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Article

Changes of the Flowering Time of Trees in Spring by Climate Change in Seoul, South Korea

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Abstract: Flowering onset has attracted much attention in ecological research as an important indicator of climate change. Generally, warmer temperatures advance flowering onset. The effect of climate warming on flowering onset is more pronounced in spring because the difference between atmospheric and water temperatures creates more rapid convection than in other seasons. We analyzed the correlation between 73 species of spring woody plants in Hongneung Arboretum in Seoul, South Korea and the spring minimum temperature and average precipitation over the past 50 years (1968–2018). The spring minimum temperature and average precipitation have increased over the past 50 years, resulting in the advance of the first flowing date (FFD) in all 73 species by 8.5 days on average. A comparison of FFD changes over time by dividing the survey period into three time periods confirmed the advance of the FFD in 50 species (68% of investigated species) by 11.1 days on average in both Period 2 (1999–2008) and Period 3 (2009–2018) relative to Period 1 (1968–1975). Additionally, a delay of the FFD by 3.2 days on average was observed in 8 species. The FFD of *Lonicera chrysantha* (Caprifoliaceae) advanced by over 40 days and was highly correlated with the increased spring minimum temperature. Analysis of the sensitivity of plant responses to climate change revealed that a temperature rise of 1°C was associated with an FFD advance of 1.2 days in all species. The species that was most sensitive to temperature change was *Spiraea pubescens* for. *leiocarpa* (Rosaceae), whose FFD advanced by 4.7 days per 1°C temperature rise. Each increase in precipitation by 1 mm was found to result in a 0.1-day advance of the FFD of all species. *Prunus tomentosa* (Rosaceae) was the most sensitive species, that advanced by 2.6 days for each 1 mm increase in precipitation. Thus, for all species, the FFD was more sensitive to the change in temperature than in precipitation. Assuming that the current greenhouse gas (GHGs) emission levels or atmospheric CO_2 concentration is maintained, Seoul's spring minimum temperature is projected to rise by 2.7°C over the next 50 years. Accordingly, considering only the global temperature change, the mean FFD of the study's 73 species is projected to advance by an additional 3.4 days.

Keywords: Phenology; first flowering date; climate change

1 Introduction

The phenomenon of global warming, characterized by an increase in mean global temperatures due to the excessive GHGs emissions such as CO_2, CFCs, and CH_4 as a result of rapid industrial development in modern society, is expected to continue [1–3]. Over the past 100 years (1900s–2000s), global warming has caused the Earth's average global temperature to rise by 0.85°C and precipitation to increase by 100 mm [4]. In South Korea, the annual average temperature rose by 1.5°C, and the annual average precipitation rose by 124 mm, steadily increasing over the last 100 years [4]. This global warming-driven climate change is one of the most serious threats to global biodiversity in general and plant phenology in particular [5–7]. Plant phenology is a field of research investigating the timing of plant life-cycle events, such as the dates of sprouting, first flowering, full bloom, leaf color change, and leaf fall, and their correlations with climatic factors such as temperature and precipitation [8]. In particular, flowering onset has attracted much attention from ecological research as an important indicator of climate change [9,10]. If plants bloom earlier in the spring than they have in the past, they may suffer frost damage. Moreover, immature pollinators cannot provide adequate pollination, making it difficult for the plants to yield fruit and eventually causing reproductive failure [11]. Thus, it is reported that global warming could eventually disrupt ecosystem balances by affecting plant community structure and gene flow between populations [11,12].

Warmer temperatures are generally known to advance flowering onset [13–15]. In particular, the effect of climate warming in spring on flowering onset is more pronounced because the difference between ambient and water temperatures brings about more rapid convection than in other seasons [16,17]. Accordingly, extensive research on shifts in flowering phenology have been conducted with spring plants around the world [6,11–13,15,18–22]. Globally, research has reported shifts in flowering phenology, with advances in the first flowering date (FFD) occurring in many regions, including the British Isles, Eastern Europe, the US, and Asia (Tab. 1).

Table 1: A study on the trend of changes in flowering time around the world

Region	Species number	Survey period	Advanced FFD
The British Isles	6	58 years (1891–1948)	−17
Hungary	*Robinia pseudoacacia*	144 years (1851–1994)	−3–8
Alberta	*Populus tremuloides*	98 years (1900–1997)	−26
Washington D.C.	100	30 years (1970–1999)	−2.4
Massachusetts	32	29 years (1852–2012)	−20
Wisconsin	23	47 years (1935–2012)	−24
Beijing	4	55 years (1950–2004)	−8.3–16

A number of studies around the world have also confirmed plant sensitivity to climate warming in terms of FFD advance per 1°C temperature rise: 4 days in central England [12]; 2–10 days in the British Isles [6]; 9.7 days in the southern part of the Island of Guernsey [7]; 12 days in Washington, DC, USA [23]; 3.2 days in Massachusetts, northwestern U.S.; 4.1 days in Wisconsin, north-central U.S. [20]; 2.7 days in Beijing, China [15]. Studies conducted thus far in South Korea have investigated shifts in flowering phenology only on a limited number of woody plant species (~10) and are thus insufficient to determine the changing flowering phenology of many plant species relative to non-Korean studies and to grasp the overall tendency of shift in flowering phenology caused by climate change.

To bridge this research gap, This study aims to: (1) Trace time-dependent changes (three time periods covering 1968–2018) in flowering onset of 73 species of woody plants flowering in spring (March-April) in

Hongneung Arboretum located in Seoul (South Korea), which has the longest FFD record-keeping history among all Korean arboretums. (2) Estimate the correlations between climatic factors, including the spring minimum temperature and mean precipitation, and the FFD of plant species. (3) Determine plant sensitivity to climate change by determining the changes to FFD in response to a 1°C temperature rise and a 1 mm precipitation increase in South Korea. (4) Predict flowering onset on the assumption that the current global warming trends are maintained over the coming 50 years (2021–2070).

2 Materials & Methods

2.1 Phenological Climate Data

In comparison with herbaceous plants, woody plants are more sensitive to global warming-driven temperature rise [12,13,18,19]. For the purpose of this study, we selected 73 spring woody plants (flowering onset: March-April) growing in Hongneung Arboretum (37°35'37.6N, 127°02'38.5E, Altitude: 34 m). The survey period covered 1968–2018, during which the records of FFD were kept, and a total of 1,337 data points for 73 species were analyzed. The data for 1969, 1971, and 1976–1998 were excluded from the analysis owing to the lack of records of FFD during those years in Hongneung Arboretum. In determining the FFD, the measurement point is generally the beginning of floral budding, but because of the ambiguity regarding its definition, most researchers set their own criteria. For example, Fitter et al. defined FFD as the time when an anther is visible [12]. Beaubien et al. selected the date on which any of the following is easily discernable: the date on which the flower bloom is first observed; the date on which up to 25% of flowers have sepals and/or petals open and stamens and/or pistils visible; the day on which 10% of flower buds are open [21]. Abu-Asab et al. defined FFD as the stage at which a mono- or diclinous flower is receptive to pollen [23]. We measured the FFD as the point in time when floral buds of at least 30% of the total number of flowering trees were open, with more than 90% of their petals open and the green scales surrounding buds had completely peeled off, considering that some floral buds have unusually fast flowering times. In cases of species where inflorescences and flowers are distinguishable, such as *Cornus officinalis* and *Spiraea prunifolia* for. *simpliciflora*, the point in time when at least 60% of the flowers per inflorescence were open in at least 30% of the total number of flowering trees. The FFD of 73 species (73 accessions) was monitored daily from March to April every year during the survey period. All individual trees produced flowers every year, so the same individual trees were monitored.

Given that the correlation between climatic factors and FFD can be determined more accurately when the climate data measured in the same region are stored in one place [14], we used the data from the Korea Meteorological Administration (KMA). We analyzed the impact of climate change on FFD by analyzing climate data from the past 50 years (1968–2018), including spring minimum temperature and average precipitation in Seoul. The spring minimum temperature was used, based on the report that the period of plant growth is highly correlated with the minimum temperature [24–26].

2.2 Statistical Analysis

Using the R-project [27] program, we performed multiple regressions to determine the relationship between one dependent variable (FFD) and two independent variables (annual minimum temperature and annual precipitation). The FFD of each species in relation to the two independent variables was analyzed separately. Then p-values of the correlation coefficients were calculated to test the statistical significance of the correlation between each climate factor of interest and FFD. When the p-value is less than 0.05, the correlation between FFD and the given climate factor was considered to be statistically significant. Then the coefficient estimate of the statistically significant variable was used to test the effectiveness of the model. A coefficient estimate value represents the change in FFD when the value of the variable of interest increases by one unit, and the values of the other explanatory variables are fixed. Type III

ANOVA analysis [27] was additionally conducted on the species concerned to identify the factors affecting FFD. Type III ANOVA is a statistical method for analyzing whether the climate factors have an important interactive effect on FFD. The FFD (month/day) of each tree was converted to Julian date, which is commonly used in most programming for statistical analysis.

2.3 *Analysis Stages*

(1) Although the survey period of this study was 1968–2018, the actual survey period was 1968–1975 and 1999–2018 because 1976–1998 was excluded from the analysis. Therefore, we divided the survey period of the recent 20 years (1999–2018) into two 10-year groups, in addition to the earlier period (1968–1975), thus dividing the entire study period into three stages. The comparisons made were the difference between Period 1 (average between 1968 and 1975) and Period 2 (average between 1999 and 2008), and the difference between Periods 1 and 3 (average between 2009 and 2018). We then compared the average FFD of the last 20 years (1999–2018), combining Periods 2 and 3, with respect to Period 1, the reference interval.

(2) We determined the correlations between FFD of individual species and spring minimum temperature and average precipitation. Then, to determine the plants' sensitivity to climate change, multiple regression analysis was used to simulate the changes to FFD per 1°C rise in temperature and 1 mm increase in precipitation.

(3) Using a multiple regression model for each of the 73 species, we computed the 95% confidence interval (lower and upper limits) and standard error for each explanatory variable. The model used for estimating confidence intervals was a multiple regression model individually fit to the FFD of each of the 73 species. As explanatory variables, we used FFD (1968–2018), average minimum temperature and average precipitation.

Three species (*Eucommia ulmoides, Juglans mandshurica*, and *Lindera erythrocarpa*) with less than 10 FFD data points each were excluded from the analysis because the model fit was not sustained in computations (1) and (3).

3 Results

The inter-period comparison between the thee time-interval periods of the survey period confirmed the advance of FFD in all 73 species by 8.5 days on average in Period 2 (1999–2008) and Period 3 (2009–2018) relative to Period 1 (1968–1975), the reference period. That is, an average advance of FFD of 8.5 days occurred over the past 50 years (1968–2018). Fig. 1 shows changes in FFD of all 70 species analyzed, including 30 species that showed statistically significant correlation between FFD and climate factors.

An inter-period comparison of changes in FFD revealed an advance in FFD by 11.1 days on average occurred in 50 species over the past 50 years in both Periods 2 and 3 relative to Period 1. Eight species had a delay in FFD by 3.2 days on average over the past 50 years in both Periods 2 and 3 relative to Period 1. Twelve species advanced in Period 2 and delayed in Period 3 relative to Period 1. When the FFD in Periods 2 and 3 are computed together, these 12 species showed 3.8-day advance in FFD over the past 50 years. Fig. 2 illustrates the changes in FFD of the 50 species that advanced and the 8 species that delayed (out of the 73 species studied) over the past 50 years in response to the rise in spring minimum temperature.

Of the 73 total species studied, 30 species showed statistically significant correlations between FFD and climate factors (Fig. 1). The species with the largest advance in FFD was *Lonicera chrysantha* in the family Caprifoliaceae: 47 and 41 days in Periods 2 and 3, respectively, relative to Period 1. Fig. 3 shows the changes

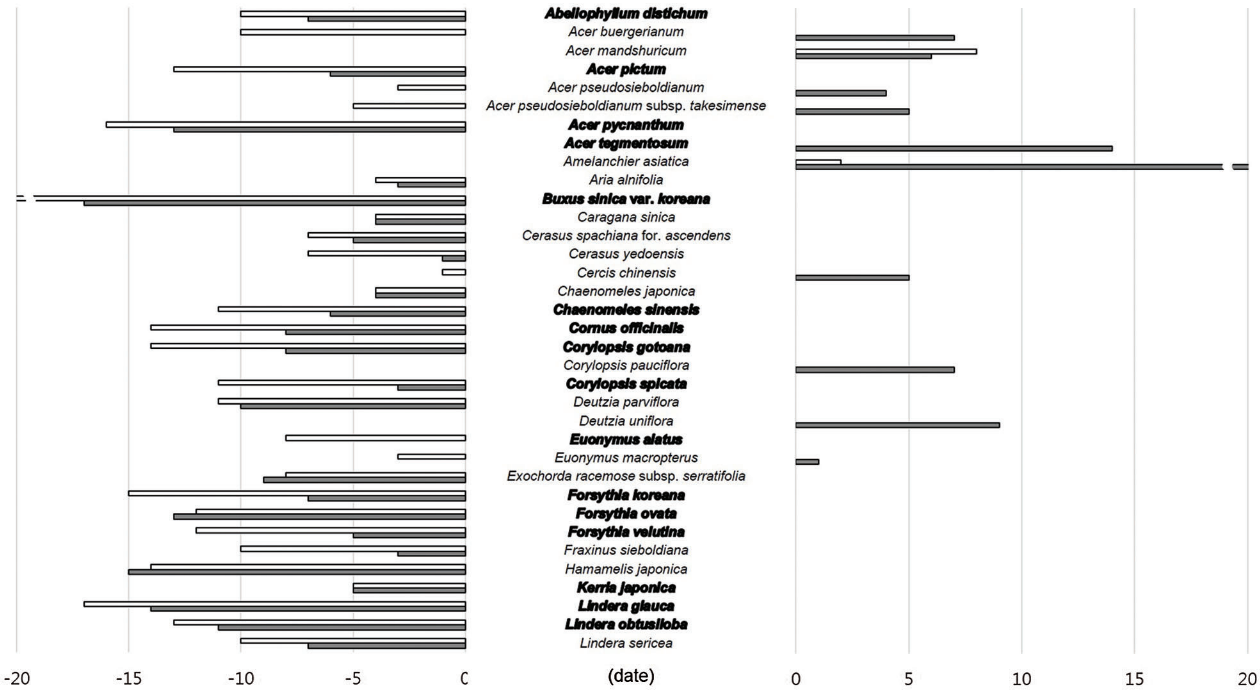

Figure 1.1: As of Period 1 (1968–1975), the FFD changes in Period 2 (1999–2008) were white and the FFD changes in Period 3 (2009–2018) were grey. Also, species that showed statistically correlated with FFD and spring climate factors are indicated in bold. The minus value means advanced FFD and the plus value means delayed FFD

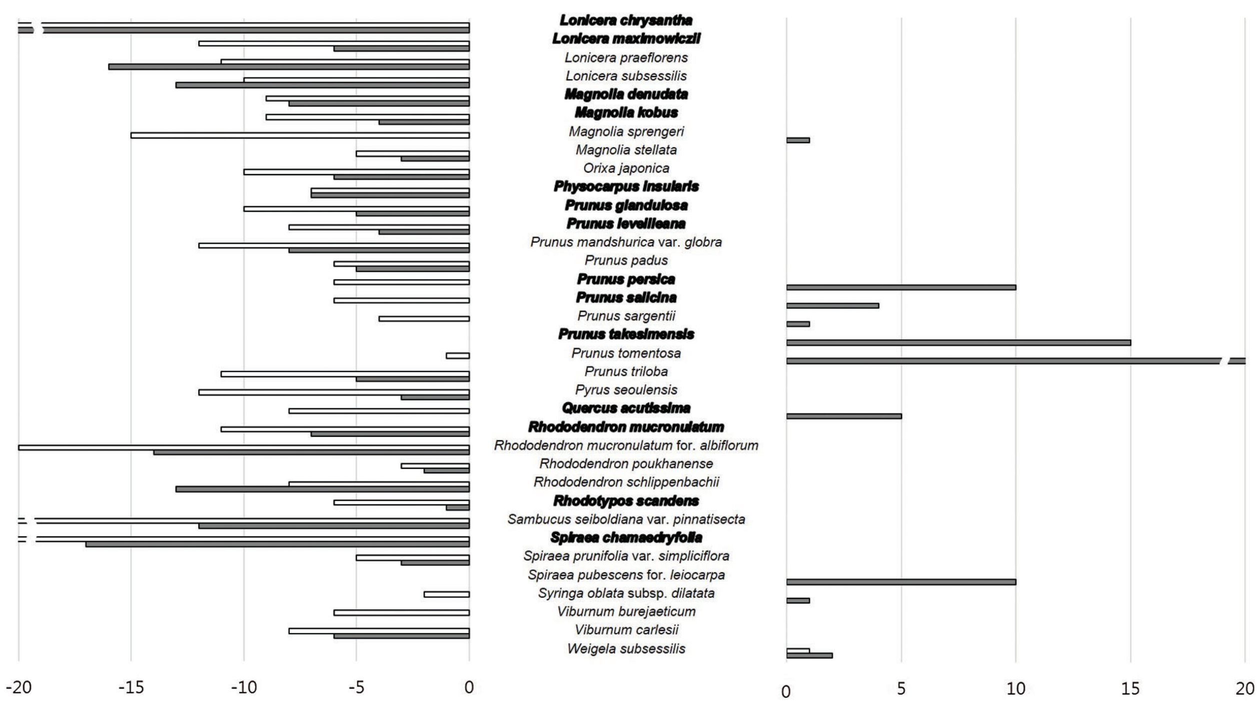

Figure 1.2: Continued

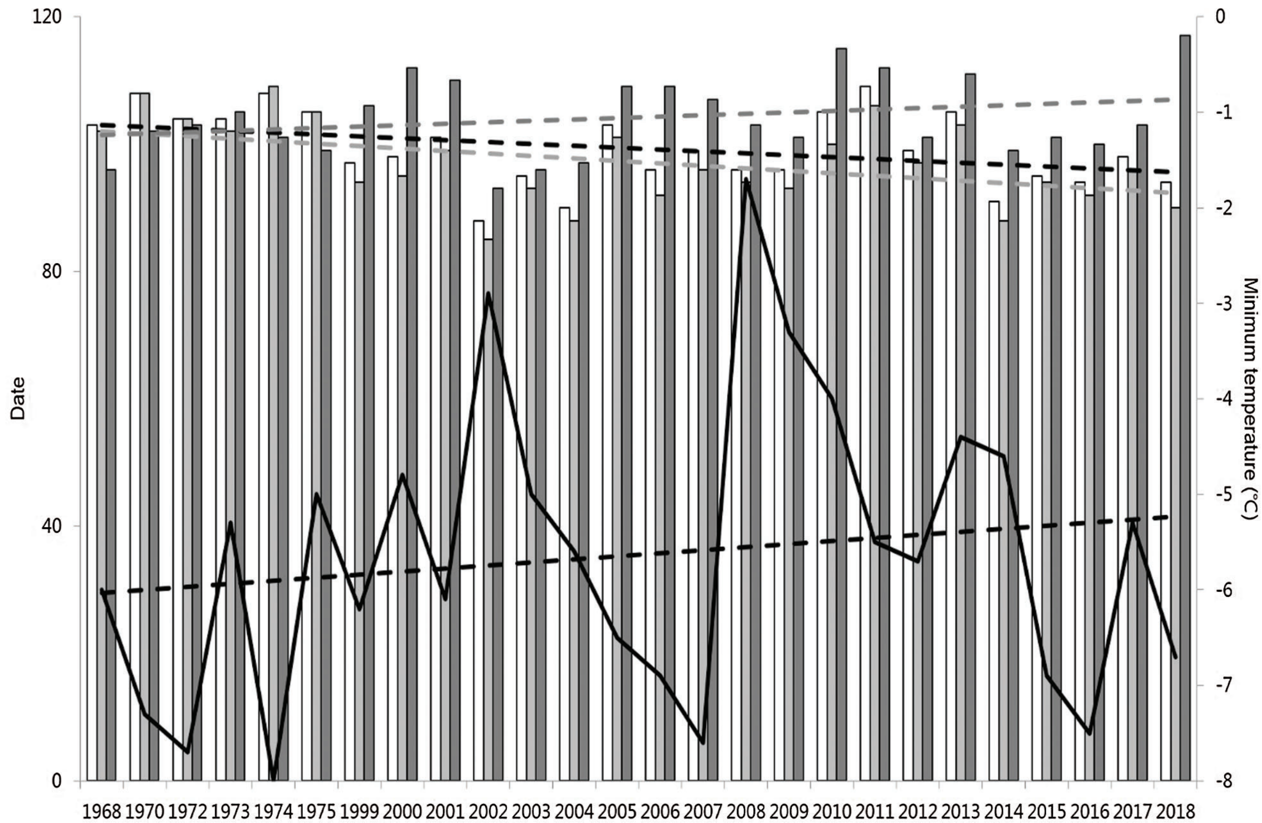

Figure 2: For the 50 years, FFD of the 50 species that advanced and 8 species that delayed (out of the 73 species studied). The FFD changes in 73 species were white, the FFD changes in 50 species were light grey, the FFD changes in 8 species were dark grey and the spring minimum temperature changes were bold black (Trend-line formula: 73 species ($y = -0.2944x + 103.24$), 50 species ($y = -0.3836x + 102.33$), 8 species ($y = 0.2243x + 101.13$), spring minimum temperature ($y = 0.0322x - 6.0689$)

in FFD of the 30 species were significantly correlated with the rise in spring minimum temperature over the past 50 years, and those of *Lonicera chrysantha*.

Tab. 2 presents the changes in FFD per 1°C rise in temperature and 1 mm increase in precipitation in all 73 species studied.

Each 1°C rise in temperature was found to entail a 1.2-day advance in FFD on average. The species most sensitive to temperature rise was *Spiraea pubescens* for. *leiocarpa* in the family Rosaceae, with a 4.7-day advance of FFD per 1°C. Each 1 mm increase in precipitation was found to entail a 0.1-day advance in FFD on average. The species most sensitive to an increase in precipitation was *Prunus tomentosa* in the family Rosaceae, with 2.6-day advance in FFD on average. Thus, the FFD of all 73 species was observed to be more sensitive to changes in temperature than in precipitation.

For each of the 70 species analyzed, the 95% confidence interval (CI, lower and upper limits), standard error (SE) and *p*-value were computed and presented in Tab. 3. Three species *(Eucommia ulmoides*, *Juglans mandshurica* and *Lindera erythrocarpa*) with less than 10 FFD data points each were excluded from the analysis because the model fit was not sustained.

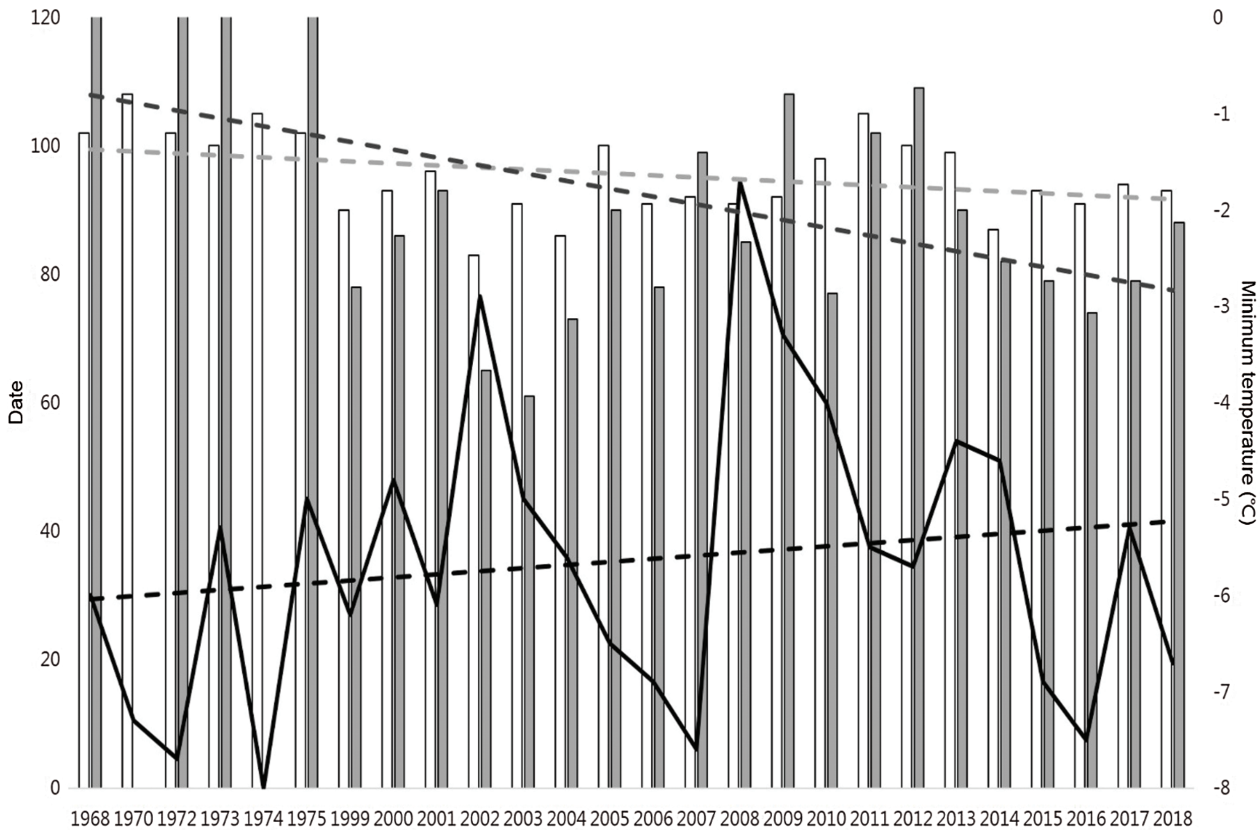

Figure 3: For the 50 years, the FFD changes in 30 species were white, *Lonicera chrysantha* changes were grey and the spring minimum temperature changes were bold black (Trend-line formula: 30 species ($y = -0.3111x + 99.738$), *Lonicera chrysantha* ($y = -1.2178x + 109.16$), spring minimum temperature ($y = 0.0322x - 6.0689$)

Table 2: Changes in first flowering date of 73 species caused by 1°C warming in temperature and 1 mm increase in precipitation (The author and naming year of scientific names have been deleted)

Family name	Scientific name	Temperature rise 1°C	Precipitation rise 1 mm
Acerceae	*Acer buergerianum*	−2.9	
	Acer mandshuricum	−1.5	−0.02
	Acer pictum	−1.1	−0.01
	Acer pseudosieboldianum	−1.4	−0.02
	Acer pseudosieboldianum subsp. *takesimense*	−1.5	−0.05
	Acer pycnanthum	−0.6	−0.01
	Acer tegmentosum	−3.5	−0.01
Adoxaceae	*Sambucus sieboldiana* var. *pinnatisecta*	−0.2	−0.03
Buxaceae	*Buxus sinica* var. *koreana*	−0.9	−0.03

(Continued)

Table 2 (continued).

Family name	Scientific name	Temperature rise 1°C	Precipitation rise 1 mm
Caprifoliaceae	*Lonicera chrysantha*	−0.09	−0.006
	Lonicera maximowiczii	−1.0	−0.09
	Lonicera praeflorens	−0.6	
	Lonicera subsessilis	−1.3	
	Weigela subsessilis	−1.4	−0.04
Celastraceae	*Euonymus alatus*	−1.0	−0.01
	Euonymus macropterus	−1.4	−0.009
Cornaceae	*Cornus officinalis*	−0.6	−0.002
Ericaceae	*Rhododendron mucronulatum*	−1.1	−0.02
	Rhododendron mucronulatum for. *albiflorum*	−0.6	−0.01
	Rhododendron schlippenbachii	−0.7	
	Rhododendron poukhanense	−0.6	
Eucommiaceae	*Eucommia ulmoides*	−1.7	−0.08
Fabaceae	*Caragana sinica*	−0.7	
	Cercis chinensis	−1.0	
Fagaceae	*Quercus acutissima*	−2.7	−0.06
Hamamelidaceae	*Corylopsis gotoana*	−2.1	−0.01
	Corylopsis pauciflora	−1.0	−1.3
	Corylopsis spicata	−1.1	
	Hamamelis japonica	−2.1	
Hydrangeaceae	*Deutzia parviflora*	−1.0	
	Deutzia uniflora	−1.5	−0.05
Juglandaceae	*Juglans mandshurica*		−0.2
Lauraceae	*Lindera erythrocarpa*		
	Lindera glauca	−1.3	
	Lindera obtusiloba	−0.6	−0.007
	Lindera sericea	−1.1	−0.01
Magnoliaceae	*Magnolia denudata*		−0.003
	Magnolia kobus	−0.06	−0.03
	Magnolia sprengeri	−1.5	−0.06
	Magnolia stellata	−1.2	
Oleaceae	*Abeliophyllum distichum*	−1.1	−0.01
	Forsythia koreana	−1.4	

Table 2 (continued).

Family name	Scientific name	Temperature rise 1°C	Precipitation rise 1 mm
	Forsythia ovata	−0.5	
	Forsythia velutina	−1.4	−0.02
	Fraxinus sieboldiana	−1.2	−0.05
	Syringa oblata subsp. *dilatata*	−1.4	−0.01
Rosaceae	*Amelanchier asiatica*	−1.2	
	Aria alnifolia	−0.8	
	Cerasus spachiana for. *ascendens*	−0.6	
	Cerasus yedoensis	−0.9	
	Chaenomeles japonica	−0.9	−0.001
	Chaenomeles sinensis		
	Exochorda racemosa subsp. *serratifolia*		−0.0001
	Kerria japonica	−2.0	−0.02
	Physocarpus insularis	−0.9	
	Prunus glandulosa		
	Prunus leveilleana	−0.8	−0.009
	Prunus mandshurica var. *glabra*	−0.4	−0.02
	Prunus padus	−0.3	
	Prunus persica	−2.6	−0.03
	Prunus salicina	−1.6	−0.02
	Prunus sargentii	−1.5	
	Prunus takesimensis	−1.4	−0.1
	Prunus tomentosa		−2.6
	Prunus triloba	−0.8	−0.007
	Pyrus seoulensis	−1.1	
	Rhodotypos scandens	−1.7	
	Spiraea chamaedryfolia	−0.7	
	Spiraea prunifolia var. *simpliciflora*	−1.3	
	Spiraea pubescens for. *leiocarpa*	−4.7	−0.03
Rutaceae	*Orixa japonica*	−1.5	
Viburnaceae	*Viburnum burejaeticum*	−1.3	
	Viburnum carlesii	−0.7	

Table 3: CI (lower limit and upper limit), SE and *p*-value of 70 species (The author and naming year of scientific names have been deleted). The dependent variable is FFD. The CIs are the upper and lower limits on the average flowering date of each 73 species (Julian date). The *p*-values of the correlation coefficients were calculated to test the statistical significance of the correlation between each climate factor of interest and FFD under the CI (95%) specified. When the *p*-value is less than 0.05, the correlation between FFD and the given climate factor was considered to be statistically significant

Family name	Scientific name	CI (Lower)	CI (Upper)	SE	*p*-value
Acerceae	*Acer buergerianum*	84.557	131.327	9.097	0.30
	Acer mandshuricum	81.815	138.775	8.949	0.66
	Acer pictum	107.59	129.988	5.088	0.03
	Acer pseudosieboldianum	95.636	123.905	6.59	0.62
	Acer pseudosieboldianum subsp. *takesimense*	93.103	127.366	7.245	0.38
	Acer pycnanthum	89.836	109.246	4.409	0.08
	Acer tegmentosum	93.144	124.325	6.593	0.02
Adoxaceae	*Sambucus sieboldiana* var. *pinnatisecta*	95.593	144.973	11.218	0.44
Buxaceae	*Buxus sinica* var. *koreana*	90.444	110.794	4.71	0.01
Caprifoliaceae	*Lonicera chrysantha*	111.869	144.751	7.826	0.0005
	Lonicera maximowiczii	77.052	108.061	7.177	0.05
	Lonicera praeflorens	77.474	103.249	5.784	0.36
	Lonicera subsessilis	78.989	112.789	7.929	0.26
	Weigela subsessilis	104.69	122.083	4.08	0.41
Celastraceae	*Euonymus alatus*	117.104	130.339	3.086	0.04
	Euonymus macropterus	106.446	130.515	5.57	0.63
Cornaceae	*Cornus officinalis*	80.377	97.283	4.039	0.05
Ericaceae	*Rhododendron mucronulatum*	87.326	102.049	3.517	0.06
	Rhododendron mucronulatum for. *albiflorum*	84.906	124.836	9.163	0.26
	Rhododendron schlippenbachii	101.138	120.26	4.344	0.51
	Rhododendron poukhanense	104.277	118.584	3.391	0.42
Fabaceae	*Caragana sinica*	111.044	124.614	3.229	0.62
	Cercis chinensis	100.364	120.67	4.812	0.81
Fagaceae	*Quercus acutissima*	101.857	120.667	2.955	0.05
Hamamelidaceae	*Corylopsis gotoana*	85.196	106.926	5.066	0.12
	Corylopsis pauciflora	77.494	96.69	4.503	0.72
	Corylopsis spicata	87.416	101.5	3.352	0.03
	Hamamelis japonica	50.525	85.839	8.329	0.31
Hydrangeaceae	*Deutzia parviflora*	103.979	132.583	6.668	0.34
	Deutzia uniflora	90.398	115.55	5.772	0.49

Table 3 (continued).

Family name	Scientific name	CI (Lower)	CI (Upper)	SE	*p*-value
Lauraceae	*Lindera glauca*	83.055	105.004	5.117	0.06
	Lindera obtusiloba	77.831	92.503	3.396	0.04
	Lindera sericea	88.459	106.018	3.94	0.35
Magnoliaceae	*Magnolia denudata*	94.153	108.409	3.378	0.24
	Magnolia kobus	95.017	109.114	3.235	0.05
	Magnolia sprengeri	98.374	130.38	6.768	0.16
	Magnolia stellata	92.081	110.322	4.144	0.51
Oleaceae	*Abeliophyllum distichum*	86.592	100.545	3.307	0.07
	Forsythia koreana	84.501	101.366	4.029	0.02
	Forsythia ovata	87.867	99.881	2.847	0.02
	Forsythia velutina	85.86	103.101	3.957	0.02
	Fraxinus sieboldiana	75.159	166.973	14.425	0.95
	Syringa oblata subsp. *dilatata*	94.874	111.581	4.005	0.78
Rosaceae	*Amelanchier asiatica*	59.13	162.913	4.084	0.28
	Aria alnifolia	107.611	134.541	5.952	0.83
	Cerasus spachiana for. *ascendens*	92.893	113.011	4.447	0.66
	Cerasus yedoensis	91.438	112.316	4.615	0.29
	Chaenomeles japonica	103.433	115.5	2.883	0.45
	Chaenomeles sinensis	114.971	132.138	4.027	0.16
	Exochorda racemosa subsp. *serratifolia*	110.372	133.56	5.367	0.80
	Kerria japonica	101.024	113.503	2.957	0.05
	Physocarpus insularis	106.335	116.522	2.434	0.05
	Prunus glandulosa	103.899	117.355	3.189	0.10
	Prunus leveilleana	97.952	107.557	2.253	0.03
	Prunus mandshurica var. *glabra*	88.434	115.994	5.976	0.54
	Prunus padus	103.25	118.676	3.638	0.74
	Prunus persica	100.754	114.281	3.073	0.01
	Prunus salicina	100.26	110.171	2.294	0.003
	Prunus sargentii	93.731	115.1	4.854	0.45
	Prunus takesimensis	74.411	90.864	3.899	0.04
	Prunus tomentosa	93.499	110.648	3.998	0.89
	Prunus triloba	95.507	118.276	5.37	0.23
	Pyrus seoulensis	89.301	125.154	8.145	0.44
	Rhodotypos scandens	109.293	120.943	2.761	0.002

(Continued)

Table 3 (continued).

Family name	Scientific name	CI (Lower)	CI (Upper)	SE	*p*-value
	Spiraea chamaedryfolia	115.863	137.324	5.003	0.02
	Spiraea prunifolia var. *simpliciflora*	101.969	115.372	3.176	0.14
	Spiraea pubescens for. *leiocarpa*	105.015	138.834	1.331	0.36
Rutaceae	*Orixa japonica*	102.423	119.4	3.857	0.15
Viburnaceae	*Viburnum burejaeticum*	93.362	124.155	6.806	0.73
	Viburnum carlesii	106.675	120.266	3.221	0.27

4 Discussion

Over the last 50 years, the spring minimum temperature and precipitation in Seoul has shown an increasing trend, which is positively related to the advancement of the FFD in 50 of the species studied (68%). This finding is consistent with that of previous research that the onset of flowering generally advances as the climate warms. In contrast, 8 of the species studied (11%) sustained delays in FFD. The factors that may have delayed their FFD are not clear. Fitter et al. reported that plants exposed to low temperatures may sustain delays in flowering [11], Freeman et al. determined that delayed flowering may occur following abnormally low temperatures, even in spring, due to climatic conditions such as the lack of sunshine due to frequent precipitation, frequent spring cold spells, and untimely heavy snow [28,29]. Most plants require a certain amount of winter chill for spring phenology and dormancy to accumulate nutrients in winter [30–33]. If winter is warmer than usual, warming is delayed; or dormancy is interrupted, and then spring phenology is also delayed [30–33]. Kiona et al. reported that during seasons with higher precipitation, and extreme high, or low temperatures, reproductive functioning of many plant species may be halted [34,35]. The eight species with delayed FFD were species that usually bloom in late spring, with records of flowering in late April/early May. From this observation it may be inferred that abnormally low temperatures during this period, when the average temperature is normally around 15°C, can cause delays in flowering. Little is known about how abnormally low temperatures in spring affect flowering phenology. Therefore, future research needs to take into account the correlations between FFD and low temperatures in winter, as well as abnormally low temperatures in spring.

This study investigated the impact of spring climate change on FFD of the plants in Hongneung Arboretum in Seoul. Changes in FFD varied, even in the same plant species, depending on the regional climatic characteristics. In general, inland areas have higher average temperatures than coastal areas, and therefore tend to show earlier flowering onset [36]. In addition to its inland location, Seoul, where Hongneung Arboretum is situated, has higher average spring temperatures than other regions due to its large urban population, various facilities, and the resultant release of artificial heat [37]. Since the greenhouse effect is aggravated by the heat island effect, the FFD of the plants growing in Hongneung Arboretum may have occurred much earlier than the same species growing in other regions [38].

The period for flowering onset of plants may vary depending on multiple factors such as topography, altitude, and CO_2 concentration [36,39–41]. Most importantly, however, it is directly affected by climate change [42]. Over the past 50 years (1968–2018), Seoul's spring minimum temperature has risen by 1.4°C on average. Unless adequate global efforts are undertaken to reduce GHG emissions, with the current levels of GHG emissions and atmospheric CO_2 concentrations (Representative Concentration Pathway (RCP) 8.5), the spring minimum temperature in Seoul for the next 50 years (2021–2070) is projected to further rise by 2.7°C, and the spring minimum temperature in Seoul in 2071 is estimated to be 11.2°C, that is 3.3°C higher than the current level (7.9°C as of 2019). Accordingly, based on the multiple regression analysis, taking into account only the change in temperature, the FFD of the 73 species growing in Hongneung Arboretum is projected to be further advanced by 3.4 days on average over the next 50 years. Therefore, a follow-up study investigating the correlation between FFD and climatic factors, by means of continuous monitoring of flowering by season and by region, will generate useful data for understanding the long-term trends of climate change.

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