Original Research

Response of Tree Seasonal Development to Climate Warming

Romualdas Juknys[1], Kęstutis Žeimavičius[2], Gintarė Sujetovienė[1]*, Jurgita Gustainytė[1]

[1]Department of Environmental Sciences, Vytautas Magnus University,
Vileikos st. 8, 44404 Kaunas, Lithuania
[2]Kaunas Botanical Garden, Vytautas Magnus University,
Ž. E. Žilibero st. 6, 46324 Kaunas, Lithuania

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Abstract

The aim of our study was to investigate the response in timing of phenological events and the duration of the growing season to climate warming for three deciduous tree species: birch, lime, and maple. The most significant advancement in phenological spring (leaf unfolding) – 14.3 days through the investigated 1956-2009 period – was detected in the case of the early-season pioneer species birch. A shift in leaf unfolding for other two late season species, maple and lime, was less expressed and consisted of 9 days through the investigated period. The changes in timing of phenological autumn were detected to be even more species specific and it was delayed by almost 16 days for maple, 12 days for lime and, in contrast, leaf fall advanced by 12 days was detected for birch. The occurrence of leaf unfolding best correlated with March and April temperatures. A statistically significant correlation of leaf unfolding with January temperatures was characteristic of early-season species – birch. The relationship between timing in leaf fall and temperature was much weaker and in most cases statistically insignificant. The growing season for maple and lime was extended by 25.4 and 21.5 days, respectively, through the study period. The length of the growing season of birch did not experience any statistically significant changes and the entire growing period shifted earlier by almost two weeks during the investigated period.

Keywords: climate warming, phenology, leaf unfolding, leaf fall, growing season, Lithuania

Introduction

The course of seasonal plant development is characterized by the sequence and duration of phenophases. A recent application of phenology, the traditional science of seasonal plant development, is connected with climate change, and particularly with climate warming studies [1-3]. Taking into account that the global average temperature has increased by 0.75±0.2ºC over the last century and a further increase of 1.4-5.8ºC is expected [4], long-term observations of plant phenology are considered to be one of the most sensitive instruments to detect and quantify the impact of climate change on vegetation [5-7].

According to current phenological studies, climate warming has advanced the biological spring including such phenological phases of plants as bud burst, leaf unfolding, flowering, and delayed biological autumn, i.e. leaf coloring and leaf fall [8, 9]. The shift of plant phenological phases and lengthening of vegetation period may cause essential consequences for different ecological processes, agriculture, and forestry. These changes may affect ecosystem structure and functioning as competitive abilities and/or productivity of species would be altered [10, 11].

*e-mail: g.sujetoviene@gmf.vdu.lt

On the other hand, changes in the timing of plant seasonal development and lengthening of the growing season increases CO_2 uptake, thus making vegetation an important feedback factor able to reduce climate warming. Actually, climate change and vegetation interaction are much more complicated and depend on regional climate features. It can dampen or, in contrast, reinforce climate warming [5, 11, 12].

In temperate regions seasonal tree development is mainly dependent on temperature while precipitation is a much less influencing factor [2, 13]. Many pheno-climatic studies have detected a significant correlation between early spring phenology (bud burst, leaf unfolding) and rising temperature, but the impact of climate warming on autumn events (leaf coloring, leaf fall) is less consistent, and in some cases the advanced end of the growing season was detected [10, 14, 15].

In Lithuania, phenological investigations are mostly based on the data of the phenological network was established by the Lithuanian Hydrometeorological service. In 1960-70 the phenological network included more than 200 locations throughout the country. In most of these locations observations were canceled from the very beginning of the 1990's. Currently phenological observations are continued in 23 stations, with the most attention given to fruit trees [16, 17].

Some reviews have attempted were made to generalize the data in response of different species to climate warming and to present aggregated values indicating changes in timing of different phenophases of all woody plants [5, 10]. However, most available data on the shift of phenophases along climate warming point out that various tree species react to climate warming differently [1, 8, 18-20].

This study is aimed at investigating the response in timing of phenological events throughout the growing season, e.g. leaf unfolding and leaf fall to changes in temperature and precipitation for three deciduous tree species: Norway maple (*Acer platanoides* L.), silver birch (*Betula pendula* Roth), and small-leaved lime (*Tilia cordata* Mill.), and to check a hypothesis that species with different physiological properties and life strategy respond to climate warming differently.

Material and Methods

Phenological and Climate Data

The data used for this study are long-term (1956-2009) phenological observations in Vytautas Magnus University botanical garden, Lithuania. The botanical garden (latitude 54º5'N, longitude 23º5'E, altitude 84 m) occupies an area of 62.5 ha and is located in suburbs of Kaunas city, far from intensive traffic, industry, and high concentrations of multi-story houses.

Three deciduous tree species, were chosen for analysis: silver birch (*Betula pendula* Roth), small-leaved lime (*Tilia cordata* Mill.), and Norway maple (*Acer platanoides* L.). These species were selected according to their contrasting physiological properties and life strategies. Silver birch is an early season pioneer (r strategist) species. In contrast, small-leaved lime and Norway maple are later leaf flushing species (late-season) and are considered stress tolerators (K strategist) species that are able to survive under changing environments with fewer changes in seasonal development [21]. The observation size was 12 individuals of *B. pendula*, 10 individuals of *T. cordata,* and 9 individuals of *A. platanoides*.

Leaf unfolding is considered to be an indicator for the beginning of the growing season and the end of leaf fall indicates the end of the growing season. The difference (number of days) between the end and the beginning of the growing season is defined as the length of the growing season. Phenological observations were performed according to standard procedures described in the Methodological Guidelines for Phenological Observation [22]. The observations were made with binoculars twice a week. The number of observation years is presented in Table 2.

Monthly temperature and precipitation data were obtained from Kaunas Meteorological Station (Lithuanian Hydrometeorological Service under the Ministry of the Environment), located 3.6 km from the botanical garden (latitude 54º9'N, longitude 23º8'E, altitude 76 m). Meteorological observations were started considerably earlier (1892) than observations of tree phenology. Taking into account that temperature and precipitation are considered the main indicators of climate, and essential temporal fluctuations are characteristic of time-series of these indicators (Figs. 1, 2), changes in these indicators were analyzed for the entire 118-year period in order to generate more reliable results on their changes.

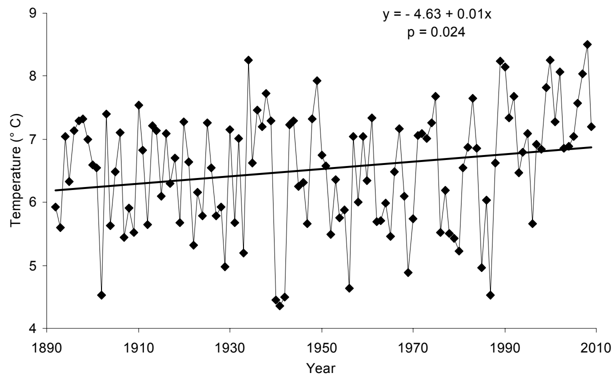

Fig. 1. Linear trend of mean air temperature in Kaunas region.

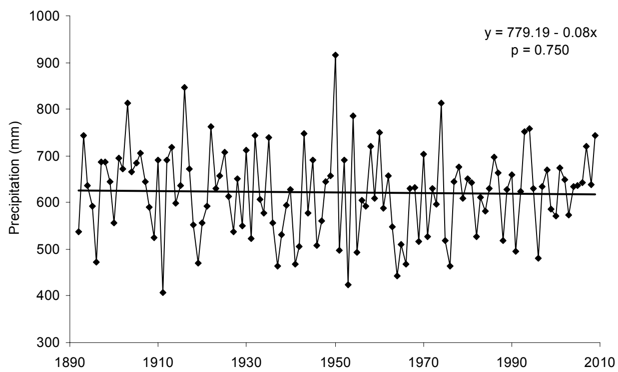

Fig. 2. Linear trend of annual precipitation in Kaunas region.

Table 1. Change of mean monthly temperature and precipitation for the period 1956-2009 (significant slopes (p<0.05) are marked in bold).

Month	Temperature (ºC)			Trend of temperature		Precipitation (mm)			Trend of precipitation	
	1956	2009	Change	Slope	p	1956	2009	Change	Slope	p
January	-5.37	-2,37	+3.00	0.058	0.103	**29.4**	**52.4**	**23.0**	**0.431**	**0.014**
February	-5.09	-2.21	+2.88	0.053	0.138	25.5	35.6	10.1	0.191	0.163
March	**-1.94**	**1.33**	**+3.27**	**0.062**	**0.010**	**26.9**	**44.6**	**17.7**	**0.337**	**0.049**
April	**5.13**	**7.75**	**+2.62**	**0.048**	**0.001**	41.1	38.1	-3.0	-0.056	0.825
May	12.00	12.77	+0.77	0.014	0.326	50.7	50.4	-0.3	0.001	0.995
June	16.33	16.28	-0.05	0.001	0.922	68.2	66.5	-1.7	-0.033	0.908
July	16.50	18.09	+1.59	0.030	0.052	76.9	76.7	-0.2	-0.003	0.992
August	**15.80**	**17.69**	**+1.89**	**0.036**	**0.004**	92.1	68.5	-23.6	-0.445	0.255
September	**11.34**	**12.73**	**+1.39**	**0.026**	**0.033**	61.5	46.9	-14.6	-0.278	0.247
October	6.93	7.36	+0.43	0.007	0.550	47.3	64.3	17	0.323	0.325
November	2.17	2.03	-0.14	-0.003	0.883	51.9	47.2	-4.7	-0.086	0.658
December	-2.98	-1.37	+1.61	0.030	0.248	40.1	46.9	6.8	0.125	0.389

Table 2. Shifts in timing for the occurrence of investigated phenophases, 1956-2009.

Phenophase	Species	Years of observations	Occurrence of phenophase, days from the beginning of year		Date shift, number of days		
			1956	2009	Number of days	Slope	p
Leaf unfolding	*Acer platanoides*	47	141	131	-9.5	-0.156	0.014
	Betula pendula	48	118	103	-14.3	-0.267	0.004
	Tilia cordata	46	153	144	-9.0	- 0.180	0.015
End of leaf fall	*Acer platanoides*	47	285	301	15.9	0.299	0.000
	Betula pendula	48	315	303	-12.1	-0.232	0.016
	Tilia cordata	45	296	308	12.2	0.228	0.012

Data Analysis

For investigated phenological records (time of leaf unfolding, end of leaf fall and duration of growing season) and climate data (annual and monthly temperature and precipitation), linear trends and their significance according to F-test (p<0.05) were calculated. Dates of phenophase occurrence were transformed to day number from the beginning of each year (January 1 is day 1). The slope of the linear trend (coefficient b) is considered an indicator of change in timing of investigated phenophases. Coefficient b indicates annual shift of investigated phenophase (days per year). The negative slope indicates advancing, while the positive slope represents a delay in phenophase. The shift of phenophase during the entire investigated period is calculated as a product of coefficient b and duration of the investigated period (54 years).

In order to determine the effects of temperature on timing of the investigated phenophases, a linear regression analysis was performed against temperature T_1 (January), T_2 (February), T_3 (March), and T_4 (April) for leaf unfolding, and against T_8 (August), T_9 (September), T_{10} (October), and T_{11} (November) for leaf fall. In this case the slope of linear trend (coefficient b) indicates a shift in timing of the investigated phenophase by one degree (ºC).

Results

Trends in Air Temperature and Precipitation

Long-term temperature changes are presented in Fig. 1. From 1892 to 2009 the mean annual temperature significantly increased at a rate of 0.006ºC (p=0.024), corresponding to

Table 3. Correlation between climatic indicators (mean monthly air temperature and amount of precipitation) and timing of phenophases (significant correlations (p<0.05) are marked in bold).

Phenophase	Species	T_1*	T_2	T_3	T_4	P_1	P_2	P_3	P_4
Leaf unfolding	*Acer platanoides*	-0.22	-0.09	**-0.33**	**-0.50**	**-0.37**	0.17	-0.08	-0.07
	Betula pendula	**-0.52**	**-0.38**	**-0.56**	**-0.50**	**-0.30**	-0.08	-0.24	-0.03
	Tilia cordata	-0.22	**-0.37**	**-0.44**	**-0.60**	-0.23	-0.13	-0.20	0.03
		T_8	T_9	T_{10}	T_{11}	P_8	P_9	P_{10}	P_{11}
Leaf fall	*Acer platanoides*	0.29	**0.46**	0.21	0.12	0.05	-0.05	0.23	-0.15
	Betula pendula	0.16	-0.14	0.01	0.18	0.28	-0.16	-0.25	-0.01
	Tilia cordata	-0.22	0.29	**0.35**	0.20	-0.21	0.05	-0.26	**0.34**

*Number beside the T (temperature) and P (precipitation) are values corresponding to number of month (i.e. T_1 means temperature of January).

the total change of 0.7ºC for this period. It is necessary to note that almost all values of the last two decades are located above the linear trend line, indicating an acceleration of the warming process at the end of the investigated period.

Precipitation decreased by 9.46 mm from 1892 to 2009 (Fig. 2), i.e. 0.08 mm per year on average. But the decrease was not statistically significant (p=0.75).

For a more detailed analysis of temperature and precipitation trends, time-series of the mean monthly temperatures and precipitation were analyzed for the period of phenological observations. The most significant warming was detected for the months in late winter (January, February) and early spring (March, April), end of summer (August), and beginning of autumn (September). A statistically significant (p<0.05) slope (coefficient b in the linear regression), is characteristic of temperatures in March, April, August, and September (Table 1).

Changes in monthly precipitation follow a very irregular pattern. An increase in precipitation during the investigated period was registered for seven months and a decrease for 5 months (Table 1). Statistically significant (p<0.05) trends (increase) are characteristic only of January and March precipitation. A trend toward a decrease in precipitation in August and September should be noted as well.

It is necessary to note that increasing August and September temperatures coincided with a decrease in precipitation during these months (23.6 and 14.6 mm, respectively), resulting in unfavorable conditions for vegetation at the very end of summer and the very beginning of autumn.

Shifts in Spring and Autumn Phenophases

The data on shifts in species phenology (leaf unfolding and leaf fall) throughout the study period (1956-2009) are presented in Table 2. Statistically significant (p<0.05) changes occurred from 1956 to 2009 in investigated phenophases for all the monitored species, though changes occurred to be species specific. The most notable advancement in leaf unfolding – 14.3 days (2.7 days per decade) was characteristic of *B. pendula*. The shift in the timing of leaf unfolding for other two investigated species – *A. platanoides* and *T. cordata* was similar and advanced by 9 days (about 1.7 days per decade).

The shift in the timing of leaf fall is detected to be much more species specific than leaf unfolding. The end of leaf fall was delayed by almost 16 days for *A. platanoides* and 12.2 days for *T. cordata* (Table 2). At the same time a statistically significant advancement of leaf fall was detected for *B. pendula* and this phenophase ended 12 days earlier in 2009 than in 1956.

As a consequence of changes in spring and autumn phenology, the growing season during the 1956-2009 period was extended by 25.5 days for *A. platanoides* and 22.2 days for *T. cordata*. Taking into account advanced spring and autumn phenophases for *B. pendula*, the length of the growing season did not experience any statistically significant changes and the entire growing period shifted earlier by almost two weeks during the investigated period.

Relationship between Temperatures and Precipitation and Occurrence of Investigated Phenophases

The correlation analysis has indicated that leaf unfolding is much more closely related to climatic indicators than leaf fall (Table 3). The response in timing of both phenophases is more closely related to temperature than precipitation. Leaf unfolding for all the investigated tree species in most cases negatively correlated with March and April temperatures (p<0.05), indicating the advancement of biological spring along with the warming of spring. The occurrence of birch leaf unfolding was also significantly (p < 0.05) related to late winter temperatures (i.e. January and February).

The occurrence of the end of leaf fall was significantly positively related with March temperatures for *T. cordata*, whereas this phenophase best correlated with the September temperature for *A. platanoides* (p<0.05).

The relationship between precipitation values and timing of the investigated phenophases was much weaker and only a few significant relationships can be noted (Table 3).

A significant negative relationship was detected between January precipitation and the leaf unfolding of *A. platanoides* and *B. pendula*, indicating advanced leaf unfolding after winters with a thick snow layer. The occurrence of the end of leaf fall was significantly ($p<0.05$) related only to November precipitation for *T. cordata*. It is necessary to note that the end of birch leaf fall was neither significantly related to temperature nor precipitation.

Discussion

During 1892-2009 the mean annual temperature increased by 0.7ºC in the study region. Faster changes took place after the early 1990s and almost all values of the last two decades are located above the linear trend line indicating the acceleration of the warming process (Fig. 1). This is in accordance with the global trends as the global surface temperature of the last two decades is ranked among the warmest periods [4]. It is necessary to note that during the period of phenological observations (1956-2009) the most notable (approximately 3ºC) warming occurred in January, February, March, and April (Table 2).

Long-term data on plant phenology can provide important information regarding the response of vegetation to climate changes [8, 14, 23, 24]. Most phenological studies have documented an advance in spring phenophases and delay of biological autumn [5, 9, 25]. Our analysis performed on the basis of 54 years of phenological observations has shown an essential shift in biological spring (leaf unfolding) and biological autumn (leaf fall) of the investigated tree species.

The response of tree spring phenology to climate changes was detected to be highly species specific. The most significant advancement in leaf unfolding (2.7 days per decade) was detected for birch, which is considered an early-season pioneer species. As noted above (Table 1), the greatest temperature increase has occurred in late winter and early spring, and it could be considered a reason why leaf unfolding time of early season species advanced the most. Other authors [10, 26] have also noticed that early-season species exibit the greatest acceleration of phenological spring. A shift in leaf unfolding for other two late-season species – maple and lime – was not as prominent as in the case of birch (advancing by 1.7 days per decade).

The changes in timing of leaf fall were even more species specific. The end of leaf fall was delayed by almost 16 days (3.3 days per decade) for maple and approximately 12 days (2.7 days per decade) for lime (Table 2). A contrary pattern was detected in changes of birch autumn phenology – leaf fall tended toward earlier dates and advanced by 12 days over the study period. Earlier autumn yellowing and fall of birch leaves have also been recorded in the northern taiga [27, 28].

The analysis of correlation between temperature and occurrence of investigated phenophases has confirmed the findings of other authors regarding a significant influence of climate warming on timing of spring phenological events [2, 14, 15]. Our investigation showed that leaf unfolding of all investigated species significantly correlated with March and April temperatures ($p<0.05$). However, in the case of early season species birch, statistically significant correlation of leaf unfolding was detected even with January temperatures (Table 3). All coefficients were negative, meaning that higher temperatures in late winter and early spring promote earlier leaf unfolding. It is noteworthy that during the investigated 54 year period the temperature (namely for months in late winter and early spring) increased the most – almost 3ºC (Table 1).

While spring phenological changes significantly correlated with temperature, the correlation between leaf fall timing and temperature was detected to be much weaker. and a significant relationship was registered only in rare cases. Leaf fall of lime significantly ($p<0.05$) correlated only with September temperatures, and leaf fall of maple – with October temperatures (Table 3). As stated by F. M. Chmielewski and T. Rötzer [14], autumn phenology is a more complex process and it is impossible to explain the beginning of biological autumn only by temperature or other climatic indicators.

The influence of precipitation on timing of seasonal development was much weaker than that for temperature. A particularly weak correlation of precipitation with leaf fall was determined and these results correspond well with other authors [2, 18, 28].

According to our study, advanced phenological spring (and for most investigated species delayed phenological autumn) resulted in essential changes in the duration of the growing season. For maple and lime the mean trends in duration of the growing season indicated a lengthening of the rate of approximately 5 days per decade. Only birch did not experience any changes in the length of the growing season due to an advanced leaf fall. Similar results were obtained in the northern taiga [27, 28], but the opposite results – lengthening of birch growing season, for example was detected in western Poland [30] and it should be considered as evidence that the response of tree seasonal development to climate warming is region-specific.

In general, the extended growing season should result in acceleration of tree growth and increase productivity. However, warmer and drier summers in recent years are able to offset the expected increase in productivity of forest ecosystems [10]. Deeper investigations on relations between changes in tree seasonal development and tree growth are necessary.

Conclusions

The response of tree phenology to climate changes is species specific. The most essential advancement in phenological spring (leaf unfolding) – 14.3 days through the investigated 1956-2009 period was detected in the case of early season pioneer species – birch. The shift in leaf unfolding for two other late-season stress-tolerant species, maple and lime, was not as prominent as in the case of birch, with the advancement of 9 days through the investigated period. The changes in timing of phenological autumn were detected to be even more species specific. It was delayed by almost 16 days for maple, approximately 12 days for lime and, in contrast, advancement of leaf fall by 12 days was detected for birch.

The occurrence of leaf unfolding for the investigated tree species best correlated with spring temperatures (March and April), i.e. with temperatures of the warmest months. In the case of early season pioneer species birch, a statistically significant correlation of leaf unfolding with January temperatures was detected as well. The relationship of leaf fall timing with temperature is much weaker and in most cases statistically insignificant, indicating that timing of phenological autumn is a complex process and can't be explained only by temperature or other climatic indicators.

The changes in timing of phenological spring and autumn resulted in an important extension of the growing season for most investigated species. Through 1956-2009, the growing season for maple was extended by 25.4 and for lime by 21.5 days. Taking into account advanced spring and autumn phenophases for birch, the length of the growing season of this species did not experience any statistically significant changes and the entire growing period advanced by almost two weeks during the investigated period.

The investigation of the relations between the extended growing season and tree growth rate would be valuable for the assessment of possible influences of current changes in tree seasonal development on forest productivity.

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