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Comparative Study of the Phenology of Seven Native Deciduous Tree Species in Two Different Mesoclimatic Areas in the Carpathian Basin

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Abstract: The impact of global warming on plant phenology is the subject of a growing number of studies. However, most of these do not focus on woody species, and few examine the entire annual phenological cycle of woody species. In this paper, we explore the phenological pattern of seven woody species native to Europe under ex situ conditions for 3 years, in two urban areas with different mesoclimates. The average temperature differs by 1.81 °C between the two sites. The investigated plants were clonally identical for each species, and the exact same care protocol was kept at both sites. Despite the large variation in the phenological pattern between years, during the study, spring phenophases occurred earlier, while the examined autumn phenophases were delayed at the site observing a higher average temperature. The phenological sensitivity of flowering was significantly higher than that of leaf bud burst. The growing season was 14.8 days longer at the site with a higher average temperature. In most cases, a significant correlation was obtained between the examined phenophases and climatic factors at both sites. Among the autumn phenophases, the strongest correlation was found between the maximum temperature between July and October and the beginning of leaf coloring.

Keywords: climate change; temperate zone; ex situ; urban area; botanical garden; spring; autumn; senescence

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1. Introduction

Climate change raises global temperatures, thus influencing ecosystem processes [1]. On average, the world has already warmed 1.1 °C, affecting natural ecosystems in Europe [2]. The observed trend of warming at a global or local scale can have serious implications on living organisms. Warming will decrease suitable habitat space for current terrestrial ecosystems and irreversibly change their composition [2]. Plant phenology, the timing of seasonally recurring phenomena in plants [3], has proven to be a very sensitive indicator for climate change impacts [4,5]. Climate can strongly influence phenology by speeding up or delaying events such as emergence, peak activity and reproduction [6,7].

In many temperate and boreal regions of the world, the timing of spring phenophases such as leaf-out and flowering is advancing due to the warming effects of climate change (e.g., [6,8–15]). Overall, flushing is expected to advance in the next decades, but this trend substantially differs between species [12,16]. Plant species with earlier leaf unfolding dates show higher temperature sensitivities [16].

Warming-induced shifts in the timing of leaf-out and flowering also alter the exposure of vulnerable leaves and flowers to late spring frosts [12,17,18]. Changes in the plant reproductive period also have important consequences on the reproductive success of populations, and thus on their dynamics [6]. For example, changes in flowering time may disrupt plant–pollinator interactions, particularly when the pollinators are seasonal (e.g., insects), and reduce the seed production of plants and food resources to the pollinators, thereby influencing the survival and success of both species [19]. Wang et al. [15] found that, regardless of whether flowering or leaf-out occurred first, the first event advanced more than the second during 1950–2013, resulting in a prolonged time interval between the two events. Other studies also found that flower and leaf phenology responded with differential sensitivity to environmental cues [20].

Autumn remains a relatively neglected season in climate change research in temperate and arctic ecosystems [21]. Changes in spring phenology have been studied, yet autumn phenology remains poorly understood [22]. Many individual studies have shown that the timing of leaf senescence in boreal and temperate deciduous forests in the northern hemisphere is influenced by rising temperatures, but there is limited consensus on the magnitude, direction and spatial extent of this relationship [23]. It has traditionally been accepted that autumn temperatures and day length are the main determinants of autumn phenology, leading to the assumption that warming temperatures will delay autumn leaf senescence in the future [24–27]. However, a growing body of evidence suggests that autumn delays will be counteracted by lagged effects of changes in spring and summer temperatures, reversing future predictions from a previously expected 2- to 3-week delay over the rest of the century to an advance of 3 to 6 days [22,28]. Other researchers claim that growth cessation might be either accelerated or delayed by warming, depending on the species and even on the ecotype [29]. A warming experiment found that the temperature treatment did not have a significant effect on the leaf coloring date, but leaf coloring dates varied significantly among years [30]. Changes in autumn phenology alter the reproductive capacity of individuals, exacerbate invasions, allow pathogen amplification and higher disease-transmission rates, reshuffle natural enemy–prey dynamics, shift the ecological dynamics among interacting species, and affect the net productivity of ecosystems [21]. Yet future growing-season trajectories remain highly uncertain because the environmental drivers of autumn leaf senescence are poorly understood [28].

Warming trends over recent decades have led to extended growing seasons in temperate forests [9,22,31]. The average growing season in Europe has extended by 5 days per 1 °C increase in mean annual air temperature [10].

Many studies in middle and high latitudes demonstrate that the temperature is the main driving force and interannual modulator of phenological change, while other factors (e.g., photoperiod) only play a secondary role as limiting factors [7]. Temperature sensitivity, or phenological sensitivity, which is expressed as the date of phenological event change per degree Celsius change of temperature (days/°C), has been widely used to characterize the plants' responses to changed temperature [16,32]. Since the temperature sensitivity of plant phenological stages determines the magnitude of phenological shifts in response to future climate warming, more attention has been paid to it, both in observational records and warming experiment studies [33].

The area of the Carpathian Basin is particularly vulnerable in terms of climate change [34–37], so it is strongly meaningful to carry out phenological research in the area. In this research, we examined the phenology of seven woody species native to the Carpathian Basin in two areas with different mesoclimates, in an ex situ experiment. Unlike previous studies, we examined the whole annual cycle of these species, keeping the same protocol during their care. We assumed (i) that leaf bud burst, budding, flowering and fruiting will occur earlier at the site with higher average temperatures, while (ii) the autumn phenophases, the beginning of leaf coloring and end of leaf fall is postponed in the area with higher average temperatures. Furthermore, we examined what temperature and other climatic factors besides the average annual temperature influence the time of occurrence of the different phenophases.

2. Materials and Methods

2.1. Study Sites

The study was carried out at two different mesoclimatic sites, one of which is located in the Gödöllő Botanical Garden of the Hungarian University of Agriculture and Life Sciences (47°35′36.2″ N 19°22′06.2″ E, 250 m elevation [38]), while the other is in the Eötvös Loránd University Botanical Garden in the central part of Budapest (Budapest 47°29′05.6″ N 19°05′05.7″ E, 114 m elevation, [39]).

During the three-year experiment, the average air temperature was 11.35 °C and the average annual precipitation was 475.1 mm in Gödöllő Botanical Garden, while in the Eötvös Loránd University Botanical Garden, the average air temperature was 13.16 °C, with an average annual precipitation of 527.4 mm. There was a difference of 1.81 °C between the three-year average temperature of the two botanical gardens (Figure 1). The distance between the two sites is 24.7 km. We used this value to calculate the phenological sensitivity. Within a radius of 250 m around the two botanical gardens, the following local climate zones (LCZ) are present. In Budapest: LCZ 5—open mid-rise 60%, LCZ 6—open low rise 20% LCZ 2—compact mid-rise 20%. In Gödöllő: LCZ A—dense trees 40%, LCZ D—low plants 50%, LCZ 6—open low-rise 10% [40,41]. In the text and graphs, we refer to the experiment sites as Gödöllő and Budapest.

A homogeneous patch was created for each selected species at the two sites.

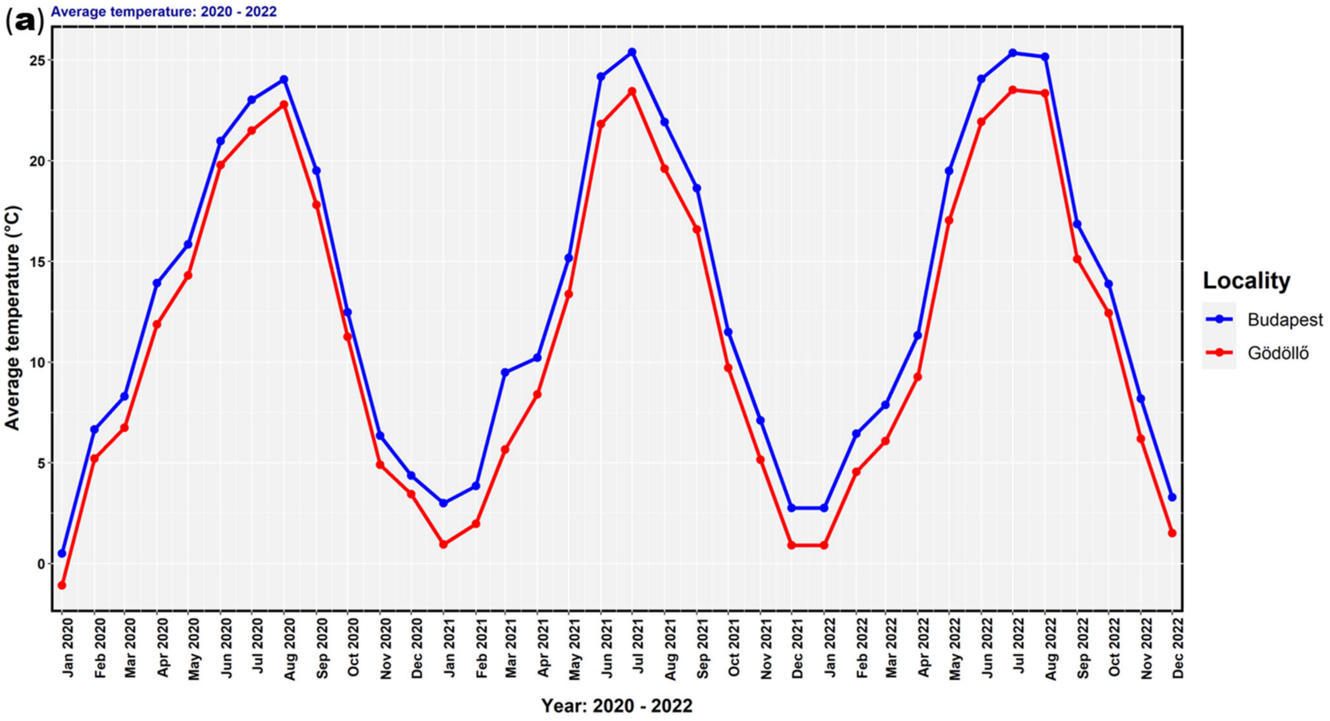


Figure 1. *Cont.*

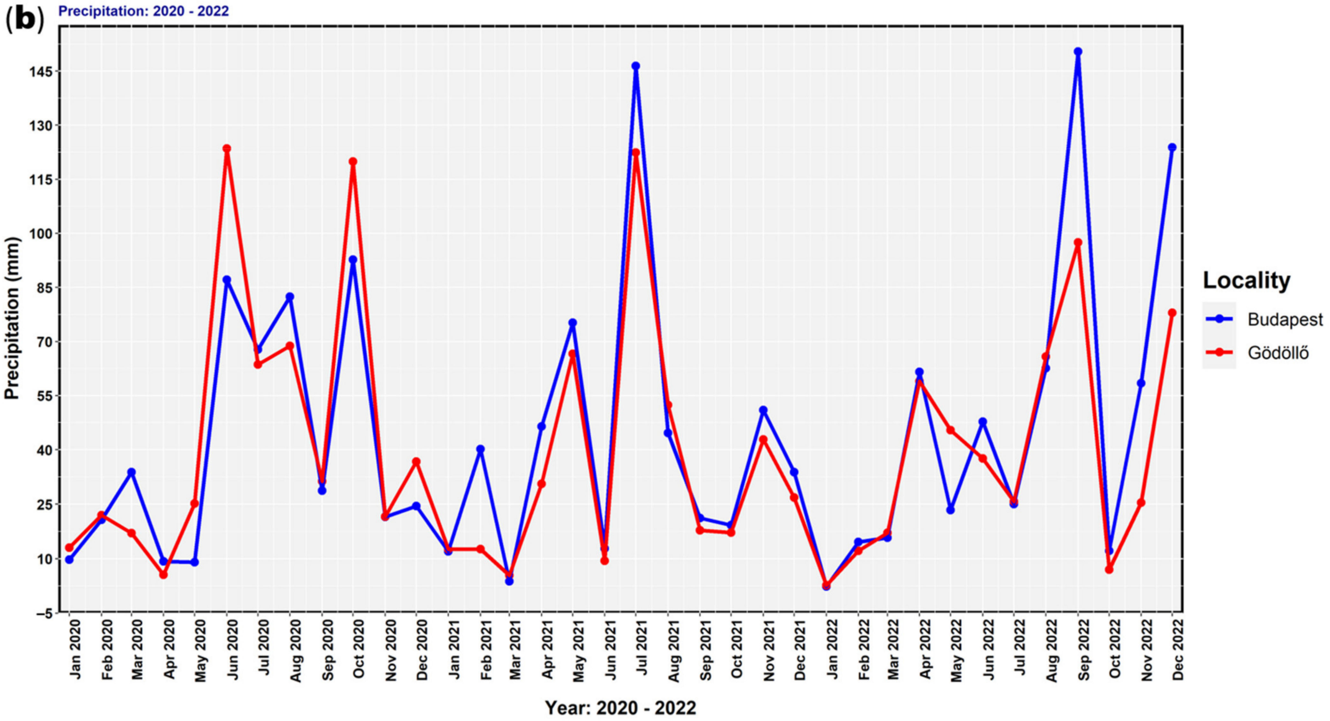


Figure 1. Climatic conditions of the sites during the duration of the experiment (March 2020–December 2022): monthly variation of mean air temperature (**a**) and sum of precipitation (**b**).

2.2. Methods

To examine the effect of the different mesoclimatic environments on the phenology of tree species, we selected seven different, (for the Carpathian Basin) native tree species: dogwood (*Cornus sanguinea* L.), smoke tree (*Cotinus coggygria* Scop.), dwarf cherry (*Prunus fruticosa* Pall.), blackthorn (*Prunus spinosa* L.), wild privet (*Ligustrum vulgare* L.), dwarf Russian almond (*Amygdalus nana* L.) and Scotch rose (*Rosa spinosissima* L.). For the nomenclature of the plants, we used the WFO Plant List [42].

To maximize genetic conformity, we used clones obtained from the Soroksári Botanical Garden of the Hungarian University of Agriculture and Life Sciences. The specimens were grown in standardized pots with a diameter of 27 cm, and were marked individually. All selected woody species were pollinated by insects.

In total, 5 repetitions were used for each species at both sites, except for *Cotinus coggygria*, for which there were only 3 repetitions in Gödöllő and 4 in Budapest, and for *Prunus fruticosa*, there was only 4 repetitions in Gödöllő, as a result of the lack of clonal material.

The ex situ experiment were set-up between December 2019 and February 2020. The same soil mixture and irrigation protocol was used for each specimen at both sites. The plants were watered twice a week in spring and autumn, and daily in summer to keep them well hydrated.

Measurements were taken for each specimen on the same day on a weekly basis at both sites for 3 consecutive years. The experiment covers the interval between March of 2020 and December of 2022.

2.3. Climate Data and Phenophase Observation Measurements of Biotic and Abiotic Data (Environmental Parameters)

The following phenophases were studied on a weekly basis: bud burst, leaf unfolding, leaf development, budding, flowering, fruiting, leaf coloring, leaf fall. We understand the date of bud burst to be the first week when the budbreak is visible, and the leaf unfolding begins. The date of bud burst, the percentage of colored leaves and dropped leaves were recorded, while the number of buds, flowers and fruits were counted during the data collection. The stages—budding, flowering and fruiting—mean the first appearance of the mentioned phases, thus the appearance of the first bud, first opened flower or first unmatured, but visible fruit (Figure 2). The leaf development was studied from the bud burst until the leaf was fully expanded in 2021 and 2022. A twig was permanently marked on each specimen, on which the length (with petiole) and width of 5 marked leaves were measured. The last week of the measurements (phenophase: end of leaf development) was the week when we recorded no or only negligible growth. Additionally, the height and trunk diameter of the individual specimens was measured yearly, at the end of the growing season.

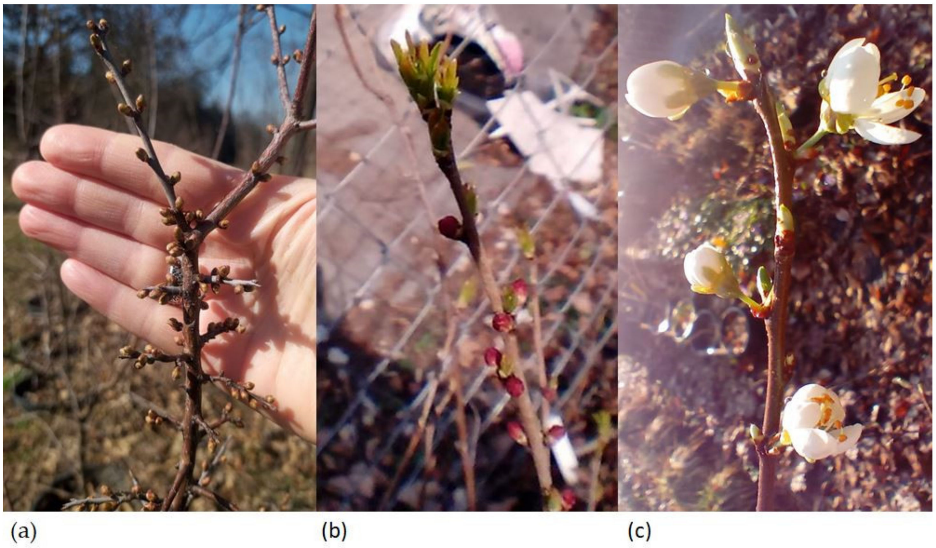


Figure 2. *Prunus spinosa*—4th week of March 2022, Gödöllő, one week before the bud burst (**a**), *Prunus tenella*—3rd week of March 2022, Budapest, the week of the bud burst (**b**) and *Prunus spinosa*—5th week of March 2021, the week of the bud burst and the first flower (**c**).

The meteorological data was collected by AgroSense weather base station (Sys-Control Kft, Budapest, Hungary) installed on both sites at the end of 2020. The two meteorological stations were equipped with the following tools: Sensirion SHT21 for temperature measurement and Davis 6466M for precipitation measurement. The measurement frequency of the weather station is 10 min, the data were sent into a cloud database in 2021 and 2022. For the year 2020, the data (daily mean temperature and daily sum of precipitation) of the nearest station of the Hungarian Meteorological Service (Lágymányos for Budapest and Aszód for Gödöllő) were used.

2.4. Statistical Analysis

Data recording and basic data compilation was carried out in Microsoft Excel 365 online version and all statistical analyses were performed using freely available software R, version 4.2.2. [43] together with RStudio script editor [44]. For advanced data processing, the additional packages "tidyverse" [45], "dplyr" [46] and "scales" [47] were also used. Package "ggplot2" [48] was used for creating advanced statistical graphs.

For modelling the relationship between the day of year and phenophases with dependence of the locality, one-way analysis of variance (ANOVA) type I (sequential) sum of squares was used, with a significance level of 0.05 [49]. Measuring of effect size was carried out with help of partial eta-squared (ηp2) from the "lsr" package [50]. To detect the difference among factor level means between response and categorial variables after ANOVA, Tukey's honestly significant difference (HSD) test was used from the "agricolae" package [51]. Calculating the factor level means (with 95% confidence intervals—CI) was carried out with help of "treatment contrasts" which was also used to determine the difference among factor level means [52]. In some cases, one-way ANOVA was also used separately for all species, and only for selected phenophases, depending on the location. These results were graphically represented with help of bar charts showing statistically significant difference at the significance level of 0.05, indicated by different letters.

Simple linear regression analysis was performed for characterization of the relationship between the day of year and meteorological features, where locality was used as the grouping factor [52]. Estimation of the unknown parameters and curve-fitting was established by minimizing the sum of the squared residuals (method of ordinary last squares—OLS). Coefficient of determination (R^2) was used to explain how well the variation of day of year can be predicted from the selected meteorological features (e.g., temperature). Finally, local regression models were also fitted, which best represent the relationship between these relationships. In this case, locally estimated scatterplot smoothing (LOESS) was performed for fitting of regression curve with a 95% confidence interval (CI) around the regression line. Smoothing method was chosen based on the size of the largest group and smoothing parameter (α) was 0.8, which means the loess curve incorporated 80% of the total data points [53].

After all statistical analyses, the assumptions of selected models were also checked at a significance level of 0.05 with help of appropriate tests and several diagnostic plots [52,54].

3. Results

The leaf bud burst (Figure 3) occurred earlier for six of the seven species in all three years at the warmer Budapest site. The difference is significant in four species. One species, *Prunus tenella*, showed the opposite effect, and the bud burst was earlier at the Gödöllő site, but the difference is not significant. By the year 2022, this was also reversed in the case of *Prunus tenella*, because the leaf bud burst occurred 14 days earlier at the Budapest site. On average, the time of leaf bud burst at the Budapest location is DOY 74.6, while at the Gödöllő location DOY 81.6; the difference is 7 days. Phenological sensitivity: −3.87 days/°C.

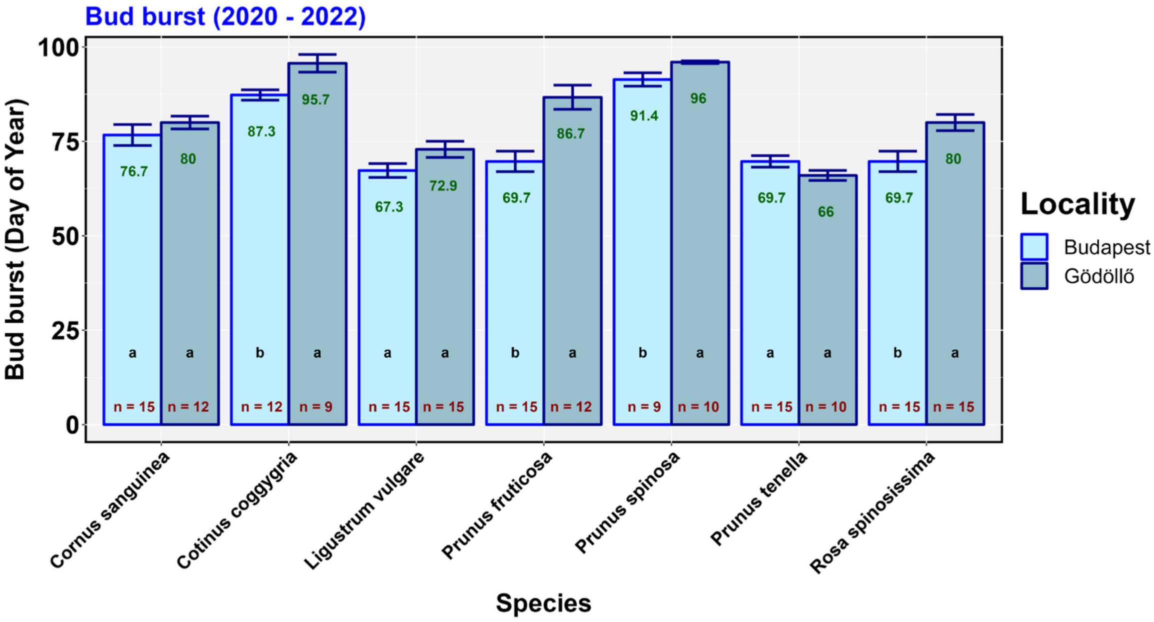


Figure 3. Date of leaf bud burst (2020–2022). The letters a and b are for the mean values, differing letters indicate a statistical significance difference at 5% significance level. The letter n is for the sample size.

The beginning of leaf coloring (Figure 4) occurred later in the case of six of the seven species at the warmer Budapest site, although the difference was only significant in one case of *Prunus fruticosa*. In the case of one species, *Prunus spinosa*, the onset of leaf coloring occurred earlier at the Budapest site. There was a relatively large difference between the years, while in 2020, the beginning of the leaf coloring of all species was earlier at the Gödöllő site, as expected; this trend was reversed in five species (*Cotinus coggygria*, *Ligustrum vulgare*, *Prunus spinosa*, *Prunus tenella*, *Rosa spinosissima*) in 2021. In 2022, the leaves of *Prunus spinosa* still began to color first at the Budapest site, and in three species (*Prunus fruticosa*, *Ligustrum vulgare* and *Cotinus coggygria*), autumn leaf coloration started at the same time at the two sites, while the other species began to color first at the Gödöllő site. The onset of the beginning of leaf coloration is significant, considering all species and the two sites together: DOY 267.43 in 2020, DOY 245.49 in 2021, and DOY 220.76 in 2022. There was a large difference between the years, but the results of the extremely dry year 2022 were not exceptional in comparison. Averaging the data of the three years, the beginning of leaf coloration is DOY 247.3 at the Budapest site, while DOY 240.5 at the Gödöllő site. The difference is 6.8 days. Phenological sensitivity: −3.76 days/°C.

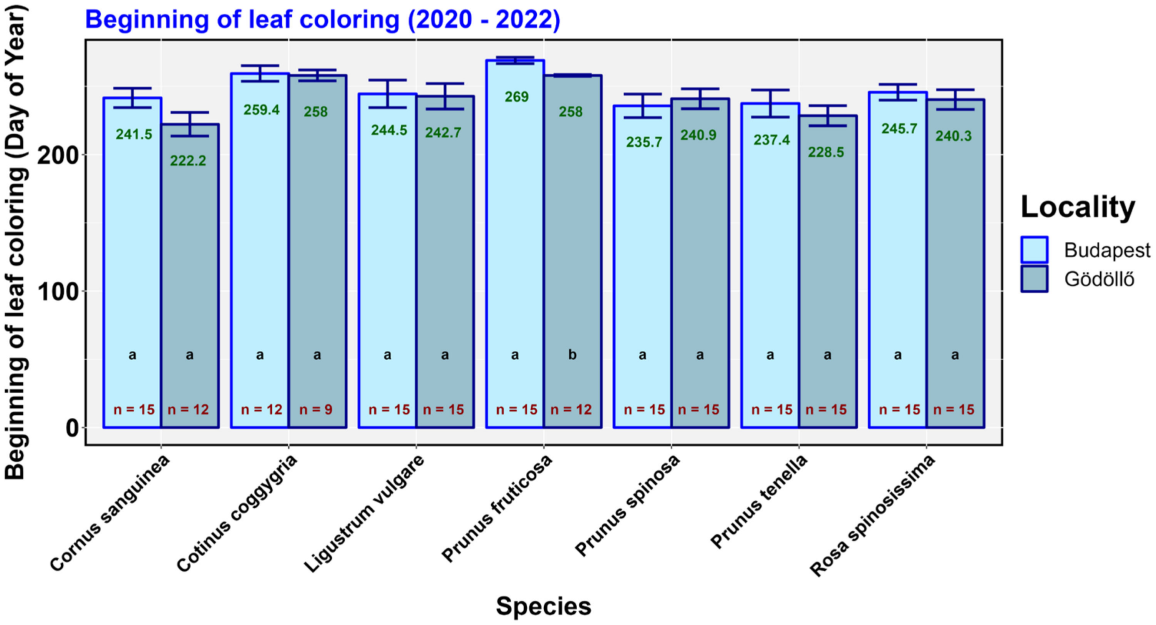


Figure 4. Beginning of leaf coloring (2020–2022). The letters a and b are for the mean values, differing letters indicate a statistical significance difference at 5% significance level. The letter n is for the sample size.

The end of leaf fall (Figure 5) occurred earlier for all seven species at the Gödöllő site. The difference was significant for two species, *Cornus sanguinea* and *Cotinus coggygria*. The time of this phenophase is on average DOY 334.7 at the Budapest site, while DOY 326.9 at the Gödöllő site. The difference is 7.8 days. Phenological sensitivity: 4.31 days/°C.

For all species (Figure 6), leaf bud burst, budding (first bud), flowering (first flower), fruiting (first fruit) occurred/appeared first at the Budapest site, while the beginning of leaf coloring and end of leaf fall occurred first at the Gödöllő site, based on the three-year data. The difference was significant only in the case of leaf bud burst and end of leaf fall (5% significance level). The time of the appearance of the first flower is DOY 121.3 at the Budapest site, while DOY 132.6 at Gödöllő. The difference is 11.3 days, based on this and the mean annual temperature, the calculated phenological sensitivity is –6.24 days/°C. The time between bud burst and first flower is 46.7 days at the Budapest site, while 51 days at the Gödöllő site. The length of the growing season (the time between the bud burst and the end of the leaf fall) is 260.1 days in the warmer Budapest site, while it is 245.3 days in the cooler Gödöllő site. The difference is 14.8 days.

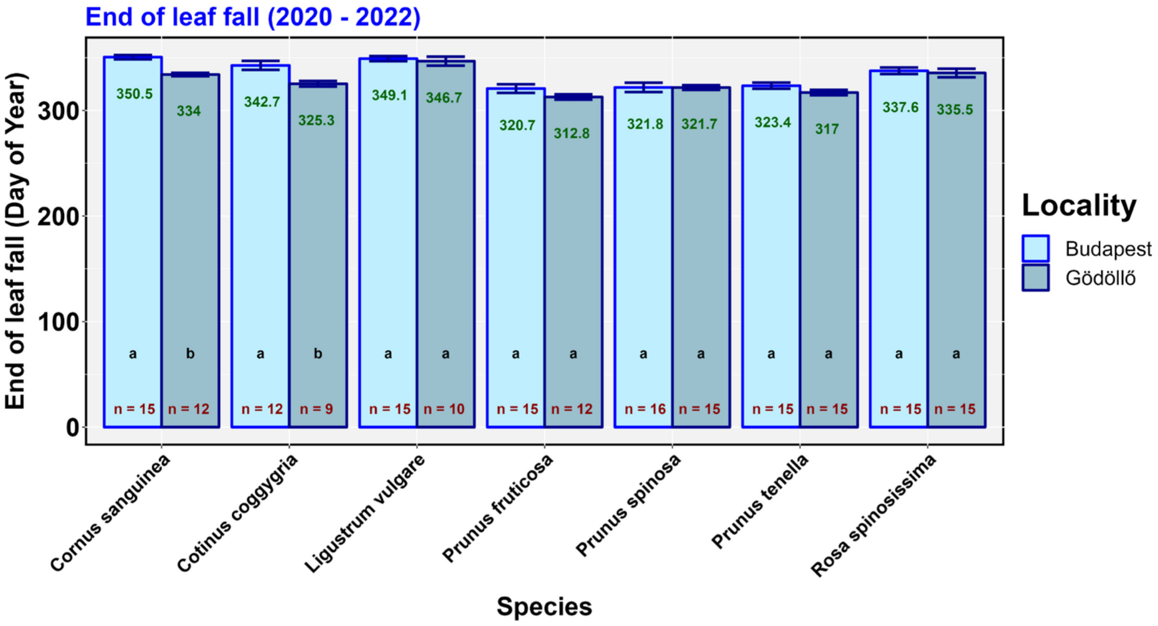


Figure 5. End of leaf fall (2020–2022). The letters a and b are for the mean values, differing letters indicate a statistical significance difference at 5% significance level. The letter n is for the sample size.

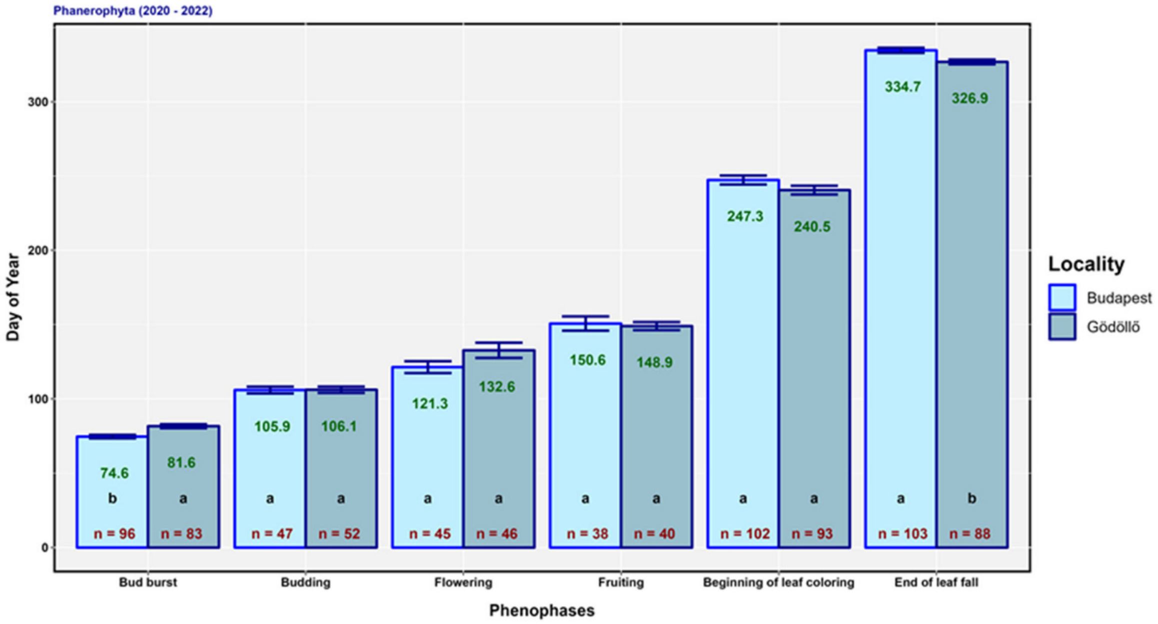
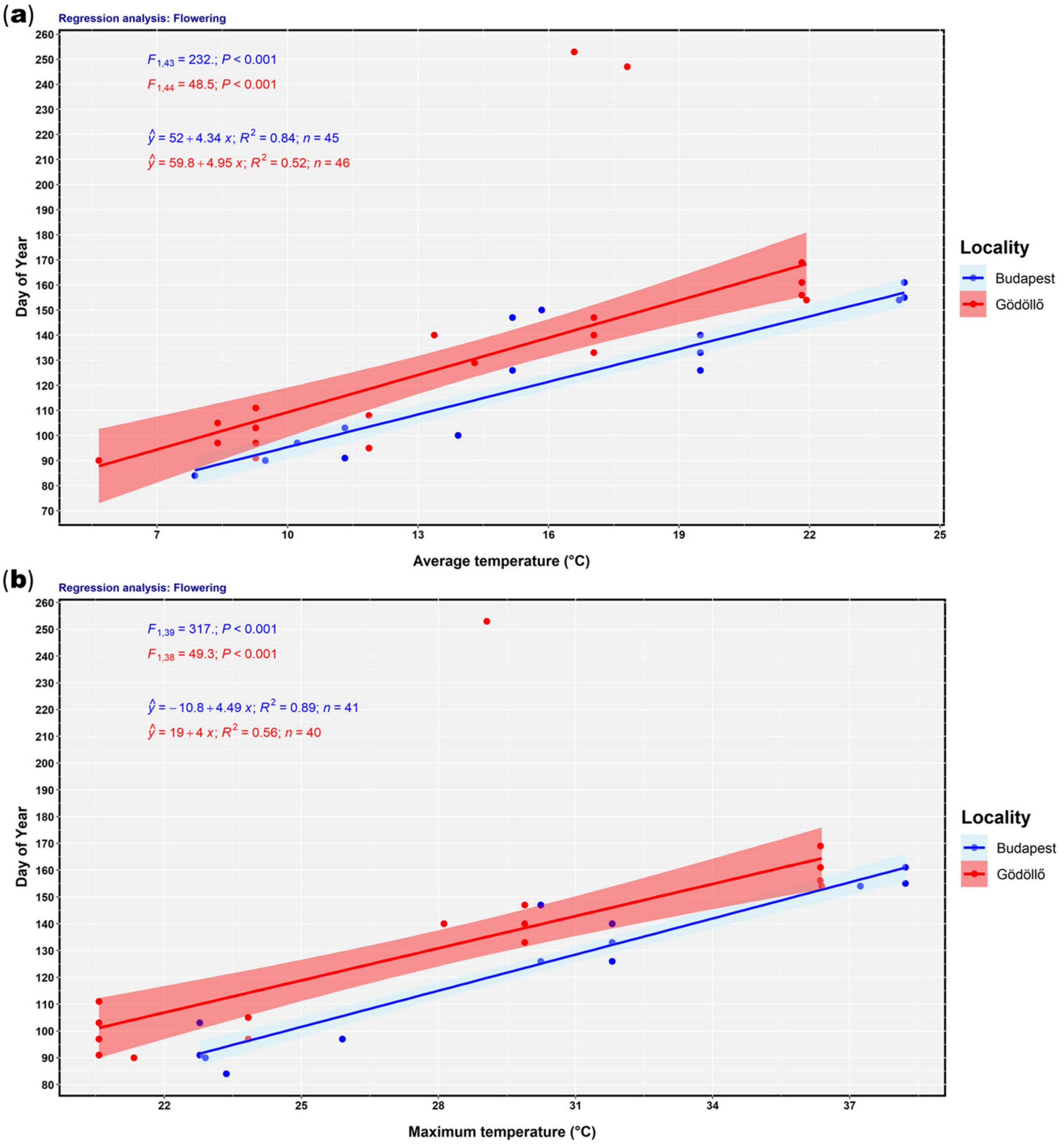


Figure 6. Average time of the studied phenophases based on all species (2020–2022). The letters a and b are for the mean values, differing letters indicate a statistical significance difference at 5% significance level. The letter n is for the sample size.

Regarding leaf bud burst (Appendices A–C), in Budapest the maximum temperature in March–April and the number of frost days, while in Gödöllő the average March–April temperature, total precipitation and minimum temperature during the same period, and the number of frost days had a highly significant ($p < 0.001$) effect. However, the correlation was not extremely strong at any location, as indicated by the r^2 values ($r^2 < 50\%$).

Concerning the appearance of the flower buds, all the examined parameters—mean temperature (March, April, May), precipitation (March, April, May), min. temperature (March, April, May), max. temperature (March, April, May), and number of frost days—had a highly significant ($p < 0.001$) effect, with the exception of the precipitation that fell during the examined period at the Gödöllő site ($p = 0.06$). We found a strong relationship ($r^2 > 50\%$) between appearance of the buds and the average and minimum temperature in the March–April–May period when examining the two sites together (Figure 7).



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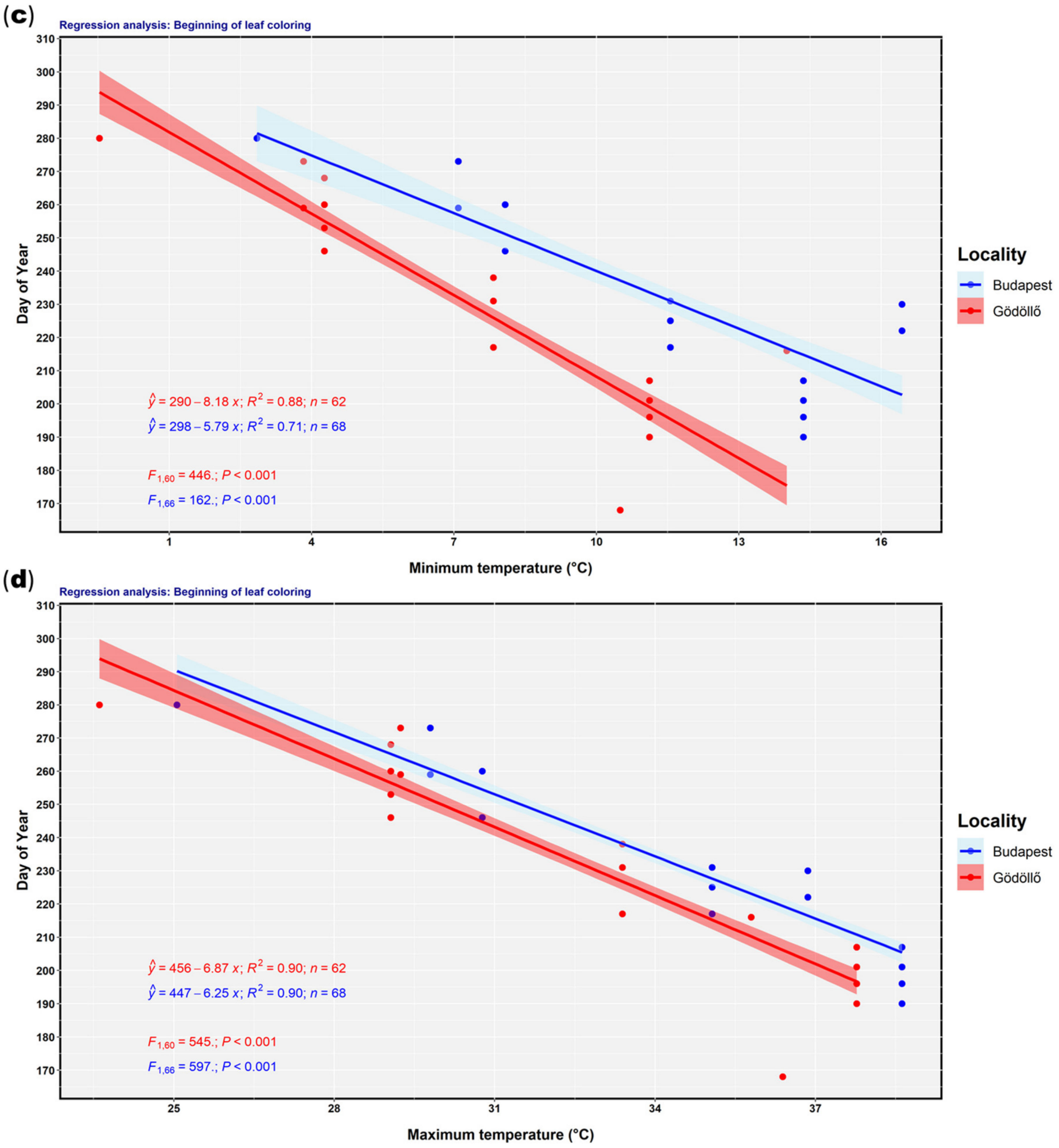

Figure 7. Results of the regression analysis of flowering (**a**,**b**), and beginning of leaf coloring (**c**,**d**), of the investigated three years (2020–2022) (r^2 is the determination coefficient, n is the number of observations). The effect of the average temperature of the March–June period on the time of the beginning of flowering period (**a**). The effect of the maximum temperature of the March–June period on the time of the beginning of flowering period (**b**) The effect of the minimum temperature of the July–October period on the time of the beginning of leaf coloring (**c**). The effect of the maximum temperature of the July–October period on the time of the beginning of leaf coloring (**d**).

The March–June average temperature (Figure 7), the minimum and the maximum temperature (Figure 7) had a strong significant effect ($p < 0.001$) on the start of flowering at both sites. We found a strong correlation ($r^2 > 50\%$) between this phenophase and the mean temperature (March–June) (Appendices A–C).

Fruiting showed a significant correlation with the temperature variables ($p < 0.001$ or $p < 0.01$), but we did not find a strong relationship with the r^2 values (Appendices A–C).

Regarding the beginning of leaf coloration, we found a strong relationship ($p < 0.001$, $r^2 > 50\%$) between the mean temperature (July–October), the number of tropical nights

(July–October), the minimum and maximum temperature (July–October) (Figure 7) and the phenological event (Appendices A–C). The effect was highly significant ($p < 0.001$) for all three variables at both sites, and all four variables had a delaying effect on the beginning of leaf coloration (Appendices A–C).

With the exception of the precipitation in November–December, all measured parameters (the average temperature, the minimum and maximum temperature in November–December, as well as the number of frost days measured in this period) had a highly significant ($p < 0.001$) effect on the time of the end of leaf fall (Appendices A–C). The higher temperature delayed it, while the number of frost days brought the end of leaf fall earlier (Appendices A–C). At the Gödöllő site, we found the strongest relationship with the November–December minimum temperature ($r^2 > 50\%$), while at the Budapest site, the relationship between the November–December average temperature, minimum and maximum temperature and the occurrence of this phenophase was also strong ($r^2 > 50\%$) (Appendices A–C).

4. Discussion

Leaf bud burst occurred earlier in all three years at the site with higher average temperature. The difference is a total of 7 days (Figure 1), which represents a phenological sensitivity of –3.87 days/°C when compared to the annual average temperatures. If we look at the difference between the average temperatures of the defining period (March–April) in terms of the phenophase (Gödöllő: 8 °C, Budapest 10.19 °C), then this means –3.2 days/°C phenological sensitivity. Our results are consistent with the results of several previous studies [16,32,55]; however, Chmielewski and Rötzer [10] showed a significantly higher phenological sensitivity for leaf bud burst, –7 days/°C. In several cases, we found a stronger, significant relationship between leaf bud burst and the parameters investigated in the correlation at the site with lower temperatures (Appendices A–C).

Regarding the appearance of the first bud (Appendices A–C), the relationship was strongest with the number of frost days at the Budapest site ($r^2 = 56\%$), while at the cooler Gödöllő site, the average, minimum and maximum temperature of the months of March–April–May were $r^2 = 63$, $r^2 = 62$ and $r^2 = 56\%$, respectively. At the location with a higher average temperature, the number of possibly occurring frost days, rather than the temperature is a limiting factor, as it was found by Vitasse et al. [56]. Further investigations need to be conducted to quantify the real impact of winter temperatures on leaf-out time.

The beginning of flowering occurred earlier at the warmer site than at the Gödöllő site (Figure 6). This is in harmony with the findings of other research (e.g., [6,8–15]). The time of the appearance of the first flower (Appendices A–C) and the average, maximum and minimum temperature of the period between March and June showed a stronger relationship at the Budapest site ($r^2 = 84$, $r^2 = 82$, $r^2 = 89\%$) than at the Gödöllő site ($r^2 = 52$, $r^2 = 58$, $r^2 = 56\%$); however, the effect was highly significant at both locations ($p < 0.001$). Further investigations are needed to find the reason for the discrepancy. Similar to the results of Buonaiuto et al. [20], we found that the phenological sensitivities of leaf bud burst and first flower differ. Contrary to the results of other studies [15,57], we found that the phenological sensitivity of flowering (–6.24 days/°C) was significantly higher than that of leaf bud burst (–3.87 days/°C) and not vice versa. A large advance of flowering may increase the risk of frost damage later on [13,15,16,57].

Contrary to spring phenology, autumn phenology responses to climate warming are inconsistent, with advanced and delayed trends as well as no response having been reported [23]. In line with most previous research [24–27,58], we found that the autumn phenophases (beginning of leaf coloring and end of leaf fall) occurred later at the warmer Budapest site, even if this difference was not significant for the majority of species (see Figures 4–6). The strongest relationship was found at this phenophase during the regression analysis (Appendices A–C); in the case of the relationship between the maximum temperature between July and October and the beginning of the leaf coloring, the r^2 was 90% at both sites. There was also a very strong ($r^2 > 70\%$) relationship between the beginning of leaf coloring and the average and minimum temperature of the period at both locations (Figure 7).

Regarding the beginning of leaf coloring, there was a big difference between the years (Figure 4); however, the results of the extremely dry year 2022 were not exceptional in comparison, which could possibly be attributed to the regular irrigation. The start of leaf coloration shifted more than 40 days earlier in the three years. It is worth noting that several recent studies claim that autumn delays will be counteracted by the lagged effects of changes in spring and summer temperatures, reversing future predictions from a previously expected 2- to 3-week delay over the rest of the century to an advance of 3 to 6 days [22,28]. One of the possible reasons for the difference and advance between years is that the soil started to prove insufficient for the plants planted in the pots, and the pots were "outgrown", which agrees with previous results [22,59], according to which drought can advance leaf coloring.

In the case of the end of leaf fall, the phenological sensitivity to the average annual temperature is 4.31 days/°C. Zhang et al. [16] found that the increase in mean autumn temperature induced a delay of 2.1 days for leaf fall. For this phenophase, we found a relatively strong (Gödöllő: r^2 = 48%, Budapest r^2 = 50%), significant ($p < 0.001$) relationship between the number of frost days and the occurrence of the phenophase. Contrary to previous research [16], we found that the phenological sensitivity of leaf fall (4.31 days/°C) was stronger than that of leaf bud burst (–3.87 days/°C).

Because previous studies [60,61] reported autumn phenology is influenced by spring phenology, it would be worthwhile to examine this relationship in the future. Just as in the case of spring phenophases, moving forward can increase the risk of frost damage [22].

In line with other research [9–11,14,62–65], we found that the growing season was longer in areas with higher average temperatures. Based on our results, the phenological sensitivity of the growing season is 8.18 days/°C. Chmielewsk and Rötzer [10] found that in the last thirty years of the 20th century it extended by 5 days per 1 °C increase in mean annual air temperature.

Based on the regression analysis, the effect of precipitation was weak or negligible for all phenophases, presumably due to irrigation. However, the survival of the experimental plants could not have been ensured without additional irrigation, especially in the extremely dry year of 2022.

In addition to the above, in the future it would be worthwhile to compare the time of occurrence of the phenophases with the daily temperature data, especially with regard to the thermal time approach, using the heating degree day and cooling degree day calculations based on the method of Richardson et al. [31]. With regard to the autumn phenophases, it would be worthwhile to examine separately the effect of average daytime and nighttime temperatures, as suggested by Chen et al. [22].

5. Conclusions

In general, it can be said that during our experiment, the spring phenophases (leaf bud burst, first bud, first flower, first fruit) occurred earlier at the site with a higher average temperature, while the autumn phenophases (beginning of leaf coloring, end of leaf fall) occurred later. Overall, our results confirmed our preliminary assumptions.

In the case of bud burst (Figure 3), we did not find a strong relationship between the phenophase and the investigated parameters (Appendices A–C); however, it can be said that this phenological event occurred earlier in all three years at the site with a higher average temperature. The phenological sensitivity was –3.87 days/°C.

Flowering (Figure 5) also occurred earlier at the warmer site. The strongest relationship (r^2 > 50%) was between flowering and the average, maximum and minimum temperature in the March–June period (Appendices A–C). The phenological sensitivity of the appearance of the first flower was –6.24 days/°C, which was the highest value among the studied phenophases.

The beginning of leaf coloration and the end of leaf fall occurred later at the site with a higher average temperature. The strongest relationship ($r^2 > 70\%$) was between leaf coloration and July–October average and maximum temperature (Appendices A–C). The phenological sensitivity of leaf coloration was 3.76 days/°C. Regarding the beginning of leaf coloring, there was a large difference between the years (Figure 4); however, the results of the extremely dry year 2022 were not exceptional in comparison, which might be attributed to the regular irrigation. It is interesting that the beginning of the leaf coloration in the two sites was pushed forward by more than 40 days during the three years (Figure 4). We found the strongest ($r^2 = 50\%$) relationship between the end of leaf fall and the average and maximum temperature in November–December (Appendices A–C). The phenological sensitivity of the phenophase was 4.31 days/°C.

Based on the regression analysis (Appendices A–C), the effect of precipitation is weak or negligible for all phenophases, which is probably attributable to irrigation.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Regression data of both sites.

Phenophase/Driving Factors	r^2	F-Statistic	n	a	b	Significance Level
Bud burst						
Mean temperature (March–April)	0.060	12.050	179	61.180	2.060	<0.001 ***
Precipitation (March–April)	0.120	25.220	179	72.170	0.260	<0.001 ***
Min. temperature (March–April)	0.030	3.370	114	85.610	1.090	0.07 +
Max. temperature (March–April)	0.010	1.000	114	61.860	0.880	0.32
Number of frost days	0.220	31.430	114	91.390	−1.140	<0.001 ***

Table A1. *Cont.*

Phenophase/Driving Factors	r^2	F-Statistic	n	a	b	Significance Level
Budding						
Mean temperature (March–April–May)	0.550	118.300	99	67.570	3.600	<0.001 ***
Precipitation (March–April–May)	0.140	15.220	99	95.430	0.260	<0.001 ***
Min. temperature (March–April–May)	0.520	86.860	83	108.590	2.910	<0.001 ***
Max. temperature (March–April–May)	0.430	60.730	83	34.200	3.010	<0.001 ***
Number of frost days	0.430	60.070	83	114.190	−2.460	<0.001 ***
Flowering						
Mean temperature (March–June)	0.580	120.800	91	59.150	4.430	<0.001 ***
Precipitation (March–June)	0.010	0.610	91	131.300	−0.120	0.44
Min. temperature (March–June)	0.560	98.740	81	111.730	3.870	<0.001 ***
Max. temperature (March–June)	0.640	142.40	81	8.750	4.090	<0.001 ***
Number of frost days (March–June)	0.360	45.210	81	135.990	−5.930	<0.001 ***
Number of tropical nights (March–June)	0.240	25.520	81	119.410	5.490	<0.001 ***
Fruiting						
Mean temperature (May–June)	0.370	44.750	78	86.000	3.380	<0.001 ***
Precipitation (May–June)	0.030	2.590	78	142.990	0.140	0.11
Min. temperature (May–June)	0.310	32.990	76	126.610	2.950	<0.001 ***
Max. temperature (May–June)	0.360	41.050	76	49.990	3.090	<0.001 ***
Number of tropical nights (May–June)	0.300	31.130	76	142.100	3.150	<0.001 ***
Beginning of leaf coloring						
Mean temperature (July–October)	0.780	664.800	195	362.110	−6.230	<0.001 ***
Precipitation (July–October)	0.170	39.190	195	227.510	0.350	<0.001 ***
Min. temperature (July–October)	0.570	172.800	130	279.580	−5.100	<0.001 ***
Max. temperature (July–October)	0.860	777.700	130	443.340	−6.300	<0.001 ***
Number of tropical nights (July–October)	0.320	61.240	130	243.770	−2.850	<0.001 ***

Table A1. *Cont.*

Phenophase/Driving Factors	r^2	F-Statistic	n	a	b	Significance Level
End of leaf fall						
Mean temperature (November–December)	0.500	187.700	191	361.800	−6.040	<0.001 ***
Precipitation (November–December)	0.030	6.140	191	326.570	0.100	0.01 *
Min. temperature (November–December)	0.400	82.370	125	314.160	−4.610	<0.001 ***
Max. temperature (November–December)	0.500	124.100	125	373.220	−3.150	<0.001 ***
Number of frost days (November–December)	0.350	65.860	125	315.130	1.550	<0.001 ***

+ statistically significant difference at 10% significance level; * statistically significant difference at 5% significance level; *** statistically significant difference at 0.1% significance level; tropical night = daily minimum temperature > 20 °C.

Appendix B

Table A2. Regression data of Budapest.

Phenophase/Driving Factors	r^2	F-Statistic	n	a	b	Significance Level
Bud burst						
Mean temperature (March–April)	0.020	2.200	96	57.600	1.950	0.14
Precipitation (March–April)	0.050	4.480	96	71.250	0.160	0.04 *
Min. temperature (March–April)	0.160	11.580	62	88.330	4.080	0.001 **
Max. temperature (March–April)	0.270	21.930	62	−109.360	8.040	<0.001 ***
Number of frost days	0.210	16.120	62	92.020	−1.920	<0.001 ***
Budding						
Mean temperature (March–April–May)	0.490	4.490	47	63.700	3.770	<0.001 ***
Precipitation (March–April–May)	0.250	15.000	47	91.070	0.360	<0.001 ***
Min. temperature (March–April–May)	0.490	36.040	40	105.440	3.150	<0.001 ***
Max. temperature (March–April–May)	0.320	17.560	40	31.510	3.050	<0.001 ***
Number of frost days	0.560	48.410	40	114.850	−3.330	<0.001 ***
Flowering						
Mean temperature (March–June)	0.840	232.300	45	51.970	4.340	<0.001 ***
Precipitation (March–June)	0.002	0.090	45	119.560	0.050	0.76
Min. temperature (March–June)	0.820	180.900	41	100.230	4.120	<0.001 ***
Max. temperature (March–June)	0.890	317.300	41	−10.770	4.490	<0.001 ***
Number of frost days (March–June)	0.410	27.500	41	130.550	−5.350	<0.001 ***
Number of tropical nights (March–June)	0.460	33.480	41	111.410	5.460	<0.001 ***

Table A2. *Cont.*

Phenophase/Driving Factors	r^2	F-Statistic	n	a	b	Significance Level
Fruiting						
Mean temperature (May–June)	0.380	21.930	38	74.140	3.910	<0.001 ***
Precipitation (May–June)	0.100	3.880	38	137.910	0.240	0.06 +
Min. temperature (May–June)	0.360	20.450	38	115.380	3.690	<0.001 ***
Max. temperature (May–June)	0.340	18.520	38	35.900	3.530	<0.001 ***
Number of tropical nights (May–June)	0.370	20.940	38	138.040	3.300	<0.001 ***
Beginning of leaf coloring						
Mean temperature (July–October)	0.820	454.800	102	356.660	−5.670	<0.001 ***
Precipitation (July–October)	0.210	27.290	102	226.390	0.360	<0.001 ***
Min. temperature (July–October)	0.710	161.600	68	298.000	−5.790	<0.001 ***
Max. temperature (July–October)	0.900	596.800	68	446.770	−6.250	<0.001 ***
Number of tropical nights (July–October)	0.540	76.740	68	251.280	−2.860	<0.001 ***
End of leaf fall						
Mean temperature (November–December)	0.650	191.400	103	371.720	−7.050	<0.001 ***
Precipitation (November–December)	0.001	0.200	103	333.560	0.020	0.66
Min. temperature (November–December)	0.720	168.200	68	313.620	−8.060	<0.001 ***
Max. temperature (November–December)	0.540	76.180	68	375.050	−3.210	<0.001 ***
Number of frost days (November–December)	0.500	64.830	68	315.950	2.260	<0.001 ***

+ statistically significant difference at 10% significance level; * statistically significant difference at 5% significance level; ** statistically significant difference at 1% significance level; *** statistically significant difference at 0.1% significance level; tropical night = daily minimum temperature > 20 °C.

Appendix C

Table A3. Regression data of Gödöllő.

Phenophase/Driving Factors	r^2	F-Statistic	n	a	b	Significance Level
Bud burst						
Mean temperature (March–April)	0.440	64.190	83	46.920	4.730	<0.001 ***
Precipitation (March–April)	0.280	31.000	83	73.660	0.370	<0.001 ***
Min. temperature (March–April)	0.620	82.930	52	109.880	4.820	<0.001 ***
Max. temperature (March–April)	0.170	10.340	52	12.490	3.390	0.002 **
Number of frost days	0.710	122.000	52	99.700	−1.370	<0.001 ***

Table A3. *Cont.*

Phenophase/Driving Factors	r^2	F-Statistic	n	a	b	Significance Level
Budding						
Mean temperature (March–April–May)	0.630	86.640	52	69.000	3.640	<0.001 ***
Precipitation (March–April–May)	0.060	3.250	52	99.180	0.170	0.08 +
Min. temperature (March–April–May)	0.620	67.840	43	111.800	3.170	<0.001 ***
Max. temperature (March–April–May)	0.560	52.700	43	32.290	3.160	<0.001 ***
Number of frost days	0.360	22.840	43	113.860	−2.040	<0.001 ***
Flowering						
Mean temperature (March–June)	0.520	48.510	46	59.770	4.950	<0.001 ***
Precipitation (March–June)	0.060	2.630	46	148.290	−0.420	0.11
Min. temperature (March–June)	0.580	51.580	40	120.110	4.700	<0.001 ***
Max. temperature (March–June)	0.560	49.340	40	18.950	4.000	<0.001 ***
Number of frost days (March–June)	0.350	20.130	40	141.700	−6.660	<0.001 ***
Number of tropical nights (March–June)	0.230	11.290	40	123.950	10.120	0.002 **
Fruiting						
Mean temperature (May–June)	0.400	24.920	40	98.250	2.780	<0.001 ***
Precipitation (May–June)	0.090	3.870	40	161.280	−0.300	0.06 +
Min. temperature (May–June)	0.310	16.460	38	132.530	2.670	<0.001 ***
Max. temperature (May–June)	0.440	28.100	38	66.620	2.600	<0.001 ***
Number of tropical nights (May–June)	0.210	9.410	38	142.910	5.280	0.005 **
Beginning of leaf coloring						
Mean temperature (July–October)	0.850	502.900	93	388.460	−7.970	<0.001 ***
Precipitation (July–October)	0.090	8.940	93	228.580	0.330	0.003 **
Min. temperature (July–October)	0.880	446.400	62	290.010	−8.180	<0.001 ***
Max. temperature (July–October)	0.900	544.800	62	456.070	−6.870	<0.001 ***
Number of tropical nights (July–October)	0.790	228.200	62	252.400	−14.060	<0.001 ***

Table A3. *Cont.*

Phenophase/Driving Factors	r^2	F-Statistic	n	a	b	Significance Level
End of leaf fall						
Mean temperature (November–December)	0.450	69.010	88	352.510	−5.250	<0.001 ***
Precipitation (November–December)	0.140	13.630	88	313.340	0.390	<0.001 ***
Min. temperature (November–December)	0.550	66.920	57	308.920	−4.120	<0.001 ***
Max. temperature (November–December)	0.360	31.390	57	365.810	−2.740	<0.001 ***
Number of frost days (November–December)	0.480	50.190	57	311.050	1.370	<0.001 ***

+ statistically significant difference at 10% significance level; ** statistically significant difference at 1% significance level; *** statistically significant difference at 0.1% significance level; tropical night = daily minimum temperature > 20 °C.

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