additionally, the growth period of a plant, determined by the unfolding and falling of leaves, is strongly affected by the UHI effect [21,60–66]. Changes in plant phenology caused by urbanization have been observed worldwide. According to [15], in the mid- and high-latitude areas of the northern hemisphere, the green-up dates of urban areas were 4–9 days earlier than those of rural areas. The authors in [67] found that the growth period of plants in an urban area was 7.6 days longer than that of rural areas in eastern United States broadleaf forests. The growth period of a plant was extended due to urbanization according to the results of many studies [15,64,68,69], most of which are linked to earlier growing dates [29]. In addition, since the leaf unfolding phenomena of the spring season shows distinct characteristics [38,67,70], plant phenology during the spring season could be the most suitable tool for monitoring climate change.

Recent research has identified significant shifts in plant phenology due to the interplay between urbanization, climate change, and the urban heat island effect, with studies across the northern mid-latitudes and China showing altered timing in the start and end of growing seasons [64,71]. Additionally, the response of plant phenology to urbanization has been shown to vary with regional temperature, indicating a complex interaction between climate gradients and urban heat islands [68,72]. Despite these advancements, there remains a significant gap in understanding the specific mechanisms driving these phenological shifts and their ecological consequences, particularly in the context of highly urbanized areas in East Asia. Moreover, the impacts of varying degrees of urbanization within a single metropolitan area on different plant species are still underexplored. Our study aims to bridge these gaps by focusing on the representative tree species in Seoul, South Korea, a city known for its pronounced urban heat island effect. By analyzing spatial differences in plant phenology relative to urbanization degrees, we aim to contribute to elucidating the underlying mechanisms, offering insights for ecosystem management and adaptation strategies to climate change, and enriching the global discourse on urban ecology and phenological change. Although many studies have been conducted on the change in the plant phenology response due to urbanization effects, few studies have been conducted on the response of plant phenology to various levels of urbanization at a fine scale within the urban domain. Therefore, it is necessary to focus on the phenology response to various levels of urbanization using a fine scale. This study aims to identify spatial differences in plant phenology according to the degree of urbanization based on the plant phenology data collected in various areas of Seoul, which show an extreme heat island effect, and to present ecosystem management strategies for climate change adaptation based on the data. To arrive at this goal, we collected data on the phenology of Mongolian oak, cherry, and abnormal growth of Korean red pine seen in various locations with different land use intensities. Therefore, it is necessary to focus on the phenology response to various levels of urbanization using a fine scale. This study aims to identify spatial differences in plant phenology according to the degree of urbanization based on the plant phenology data collected in various areas of Seoul, which show extreme heat island effects, and to present ecosystem management strategies for climate change adaptation based on the data.

2. Materials and Methods

2.1. Study Area

This study was carried out in Seoul, the capital with the most extensive and long urbanization history in Korea. This investigation aims to elucidate the impacts of varying land use intensities on plant phenology. For this purpose, Mongolian oak, a species with a broad distribution, was selected as the primary subject of study. Additionally, cherry and pine trees were chosen as comparative species (Figure 1).

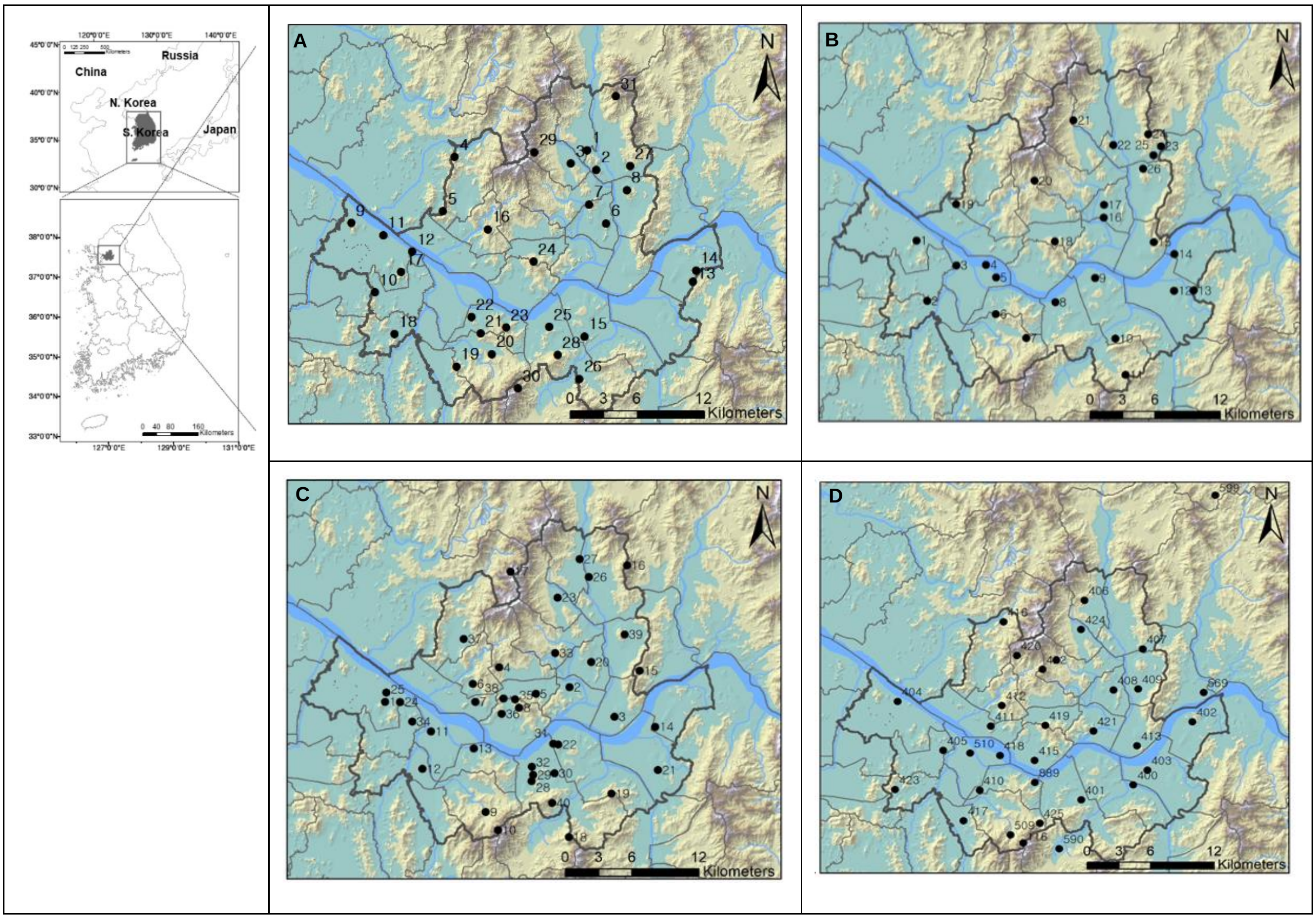

Figure 1. A map showing the study sites. (**A**) The sites for study of green-up dates of *Q. mongolica*, (**B**) the sites for study of flowering date of cherry, (**C**) the sites for study of abnormal growth of Korean red pine, and (**D**) the sites where the meteorological data were collected.

To compensate for the resolution of large-scale MODIS satellite images, the mountain with a high occupancy ratio of Mongolian oak forest among the mountains in Seoul was selected as the study site. The study sites shown on the map represent the place where the widest Mongolian oak community is located within the selected mountain.

2.2. Land Use Pattern in Seoul

Based on the landscape ecological map generated for Seoul, the urban area occupied, at its widest, 60.8% of the total area, followed by secondary forests (12.7%), plantations (8.6%), river and reservoir (5.6%), landscape architectural plantation (4.5%), agricultural fields (2.5%), grasslands (2.4%), inaccessible area (2.3%), and bare ground (0.7%) (Figure 2). Forests, which are composed of secondary forests and plantations and agricultural fields, were usually concentrated to the city's fringe, and the urban center had little vegetation. Moreover, vegetation in the urban center was of low ecological quality, as most was fragmented into small patches and consisted of species introduced by landscape architects without ecological consideration or exotic plants [73,74]. Therefore, green space showed severe imbalanced spatial distribution (Figure 2).

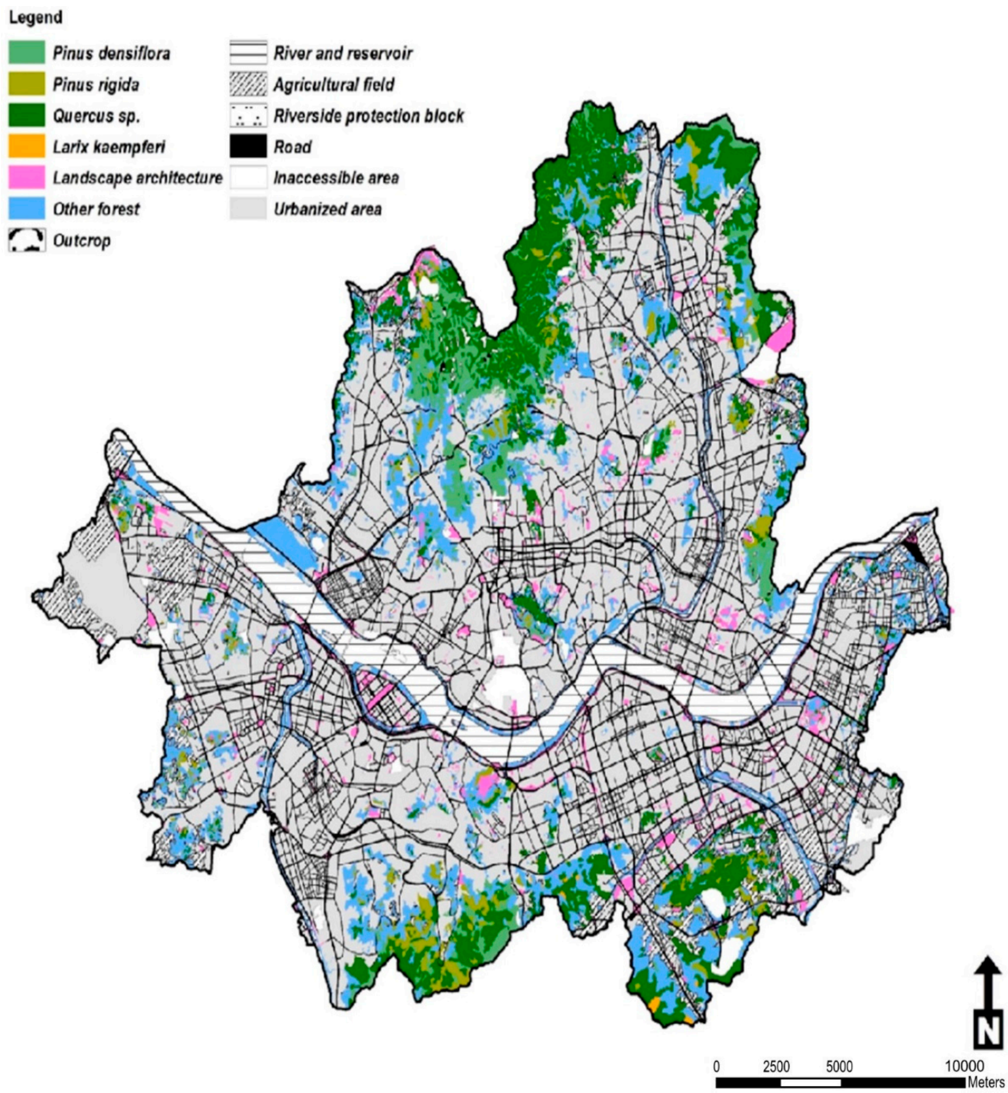

Figure 2. A map showing spatial distribution of vegetation and land use types in the Seoul metropolitan area (redrawn from Seoul City [75]).

2.3. Calculation of Urbanization Ratio

The urbanization ratios at the designated study sites were quantified by analyzing the biotope map of Seoul. These ratios were calculated using ArcGIS 10.1 software (ESRI, Redlands, CA, USA), defined as the proportion of urbanized land to the total land area within a 5 km radius from each study site.

2.4. Analysis of Phenology Based on Satellite Image

This research targeted *Quercus mongolica* Fisch. ex Ledeb., a predominant species in the deciduous broad-leaved forests of Korea, known for its sensitivity to temperature increases associated with climate change [56]. Growing at higher altitudes in South Korea, this species experiences pronounced phenological shifts. Utilizing remote sensing data, the study delineated the annual phenological cycle into four distinct stages: green-up, maturity, senescence, and dormancy (Figure 3) [17,56,61]. Phenological signals are minimal during the dormancy phase, escalating sharply during green-up, stabilizing at high values in maturity, and then declining significantly in the senescence phase, eventually returning to the lowest levels as dormancy recommences. The inflection points on the phenological signal curve, indicative of rapid curvature changes, denote the commencement of each stage [17]. The methodology also encompasses a formula for calculating the curvature K value at these inflection points:

$$f(t) = a + \frac{c}{1 + exp(a + bt)} + d \quad (1)$$

$$K = \frac{f''(t)}{\left(1 + (f\prime(t))^2\right)^{\frac{3}{2}}} \quad (2)$$

where t is time, c is the amplitude of the increase or decrease in green value, d is the baseline value of the dormant season, and a and b control the lower and upper limits of the function [17,64,65,68].

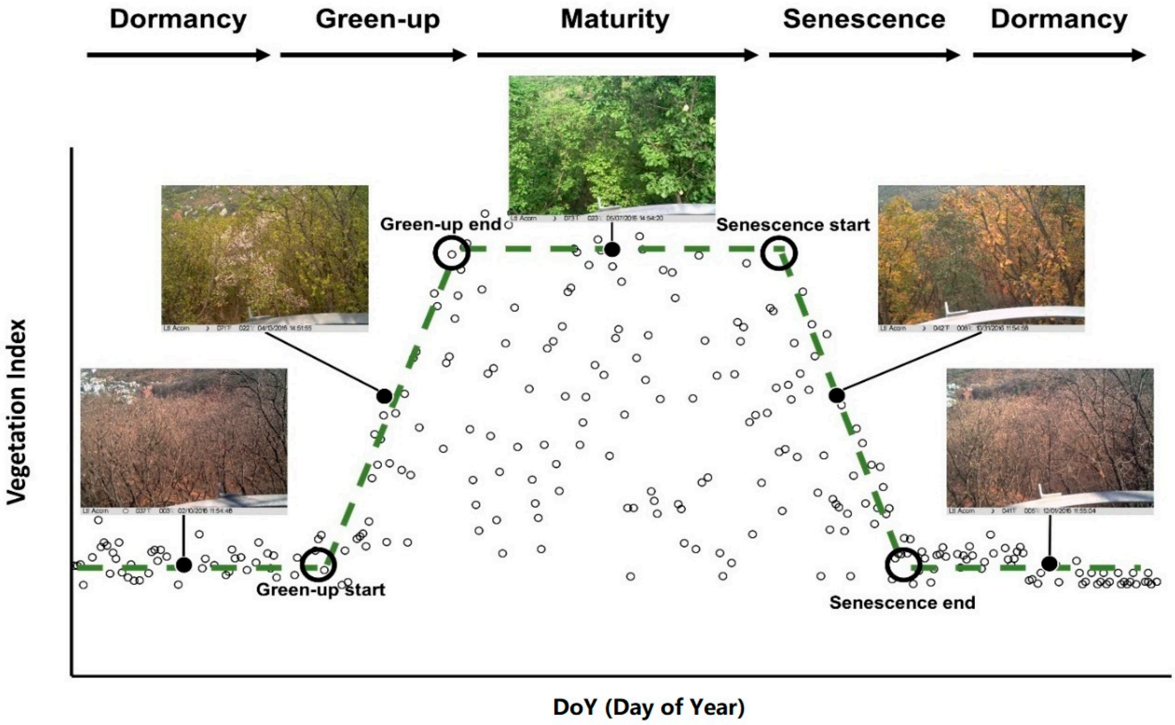

Figure 3. An illustration of phenological phases extracted from remote sensing data.

2.5. Calculation of Vegetation Index

The MOD09GA dataset includes seven spectral bands, covering visible and near-infrared light. MODIS EVI calculations use red (Band 1: 620–670 μm), green (Band 4: 545–565 μm), blue (Band 3: 459–479 μm), and near-infrared (Band 2: 841–876 μm) bands. The Enhanced Vegetation Index (EVI) used in the vegetation index makes improvements to traditional indices by reducing spatial variations, especially in diverse regions, using the blue band. This enhances its ability to detect seasonal changes in vegetation and canopy characteristics [60]. The specific formula applied for EVI computation in this analysis is as follows:

$$\mathrm{EVI} = 2.5 \times (\rho NIR - \rho RED)/\{\rho NIR + (6 \times \rho RED - 7.5 \times \rho BLUE) + 1\} \tag{3}$$

where ρNIR, ρRED, and $\rho BLUE$ are values in the near-infrared, red, and blue bands. MODIS satellite images were reprojected to TM (Transverse Mercator) coordinates because they use sinusoidal projection. Based on the extracted data, the EVI for each study site was derived. Subsequently, the EVI was derived by employing the smooth curve fitting technique to mitigate variations and extract trends, as interpretational errors may arise from data inaccuracies and weather-related fluctuations [17]. In this study, the EVI was smoothed to the 80th percentile utilizing an exponentially weighted moving average (EWMA). The EWMA was defined as follows:

$$S_t = \alpha \times Y_t + (1 - \alpha) \times S_{t-1}\ (t > 1, S_1 = Y_1) \tag{4}$$

where t is the day of the year (DoY); S_t is the EWMA value at the DoY; Y_t is the EVI value at the DoY; and α is the smoothing coefficient.

Phenological signal curves were derived using the calculated EVI, and the inflection point K, where the value increases rapidly, was confirmed as the green-up date.

2.6. The Flowering of Cherry

In order to investigate the flowering dates of cherry trees, a location with the presence of more than three cherry tree individuals was chosen as the research site. The flowering dates were determined by selecting three individual trees from each site (refer to Figure 1). The flowering date of cherry tree was set as the time when three or more flowers bloomed per tree. The flowering dates of the cherry trees were then interpolated using the Inverse Distance Weighted (IDW) model.

2.7. The Abnormal Growth of Korean Red Pine

Lammas growth is shoots that form after a pause in summer growth [76]. However, often, Lammas growth continues from late summer through to fall and into winter, showing different characteristics from typical Lammas growth. We identified this specific phenological event as abnormal growth.

To assess the frequency and length of abnormal shoot growth in Korean red pine (*Pinus densiflora*), 40 survey sites were selected (Figure 1). The frequency of abnormal shoot growth was calculated as the proportion of branches exhibiting abnormal shoots relative to the total branch count. The length of the shoots was measured on branches at the third node from the apex. These measurements were conducted using a tape ruler with millimeter precision on three branches from three trees selected at random. Specifically, the terminal shoots on each branch were measured [15,67]. The frequency and length of the abnormal shoots in Korean red pine were then interpolated using the Inverse Distance Weighted (IDW) model.

2.8. Collection and Analysis of Meteorological Data

The monthly mean temperature was determined from temperature data collected in ten-minute intervals from 1997 to 2021 at Automatic Weather Stations (AWSs) (refer to Figure 1). These data were then recalculated to ascertain the mean temperature for each season: spring (March–May), summer (June–August), autumn (September–November), and winter (December–February). This allowed for an analysis of seasonal mean temperature variations. The air temperature data from each AWS were interpolated using the co-kriging (CK) model (Figure 3).

2.9. Statistical Analysis and Mapping

The statistical analysis was carried out using SPSS 19 (IBM Corp, Armonk, NY, USA) and Excel (Microsoft Office 2010, Microsoft Corp., Redmond, WA, USA). Maps were constructed by utilizing the Arcgis 10.1 program. Data were visualized by applying the 'ggplot2' package of R program 4.2.2 (R Core Team, Vienna, Austria) [77].

3. Results

3.1. The Spatial Distribution of Plant Phenology

The green-up dates of Mongolian oak appeared between DoY 91 and 98. In the isopleth map, the green-up date of the Mongolian oak in Seoul was expressed; the date was earlier in the urban center, and it was delayed as it moved toward the outskirts (Figure 4).

The cherry blossom dates appeared between DoY 91 and 98. In the isopleth map, the flowering date of the cherry in Seoul was expressed; the date was earlier in the urban center and tended to be delayed as it moved toward the urban outskirts (Figure 4).

The frequency of abnormal shoots of Korean red pine was higher in the urban center, and the trend tended to decrease as it moved toward the urban outskirts, and the length of the abnormal shoots tended to be similar to the frequency (Figure 4).

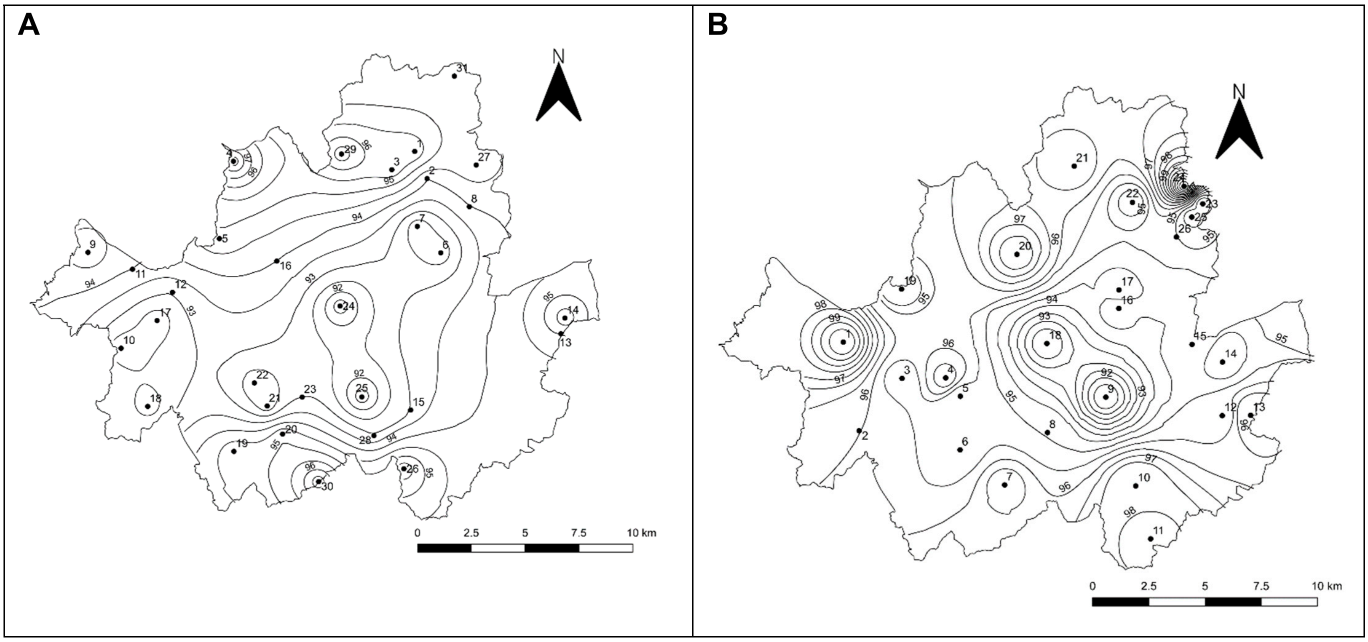

Figure 4. *Cont.*

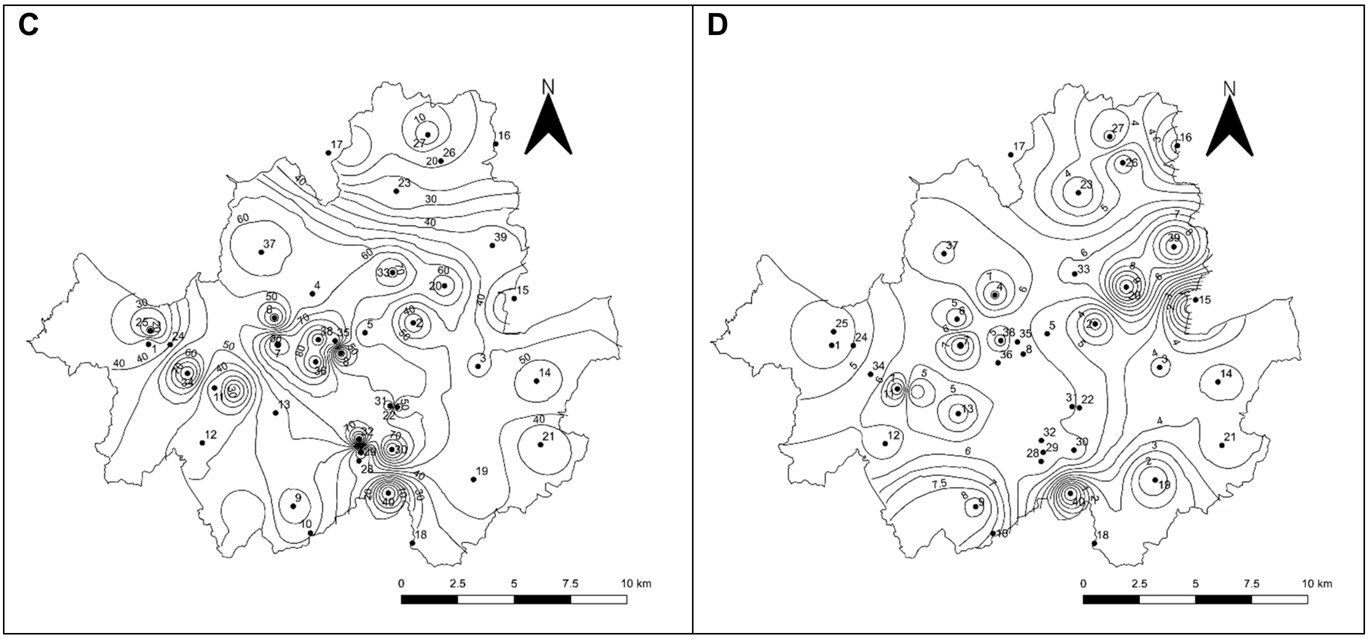

Figure 4. The isopleth map of the collected data from the study sites. (**A**) DoY for green-up date of *Q. mongolica,* (**B**) DoY for flowering date of cherry, (**C**) frequency of the abnormal shoots occurring in Korean red pine, (**D**) lengths of the abnormal shoots occurring in Korean red pine. Dot numbers indicate site number and numbers on the isopleth line indicate DoY.

3.2. Correlation between Phenology in Different Plants

As a result of analyzing the correlation between the leaf unfolding date of the Mongolian oak, the flowering date of the cherry, and the frequency and length of the abnormal shoot of the Korean red pine trees, there was a significant correlation between the phenology of all the plants (Table 1).

Table 1. Correlation coefficients between green-up date of the *Q. mongolica*, flowering date of cherry, frequency of the abnormal shoots, and abnormal shoot length occurring in Korean red pine.

	Flowering Date	**Frequency**	**Length**
Green-up date	0.401 **	−0.543 **	−0.204 *
Flowering date		−0.411 **	−0.288 **
Frequency			0.495 **

* denotes significance at the 5% level. ** denotes significance at the 1% level.

3.3. The Spatial Distribution of Air Temperature within Seoul City

Figure 5 shows the spatial distribution of the air temperature in Seoul measured in the automatic weather station. The air temperatures were higher in the urban center formed along the Han River and tended to lower as they moved toward the urban outskirts of Seoul. A relative cold area was observed in mountainous areas, which are near the borderline of Seoul, except the southwestern and southeastern borderlines where the sprawling expansion of urbanization has already progressed. Such a spatial distribution of air temperature is closely linked to the land use pattern (Figure 5).

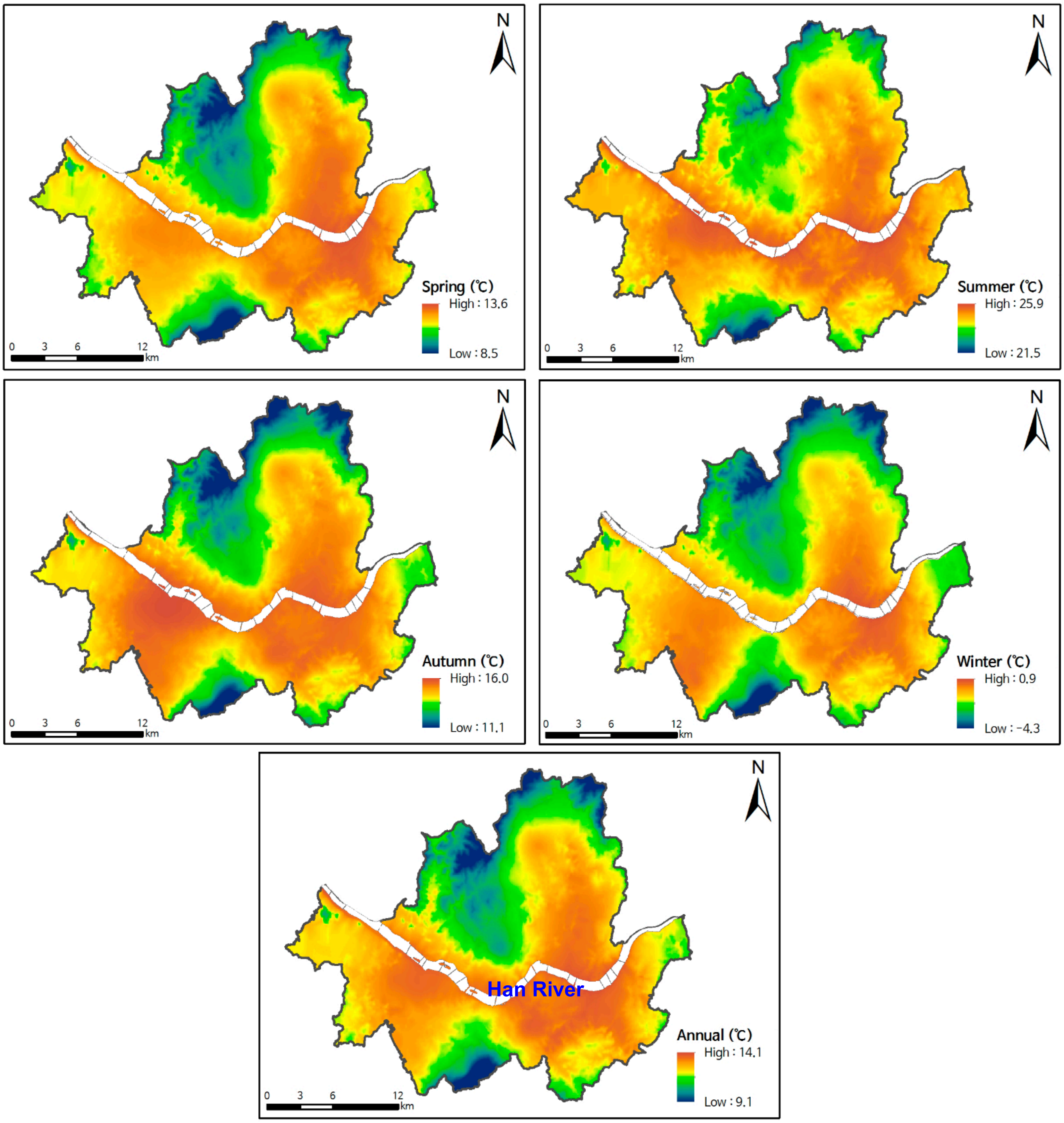

Figure 5. A spatial distribution map of the mean air temperature (°C) in Seoul for recent 25 years from 1997 to 2021.

3.4. Relationship between Urbanization Rate and Air Temperature

The urbanization rate of the study sites showed a significant positive correlation with air temperature ($p < 0.01$) (Figure 6). On the other hand, the leaf unfolding date of the Mongolian oak showed a significant negative correlation with both the urbanization ratio and air temperature ($p < 0.01$) (Figure 6).

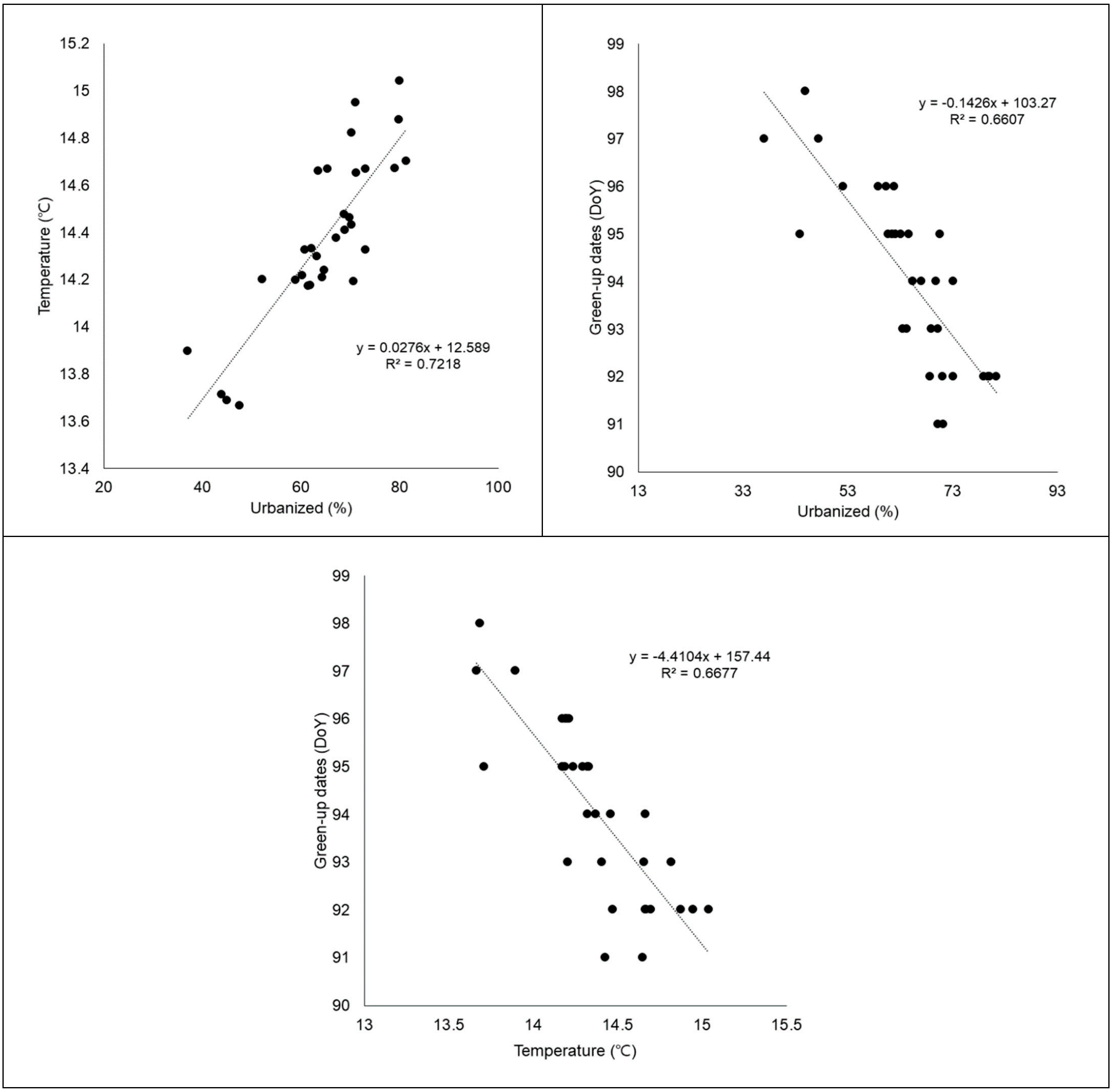

Figure 6. Relationships between urbanization rate, air temperature, and green-up date of *Q. mongolica*.

4. Discussion

4.1. Difference in Plant Phenology among Study Sites with Different Urbanization Ratio in Seoul

Climate change can have a great influence on plant phenology as the seasonal events of plants are very sensitive to environmental changes such as temperature changes [38]. Local climate change due to urbanization is causing significant changes in plant phenology [29]. In China, as the Land Surface Temperature (LST) rises by 1 °C, the SOS was advanced by 9–11 days, and the EOS was delayed by 6–10 days [69]. In eastern North America, SOS was shown to advance by three days as the mean temperature rose by 1 °C [15]. In Seoul, the flowering date was advanced by up to 13 days for 20 years between 1991 and 2010, and the falling of leaves during the fall season was delayed by up to 15 days [70]. Cherry has bloomed 8–16 days earlier for the past 100 years in several urban areas of South Korea [29], and the germination and flowering date of 10 common trees in Korea was advanced by 4 to 16 days for about 60 years from 1945 to 2007, and the peak period of leaf coloring was delayed by 7 to 8 days for about 20 years from 1989 to 2007 [78].

In this study, the leaf unfolding date of the Mongolian oak was the earliest in the urban center and slowed down as it approached the urban outskirts (Figure 4). These results were confirmed to be due to the temperature difference caused by the difference in the urbanization degree of each study site (Figure 5). These results showed similar trends to the differences in the occurrence frequency and length of the abnormal shoot in the Korean red pine and the cherry blossom date among sites with different urbanization degrees in Seoul (Table 1).

The cherry blossom dates differed by one to two weeks between urban centers, where greenery spaces were largely scarce, along with the urban outskirts in Seoul (Figure 4). According to a study by Song and Lee [79], the cherry blossom date in downtown Seoul coincided with the cherry blossom date in Gumi, which is located about 200 km south of Seoul. This result could be interpreted in the way that the climate characteristics of downtown Seoul are becoming similar to those of the southern part of the Korean Peninsula due to the urban heat island effect. It was found that the air temperature of downtown Seoul and the outskirts of the city temporarily showed a difference of about 10 °C [80], and an annual mean of 5 °C [81].

In the past, the abnormal shoot growth of the Korean red pine was rarely observed in seedlings cultivated in nurseries. However, the frequency of the abnormal shoot growth of the Korean red pine has increased recently, and it is easily observed throughout South Korea. Abnormal shoot growth may be caused by a variety of factors, but most of them have been known to be associated with late summer rain [76] or warm weather [82]. The abnormal shoot growth of the Korean red pine showed a higher frequency and longer length in urban centers with relatively higher temperatures compared to the urban outskirts (Figure 4). Looking at these results, it is judged that the temperature increases due to urbanization increased the frequency of abnormal shoot occurrence and promoted length growth in Korean red pine.

The early flowering of plants increases the probability of suffering frost damage, affecting the pollen formation and reproduction of plants [78]. Changes in flowering period can also have a very negative impact on the pollination process [83]. Differences in plant phenology between urban and natural areas can lead to reproductive isolation, especially in plants with short flowering periods [56] and those that block or limit gene flow between both areas and accelerate species differentiation [84].

Differences in plant phenology depending on the degree of urbanization identified through this study can be an important basis for proving the impact of urbanization on climate change and assessing the potential impact of urbanization-induced climate change on plant life history in the future. Furthermore, the results of this study are expected to serve as important information in developing climate change adaptation strategies.

4.2. Effects of Urbanization on Climate Change

Although attention is focused on greenhouse gas emissions as a factor affecting climate change, changes in land use due to urbanization also have a significant impact [85]. A study by Fujibe [86] shows that the urban heat island effects in some regions had a greater impact on climate change than greenhouse gases. Urbanization can change ecosystem processes such as the carbon cycle by increasing the mean daily CO_2 concentration in the atmosphere of urban areas, and land use changes and increased impermeable surfaces due to urbanization can increase local temperatures [87–89]. Urbanization increased the mean daily (24 h) atmospheric CO_2 concentration compared with rural areas. The daily temperature increased by 0.6–0.7 °C, 1.0–1.1 °C, and 1.9 °C in semirural, suburban, and urban sites, respectively [90]. In other words, the degree of temperature increase responded to the intensity of land use.

In urban areas, the population is concentrated, and the heat island phenomenon occurs frequently due to the resulting increase in land use intensity. On the other hand, urban sprawl can lead to local climate change by cutting down more forests, destroying habitats, and causing greenhouse gas and carbon emissions [9,12,13,61]. Cities are usually exposed to severer climate change due to local effects such as greenhouse gas-induced radiative forcing and urban heat island effects, and warming and extreme high temperatures caused by urbanization and increased energy consumption have been shown to be as significant as the effects of doubled CO_2 levels in some areas [28]. In Korea, from 1971 to 2000, the daily minimum, maximum, and mean temperatures all rose due to the rapid increase in the urbanization rate and population [91]. In particular, in the case of Seoul, where the population density is high and residential and commercial facilities are concentrated, the number of tropical days with a maximum temperature above 30°C has been on the rise since 1970 [92].

Cities are often referred to as urban heat islands, with the urban center having the highest temperatures. This is primarily due to the low amount of vegetation in urban center compared to the suburbs and beyond (Figure 2). Cities also use large amounts of energy, and emit this energy as waste heat, further exacerbating the urban heat island effect. On the other hand, forests and other vegetation types use large amounts of solar energy and evaporate water by means of transpiration to cool leaf surfaces. Evaporative water used through transpiration also contributes to reducing air temperatures in urban areas. Forests and other vegetation can also contribute indirectly to temperature reduction by reducing urban energy consumption through intercepting and using solar energy and by reducing building energy demand through shading and reducing wind speed. Therefore, low vegetation coverage in urban center results in larger temperature gradients between the urban center and urban fringe or beyond [93–95]. Indeed, Seoul's heat island effect is very large [96,97], as the temperature difference between the urban center and boundary was about 5 °C (Figure 4). The urban heat island is closely linked to the land use pattern (Figure 3).

Urbanization is progressing at an unprecedentedly rapid rate, and the resulting climate change is showing the same trend [98,99]. This rapid and uncontrollable acceleration of urbanization has led to environmental degradation, causing pollution as well as unpredictable climate patterns [99–102]. These environmental changes in cities do not only influence the city itself. In particular, climate change caused due to urbanization is expanding on a global scale [5,8,98]. The loss of vegetation due to urbanization not only causes a decrease in biodiversity but also affects the cycle of water, nitrogen, and other factors, as well as the reduction in biodiversity [4,5,103]. The loss of or reduction in vegetation can also increase CO_2 emissions, further deepening microclimate changes in the region, which in turn can accelerate climate change around the world [5].

4.3. Ecosystem Management for Climate Change Adaptation

It is widely recognized that land use is affecting the global climate [104]. Land use and land cover changes (LULCCs) and land management changes (LMCs) modify the physical–chemical and biological processes by altering land surface, resulting in climate change. Depending on socioeconomic drivers and regulatory policies at various levels (local, regional, national, or transnational), human activities interfere with land, resulting in different levels of land use, such as nature, semi-nature, agriculture, urban, and semi-urban areas. In particular, densely populated urban areas can lead to significant environmental impacts, including climate change, due to intensive land use. A further review of the relationship between the two is needed to reveal the impact of land use on climate change, and it is absolutely necessary to prepare a correct climate change adaptation strategy in the future [105].

Environmental degradation from land transformation can cause negative feedback pathways in the ecosystem. For example, massive deforestation in an area can disrupt the carbon cycle of the area. It is widely known that excessive land use, along with the excessive use of fossil fuels, increases the concentration of carbon dioxide in the atmosphere and consequently leads to climate change today. According to the results of a study at the national level in Korea, the intensity of land use by local governments was significantly correlated with the increase in local temperature and carbon budget [106]. As shown in the results of this study (Figures 4–6), even at the local level, the increase in temperature tends to be proportional to the land use intensity, and the phenology of plants affected by climate also responded to such changes.

It has been confirmed from various examples that it is closely related to climate change and land use intensity. Climate change can alter weather patterns and affect the disturbance regime. In consequence, climate change is expected to increase disturbance, resulting in ecosystem disturbance [11,107]. This intense disturbance would cause even more disturbance in the ecosystem, worsening the carbon budget and aggravating climate change. It would cause negative feedback effects in so-called climate change. In this context, measures are required to curb climate change through the restoration of damaged ecosystems [105].

Natural areas with a high degree of ecological integrity can better buffer the impacts of climate change [108–110]. Therefore, restoring degraded nature as well as conserving existing nature can contribute either to the mitigation or adaptation of climate change [105,111]. Ecological restoration, particularly in terms of the reforestation and restoration of degraded land, is often recognized as one of the important responses to climate change because such activities help influence the planet's carbon budget in a positive way [105,106,112,113].

Many actions can be taken to mitigate climate change. We can adopt the conservation and restoration of natural ecosystems as a strategy that enables humankind to adapt to climate change impacts [114–116]. Natural resources can also help us to adapt to the impacts of climate change that we are already experiencing [114,117,118]. Sound natural systems help us adapt to climate change by absorbing and storing carbon. In fact, it is estimated that approximately 20% of greenhouse gas emissions result from deforestation and forest degradation. Therefore, conserving forests can store substantial amounts of carbon [119–123]. Conserving and sustainably managing our terrestrial and aquatic ecosystems can lead to obtaining the necessary rapid results in order to mitigate climate warming. Even at the small scale of the site level, we can use vegetation to reduce energy use and create thermally pleasant environments by creating shade from the hot summer sun and encouraging evapotranspirational cooling [124–127]. Jung et al. [128] found that the improvement in land use patterns by the creation of an urban park and a park fountain impacted both the occurrence and the growth of abnormal shoots in the Korean red pine. They interpreted that their results are due to the cooling effects of evapotranspiration from vegetated landscapes and evaporation from a water body.

As we understand the ecological functions that create surface climates and the specific landscape features that alter these functions, we can make the climate favorable for us by taking advantage of natural landscape processes. The field of land use planning that deals with these topics is contributing to climate change adaptation by creating a design in harmony with the environment [125,126,129–133].

5. Conclusions

The urban heat island phenomenon not only causes an increase in surface temperature but also increases energy consumption and promotes climate change. Urbanization not only causes local climate change on a daily, seasonal, and annual scale but also increases extreme weather events. Moreover, warming and extreme weather events due to urbanization and increased energy consumption are simulated to be as large as the doubled CO_2 effects in some regions. In those respects, microclimate change due to urbanization could be regarded as climate change at a local level.

Urbanization also changes ecological processes such as the carbon cycle, increasing the CO_2 concentration in the atmosphere (CO_2 dome formation). In this respect, the urban area is an important research area where the potential effect of future climate change can also be evaluated. Plant phenology is usually used as an indicator to monitor the response of climate change to ecosystems because they respond sensitively to meteorological factors such as temperature and precipitation. The phenological response of the plants we studied well reflects the local microclimate changes caused by urbanization.

The response shown by the phenology of plants as an indicator of climate change is expected to be an important reference in preparing urban plans to buffer climate change and achieve climate change adaptation in the future. In fact, climate change is not only a global issue but also a local issue. The importance of action at the local level is emerging as a means to secure sustainability at the global level. As the urban nature of consumption and production practices is becoming stronger these days, this call for action is often interpreted as the need to achieve the sustainable development of cities. To achieve urban sustainability, environmental performance has to be improved to not only improve environmental quality within these boundaries but also to reduce the transfer of environmental costs to other people, other ecosystems, or the future. This fact suggests that addressing climate change should be a key component of urban sustainable development.

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