

EARLIER SPRING BUDBURST IN OKLAHOMA DECIDUOUS TREES: A
SIXTEEN-YEAR LONGITUDINAL STUDY

Stanley A. Rice
Professor Emeritus
Department of Biological Sciences
Southeastern Oklahoma State University
Durant OK 74701

Mailing address:
P. O. Box 702722
Tulsa OK 74170-2722

Key words:

Phenology
Climate change
False spring

Abstract

A sample of over 350 deciduous trees of 22 species in south central Oklahoma burst their buds about one day earlier each spring during the period 2006-2021 (n = 6,068 observations). This rate greatly exceeds that of deciduous trees and shrubs in other parts of the Northern Hemisphere. The species that opened their buds earliest each spring were the ones that showed the greatest change in budburst time. Earlier spring budburst was associated with increasing winter temperatures.

Introduction

Budburst of deciduous trees and shrubs has been occurring earlier in the spring in the Northern Hemisphere during recent decades (Parmesan 2006, Schwartz 2013), especially forests in higher latitudes (Park et al., 2015). This includes forests in North America (Schwartz, Ahas, and Aasa 2006; Miller-Rushing et al., 2006; Richardson et al., 2006; Morin et al., 2009; Schwartz et al. 2013; Primack 2014; Xie et al., 2015; Yu et al., 2016), Europe (Sparks and Carey 1995; Sparks et al., 2000; Menzel 2006; Schieber 2006; Rousi and Heinonen 2007; Menzel et al., 2008; Cole and Sheldon 2013), and Asia (Ibáñez et al. 2010, Luo et al., 2014, Kim et al. 2021). This pattern is confirmed both by satellite imagery and ground observation. Comparison of current budburst patterns with those recorded in herbarium specimens and photographs demonstrate that spring comes over a month earlier at the beginning of the twenty-first century than in the middle of the nineteenth century (Miller-Rushing et al. 2006; Primack 2014; Primack and Gallinat 2016). These studies confirm the wide consensus that global warming and related aspects of climate change are occurring at a rapid pace.

Earlier budburst dates serve as indicators of climatic warming because they integrate many environmental factors, including the sometimes wildly varying temperatures. Budburst dates do not show as much between-year variation as do weather components such as temperature.

Few studies have considered phenological changes in woody plants in southern latitudes, such as presented in this study. I evaluate the hypotheses that (1) earlier budburst has occurred in deciduous trees in south central Oklahoma over a sixteen-year period, and (2) this advance in budburst time is sometimes associated with a change in weather conditions during that period.

Methods

Selection of species and individuals

I chose 417 trees of twenty-two species of winter-deciduous trees native to Oklahoma for this study (Table 1). All the individual trees occur within the city limits of Durant, Oklahoma (34.0 N, 96.4 W, 194 m above sea level), which typically has chilly moist winters and hot dry summers. Because all the trees were in the same general location, I was able to observe each tree at least once, usually twice, a week or more during the spring months (late January to early April) for the entire sixteen years (2006-2021). Ease of access was the principal basis on which I chose species and individuals.

While I cannot be certain that all the individual trees came from local provenances, I omitted species that occur mainly as cultivars (e.g. *Pyrus calleryana*) or for which, even if they are native, there is an extensive horticultural market (e.g. *Cercis canadensis*). *Liquidambar styraciflua* is native to a portion of Oklahoma about a hundred kilometers to the east of Durant, and therefore did not come from immediately local provenances. Most individuals of *Quercus stellata* were probably a century old (based on tree ring counts of a few stumps), and some may predate the white settlement of Durant. Also, Durant appears to have an urban heat island effect (unpublished data) similar to that of Oklahoma City (Basara et al., 2010). For these reasons, the external validity of these data is limited.

By the end of the experiment, there were 353 trees, representing a 15 percent mortality. Some of the species suffered greater mortality than others. In some cases, e.g., birch (*Betula nigra*), high mortality could have resulted from population drift. Other species, such as black oak (*Quercus velutina*) and American elm (*Ulmus americana*), suffered from microbial disease. The total number of observations over the sixteen years, which includes trees that died during the study period, was 6,068. In this longitudinal study, I added no new trees to the data set during the observation period.

I observed a different number of individuals within each species. This was necessary because the most abundant trees in Durant came from a relatively few species: pecan (*Carya illinoensis*), sweetgum (*L. styraciflua*), sycamore (*Platanus occidentalis*), and especially post oak (*Q. stellata*). Durant is in the cross-timbers plant community, which post oak dominates. These four species have an outsized effect on the overall pattern of budburst timing, although all the other species (except silver maple *Acer saccharinum*) showed the same pattern of earlier budburst during the study period.

The trees also represent a range of average spring budburst times, from the earliest species (American elm) which had an average budburst date of 6 February during the study period, to the latest species (pecan) which had an average budburst date of 27 March (Table 2).

Table 1. Species and numbers of individuals used in this study.

	Species		Number of individuals, 2006	Number of individuals, 2021	Percent mortality
	All		417	353	15
1	<i>Acer saccharinum</i>	Silver maple	22	6	73
2	<i>Betula nigra</i>	River birch	2	0	100
3	<i>Carya illinoensis</i>	Pecan	85	62	27
4	<i>Carya texana</i>	Black hickory	5	2	60
5	<i>Catalpa bignonioides</i>	Catalpa	11	6	45
6	<i>Celtis laevigata</i>	Sugarberry	15	11	27
7	<i>Diospyros virginiana</i>	Persimmon	2	2	0
8	<i>Fraxinus americana</i>	White ash	8	6	25
9	<i>Juglans nigra</i>	Black walnut	3	2	33
10	<i>Liquidambar styraciflua</i>	Sweetgum	39	31	21
11	<i>Maclura pomifera</i>	Bois-d'arc	5	3	40
12	<i>Morus alba</i>	White mulberry	11	7	36
13	<i>Platanus occidentalis</i>	Sycamore	23	23	0
14	<i>Populus deltoides</i>	Cottonwood	6	5	17
15	<i>Quercus marilandica</i>	Blackjack oak	8	7	13
16	<i>Quercus muhlenbergii</i>	Chinkapin oak	6	6	0
17	<i>Quercus nigra</i>	Water oak	11	10	9
18	<i>Quercus shumardi</i>	Shumard oak	11	9	18
19	<i>Quercus stellata</i>	Post oak	125	110	12
20	<i>Quercus velutina</i>	Black oak	8	0	100
21	<i>Sideroxylon lanuginosum</i>	Chittamwood	2	2	0
22	<i>Ulmus americana</i>	American elm	10	4	60

Each year I recorded budburst dates on paper maps showing the location of each individual tree. Because most of the trees were on private property, I often had to observe them from a short distance (usually less than 3 m, always less than 20 m).

Determination of budburst date

I identified budburst as the day on which bud scales had separated enough to allow yellow or green internal tissue to be visible on at least two south-facing branches, consistent with the GLOBE protocols (GLOBE 2018) (Figure 1a-c). This protocol was necessary to avoid observational error, especially since many buds swell before opening. In post oaks, buds may begin swelling the previous autumn, and the previous year's catkins may remain on the stem, creating a false impression of early budburst. In the cottonwoods in this sample, all the branches were too high to allow a direct examination of green tissue. The cottonwood budburst date, therefore, represents the time of visible catkin emergence. This may explain why the cottonwoods, usually considered one of the earliest species to burst their buds in North America, appeared in this study to burst their buds later than several other species.

Figure 1. The appearance of newly opened buds in post oak (a), mulberry (b), and sugarberry (c).

(a)



(b)



C:



I recorded all budburst dates immediately on the paper maps and later in Excel files. Before statistical analysis, I transformed them into integer Julian dates (1 January = day 1).

Statistical analysis

I analyzed the results by ANOVA using SPSS software (IBM.com 2022). I analyzed the effects of year and species (independent variables) and their interaction on budburst date (dependent variable) for the entire data set as well as separately for each species. Each tree each year was represented by just one dependent value (budburst date). Because of repeated measures on the same trees, I analyzed budburst dates using individual as a covariate within each species. I also analyzed the effects of habitat location (two hilltop residential locations; two locations on the campus of Southeastern Oklahoma State University, on a hilltop; and Carl Albert park near Mineral Bayou). To make sure that the overall results were not influenced by a departure from a normal distribution, I also analyzed the results non-parametrically (IBM.com 2022). I compared the budburst dates in this study with those published by Rice (2003), which were based on different individuals in some of the same species used here.

Finally, I analyzed the relationship between budburst dates and climate data obtained from Mesonet, a climate data repository maintained by the Oklahoma Climatological Survey (Oklahoma Climatological Survey 2022a).

Results

Overall changes in budburst date during the study period

Table 2 presents the overall ANOVA general linear model for the entire data set (n = 6068). The independent variables are year and species, plus an interaction term. Both independent variables, and the interaction, were highly significant. The interaction indicates that the budburst dates of different species responded differently over the years.

Table 2. ANOVA of the effects of year, species, and their interaction on budburst Julian date.

Source	df	MS	F	p
Year	15	7147.0	172.9	<0.001
Species	21	39372.0	952.5	<0.001
Year x Species	307	673.5	16.3	<0.001
Error	5724	41.3		
Total	6067			

Non-parametric analysis of the whole data set confirmed the significance of year and species. Budburst date and year remained significantly correlated (Spearman rank correlation $p < 0.001$).

Table 3 presents average budburst dates, regression coefficients (days per year), F ratios, sample sizes, and significance values for the overall regression analysis and for each species separately. Negative coefficients indicate earlier budburst. All but four species showed significantly earlier budburst over the study period. Three (persimmon, mulberry, and cottonwood) showed no significant change, and silver maple budburst occurred later over the sixteen-year period. Spearman's rank correlation (ρ) is presented for comparison to the parametric regressions. The results of the non-parametric analyses were in most cases very similar to those of the linear regressions.

Table 3

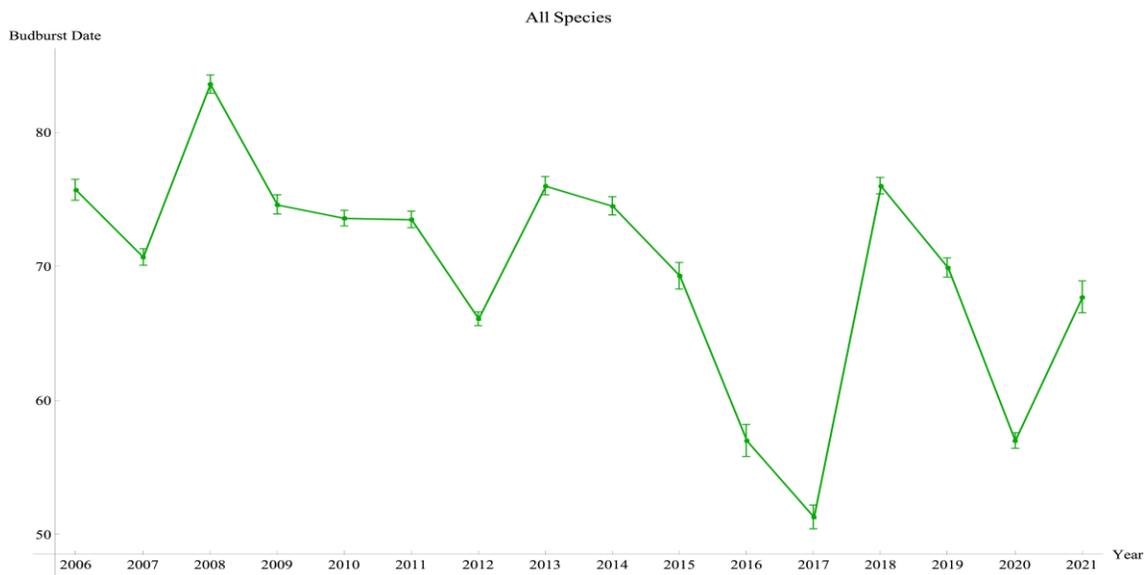
Species	Coefficient	r ²	n	F	p	ρ , Spearman Rank Correlation	Average budburst date (Julian date)
All	-0.994	0.072	6068	469.2	<0.001	<0.001	11 Mar (70.2)
<i>Acer saccharinum</i>	0.608	0.121	203	27.7	<0.001	<0.001	10 Feb (41.1)
<i>Betula nigra</i>	-2.180	0.417	16	10.0	0.007	0.009	20 Mar (78.9)
<i>Carya illinoensis</i>	-0.852	0.180	1297	284.3	<0.001	<0.001	27 Mar (86.1)
<i>Carya texana</i>	-2.570	0.519	55	57.2	<0.001	<0.001	16 Mar (75.4)
<i>Catalpa bignonioides</i>	-0.571	0.084	136	12.3	0.001	0.008	22 Mar (80.8)
<i>Celtis laevigata</i>	-0.398	0.044	200	9.1	0.003	0.003	17 Mar (76.3)
<i>Diospyros virginiana</i>	-0.415	0.087	32	2.9	0.101 ns	0.099 ns	27 Mar (85.6)
<i>Fraxinus americana</i>	-0.481	0.057	115	6.8	0.010	0.099 ns	24 Mar (83.4)
<i>Juglans nigra</i>	-1.295	0.252	38	12.2	<0.001	0.001	20 Mar (78.7)
<i>Liquidambar styraciflua</i>	-2.357	0.587	569	804.8	<0.001	<0.001	24 Feb (55.1)

<i>Maclura pomifera</i>	-0.741	0.127	62	8.8	0.004	0.003	21 Mar (80.0)
<i>Morus alba</i>	-0.327	0.022	154	3.4	0.068 ns	0.458 ns	10 Mar (69.0)
<i>Platanus occidentalis</i>	-1.109	0.195	368	88.4	<0.001	<0.001	15 Mar (74.3)
<i>Populus deltoides</i>	-0.237	0.027	88	2.4	0.123 ns	0.439 ns	16 Mar (74.6)
<i>Quercus marilandica</i>	-2.405	0.521	122	130.5	<0.001	<0.001	27 Feb (57.5)
<i>Quercus muhlenbergi</i>	-1.022	0.190	96	22.0	<0.001	<0.001	11 Mar (70.0)
<i>Quercus nigra</i>	-2.745	0.646	166	297.2	<0.001	<0.001	1 Mar (59.9)
<i>Quercus shumardi</i>	-0.904	0.121	161	21.9	<0.001	0.001	12 Mar (70.6)
<i>Quercus stellata</i>	-1.228	0.163	1958	381.9	<0.001	<0.001	8 Mar (67.0)
<i>Quercus velutina</i>	-2.013	0.386	83	51.0	<0.001	<0.001	2 Mar (60.6)
<i>Sideroxylon lanuginosum</i>	-0.614	0.129	32	4.4	0.044	0.168 ns	12 Mar (71.2)
<i>Ulmus americana</i>	-0.787	0.200	116	28.5	<0.001	<0.001	6 Feb (37.7)

The overall regression coefficient (-0.994) showed that these trees opened their buds about one day earlier per year. The average budburst dates ranged from 6 February for elms to 27 March for pecans. Because the samples (each species each year) are skewed, the numerical values of the coefficients should be read with some caution. I make no claims about the regression coefficients of each species. Nor do I claim that a linear regression is better than a quadratic regression for any of the species.

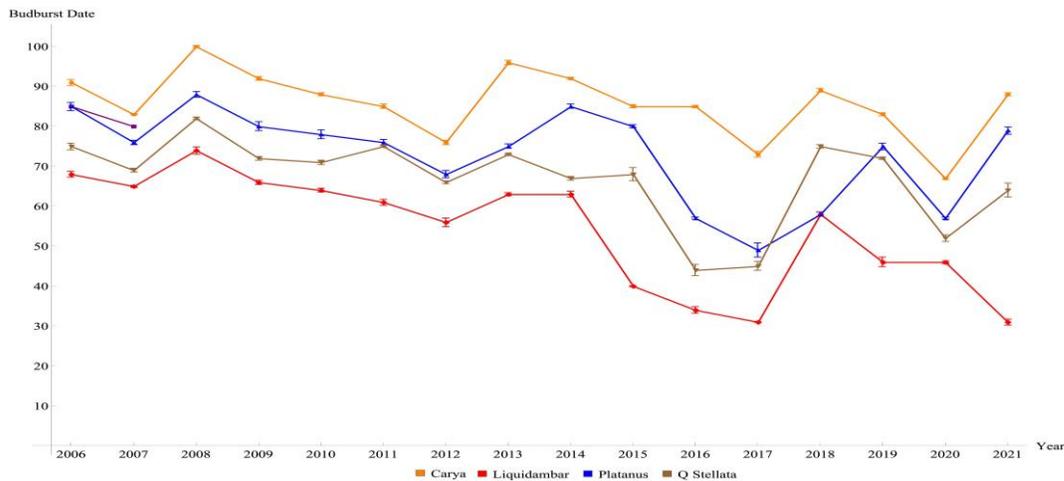
Despite large between-year differences, earlier budburst is evident (Figure 2).

Figure 2. Budburst Julian dates for all species collectively (means and standard error).



The four species with the greatest number of observations also had significantly earlier budburst over the study period (Figure 3).

Figure 3. Means and standard errors in Julian budburst date for the four most common species: pecan (orange), sycamore (blue), post oak (brown), and sweetgum (red) over the study period.



All four species show significantly earlier budburst. The 2021 results, in which budburst times in Figure 3 diverged, were due to a nationally famous cold snap in February (discussed below). All the sweetgums had opened during the warm temperatures before the cold snap, resulting in a very early average budburst date; all the sycamores and pecans, and some of the post oaks, opened after the cold snap, resulting in a later budburst date than in most previous years.

Calculation of earlier budburst by different methods

The correlation coefficients for sweetgum, blackjack oak, and water oak (about 2 ½ days per year) at first appeared impossible and I suspected they may be a statistical artifact. I therefore calculated the change in budburst from 2006 to 2021 in two different ways (Table 4). In the first, I used the predicted values for 2006 and 2021 from the linear regression. In the second, I compared the average budburst dates in 2006-2008 (the first three years of the study) with those in 2019-2021 (the last three years) from the raw data. In both cases, the same general trend emerges. Species with high mortality (silver maple, birch, black hickory, black oak, and elm) were not included in this table. I include the

budburst dates from Rice (2003), based on a different set of trees, to indicate that the trend toward earlier budburst had begun prior to the 2006-2021 period.

Table 4. Julian budburst dates calculated by regression and by comparison of means, and a comparison with budburst dates from before the beginning of this study period.

Species	Average budburst date in 2002 (Rice 2003)	Predicted budburst dates from regression equations (this study)		Earlier budburst from regression equations	Observed average budburst dates (this study)		Earlier budburst from averages (this study)
		2006	2021		2006-2008	2019-2021	
All species		20 Mar	2 Mar	18 days	20 Mar	6 Mar	14 days
<i>C. illinoensis</i>	10 Apr	3 Apr	21 Mar	12 days	2 Apr	19 Mar	14 days
<i>C. bignonioides</i>		26 Mar	17 Mar	9 days	25 Mar	18 Mar	7 days
<i>C. laevigata</i>	9 Apr	20 Mar	14 Mar	6 days	19 Mar	12 Mar	7 days
<i>D. virginiana</i>		31 Mar	24 Mar	7 days	30 Mar	24 Mar	6 days
<i>F. americana</i>	27 Mar	26 Mar	19 Mar	7 days	27 Mar	17 Mar	10 days
<i>J. nigra</i>	31 Mar	26 Mar	7 Mar	19 days	28 Mar	14 Mar	14 days
<i>L. styraciflua</i>	2 Mar	12 Mar	6 Feb	35 days	9 Mar	10 Feb	28 days
<i>M. pomifera</i>	8 Apr	25 Mar	13 Mar	12 days	24 March	16 Mar	8 days
<i>M. alba</i>		11 Mar	6 Mar	5 days	14 Mar	13 Mar	1 day
<i>P. occidentalis</i>	17 Mar	22 Mar	6 Mar	16 days	23 Mar	10 Mar	13 days
<i>P. deltoides</i>	13 Mar	16 Mar	12 Mar	4 days	17 Mar	13 Mar	4 days
<i>Q. marilandica</i>	17 Mar	16 Mar	9 Feb	36 days	10 Mar	9 Feb	29 days
<i>Q. muehlenbergi</i>	17 Mar	17 Mar	1 Mar	16 days	18 Mar	7 Mar	11 days
<i>Q. nigra</i>	24 Mar	20 Mar	7 Feb	42 days	16 Mar	12 Feb	33 days
<i>Q. shumardi</i>		18 Mar	4 Mar	14 days	17 Mar	4 Mar	13 days
<i>Q. stellata</i>	19 Mar	17 Mar	27 Feb	19 days	15 Mar	2 Mar	13 days
<i>S. lanuginosum</i>		15 Mar	6 Mar	9 days	17 Mar	8 Mar	9 days

Early and earlier: Relationship of budburst date to rapidity of earlier budburst

Three species (sweetgum, blackjack oak, and water oak) opened their buds much earlier, and also showed the greatest shift in budburst date, over the study period (last columns of Tables 3 and 4). There is a significant correlation between budburst date and rate of change in budburst date, but the regression is not valid, since it represents two separate groups of species (sweetgum, blackjack oak, and water oak, vs. all the others). Within neither of these groups was the regression significant. These results are, however, consistent with the pattern that species that open their buds early also shifted their budburst time the most.

Other factors that influence timing of budburst

Because of repeated observations on the same individuals, I analyzed general linear models for each species separately, this time using the individual tree as a covariate. While in many cases the covariate was significant, its influence was always small. For example, in the four tree species with the largest number of individuals, individual sycamores and post oaks had significantly different budburst times, but not in pecans or sweetgums (Table 5).

The individuals within these four species grew in six different locations. In each of the four species, the location had a significant effect on budburst time. In particular, trees on the hilltop burst their buds earlier than trees along the creek. The significant location x year interaction in three of the species indicated that the locations with earliest budburst depended on the year.

Table 5. Separate analyses of effects of year, individual, location, and interaction for each of the four most abundant tree species.

Species	p, year	p, individual	p, location	p, location x year interaction
Pecan	<0.001	0.930	<0.001	<0.001
Sweetgum	<0.001	0.115	0.023	0.036
Sycamore	<0.001	0.002	<0.001	<0.001
Post oak	<0.001	<0.001	<0.001	<0.001

Effect of temperature and moisture on budburst dates

I obtained monthly weather summaries from the Oklahoma Meteorological Survey (Oklahoma Climatological Survey 2021a). Monthly average air temperatures, precipitation, and four-inch soil temperatures are available throughout the study period. I used data from the Durant substation, which is about 10 km south of the study area. Because these data were not measured at the exact locations of each tree, and to avoid repeated use of the dependent variable (budburst date), only a general analysis (using species and monthly averages) is possible.

I analyzed the effects of the following independent variables on average budburst date for the four major species (pecan, sweetgum, sycamore, and post oak). I analyzed average air temperatures for January, February, March, and the average for these months. I analyzed

average four-inch soil temperatures under sod for the same periods. I analyzed total precipitation during the months of September, October, December, January, February, and March preceding and during each year. Each of these analyses therefore had 64 data points (16 years, 4 species). I present a summary of the results in Table 6.

Table 6. F and parametric significance values, and Spearman’s rank correlation significance, between budburst date and each of the variables listed above.

Independent variable	F	Parametric p	Spearman ρ
Average air temperature			
January	1.904	0.049	0.070
February	1.941	0.045	0.070
March	1.911	0.052	0.013
3 months	1.947	0.047	0.105
Average soil temperature			
January	1.926	0.046	0.063
February	1.920	0.047	0.005
March	1.543	0.131	0.027
3 months	1.904	0.049	0.041
Precipitation, 6 months	1.784	0.066	0.080

These results suggest that the years with earlier budburst were also the years with warmer winter temperatures. Most of the parametric correlations are significant, the rest are marginally significant except for March average soil temperature. Spearman’s rank correlation gave similar results, though most of these correlations are only marginally significant. Air temperatures directly affect bud activity, while soil temperatures may affect the rise of sap. Greater fall and winter precipitation may also cause earlier budburst, though the evidence for this is only marginally significant.

Changes in temperature and moisture during the study period

The Oklahoma Meteorological Survey has analyzed temperature and moisture trends since 1895 (Oklahoma Climatological Survey 2021b). I obtained graphs for January and February temperatures and precipitation for the south central region of Oklahoma. Winter temperatures have increased during the study period, with the exception of the anomalous cold February of 2021. Winter precipitation has also increased during the study period.

The long duration of this longitudinal study included four periods of El Niño Southern Oscillation, which caused warm temperatures in south central Oklahoma: 2006-2007, 2009-2010, 2014-2016, and 2018-2019 (National Weather Service Climate Prediction Center 2021). El Niño cycles can strongly influence budburst dates (McCabe et al., 2012). Overall earlier budburst occurred despite these El Niño cycles.

Discussion

A broad consensus in the scientific community is that global climate change is causing numerous biological and ecological effects on the world, including earlier phenological events in plants (Linkosalo et al. 2009; Polgar and Primack 2011). Earlier budburst is confirmed both in wild plant species and by indicator species such as genetic clones of lilac (Schwartz 1994). Messinck's (2017) study on Oklahoma post and blackjack oak indicates that budburst is influenced by temperature and moisture, as well as photoperiod and branch position. The results of the current study are consistent with all other multi-species phenological studies.

The trees in this study opened their buds, on average, a day earlier per year. This rate exceeds that reported in other studies. These results suggest that climate change is occurring more rapidly in regions such as south-central Oklahoma than in the northern continents as a whole. Zhao and Schwartz (2003) found that southern Wisconsin plant species exhibited more phenological advancement than did northern Wisconsin species. It is possible, therefore, that budburst dates in southern forests such as those in south central Oklahoma have become earlier more than northern forests.

It is obvious that the rapid change in budburst dates observed in this study could not have occurred indefinitely into the past, nor can they continue into the future. Warmer winters may delay spring budburst if the buds do not experience adequate chilling to break dormancy (Nanninga et al. 2017; Fu et al. 2015; Schwartz and Hanes 2010; Rice and Ross 2013). Most notably, *Liquidambar styraciflua* was also the species that responded most to experimental warming in Gunderson et al. (2012). Rice and Ross (2013) showed that pecans benefited from four weeks, and sycamore from two weeks, of chilling after they had begun their autumn dormancy, using some of the same trees as the current study. This raises the possibility that shorter and warmer winters in south-central Oklahoma might favor the growth of sweetgum, which can make full use of the warmer temperatures, relative to that of pecan, the budburst of which might even be delayed by lack of adequate winter chilling. Budburst timing can be influenced by the amount of winter precipitation (Fu et al. 2014), which might be very important in south central Oklahoma where winters are frequently dry. Trees that open their buds later in the spring may have a photoperiod requirement in addition to a chilling requirement (Basler and

Körner 2012, Ye et al. 2020, Wang et al. 2020). This may place an upper limit on how much earlier some species such as pecan can burst their buds regardless of how much springtime warming may occur.

The tree species that consistently open their buds the earliest also tend to be ecological opportunists that grow rapidly and have less rigorous physiological control of budburst (Caffara and Donnelly 2011). It is therefore possible that the increasing temperatures associated with global climate change may favor the increased dominance of opportunistic species over others (Polgar, Gallinat, and Primack 2014). In this study, opportunistic species sweetgum, blackjack oak, and water oak showed the greatest change in budburst time, but other ecological opportunists in this study, such as sugarberry, did not.

Two of the tree species with the earliest budburst at the beginning of the study suffered greatly from drought and disease. Almost all the silver maples (*A. saccharinum*) included in the sample in 2006 died during the drought and heat wave of summer 2012, while Dutch elm disease claimed most of the *U. americana* in the sample. This attrition effect did not, however, affect the overall conclusion of this analysis, since the elimination of the earliest budburst values would, if anything, cause an underestimate of budburst response to earlier spring temperatures.

One of the dangers posed by climatic warming is false springs resulting from a deep freeze after the initiation of budburst. I observed dramatic bud death followed by secondary refoliation not in this study area but in a band of post oak forest just south of Henryetta (35.4 N, 96.0 W). After the February 2021 freeze that reached -27 C near Henryetta, budburst in thousands of post oaks produced chlorotic, defective leaves which were evident for several weeks. Refoliation produced functional green leaves in nearly all of these trees by early summer. The possible loss of acorn and/or photosynthate production remains unstudied. A false spring may severely impact primary productivity the following season and possibly alter the balance of tree species dominance (Hufkens et al., 2012). Climate change has resulted in the increased risk of false-spring freezing damage (Marino et al. 2011; Augspurger 2013).

The floristic origins of the species may also affect budburst times. Rice (2003) found that species in families of Arcto-Tertiary origin opened their buds earlier than those in families of Neotropical origin. In Rice (2003), species in families of Arcto-Tertiary origin had an average budburst date of March 7, while the species in families of Neotropical origin had an average budburst date of March 17. However, with only five species in families of Neotropical origin (*Catalpa*, *Diospyros*, *Maclura*, *Morus*, and *Sideroxylon*), it is not valid to claim significance for this effect in the present set of data. Moreover, based

on the phylogenetic effect, the six oak species in this study might be considered one, not six, examples of earlier budburst (Webb et al. 2002).

Budburst dates almost always have non-normal distributions. When the weather becomes warm or wet enough, many buds in a population open early, with late stragglers. Occasionally, budburst dates can have a bimodal distribution. The most pronounced example of this was the nationally famous freeze of 9 Feb to 20 Feb 2021, when temperatures dipped as low as -22 C in Durant. All of the sweetgum trees had already opened their buds by 4 Feb. The sycamores had not yet begun to open their buds. Among the post oaks, 28% had burst their buds by 4 Feb, and the remaining 72% resumed budburst on 22 Feb. A similar, though less extreme, bimodal pattern occurred in 2018. Because of this departure from normality, I used both parametric and non-parametric analyses, both of which indicate earlier budburst in most of these tree species from 2006 to 2021. Budburst dates from Rice (2003) addressed a different hypothesis but suggest that budburst dates had been getting earlier before the beginning of the current study (Table 4).

The results of this sixteen-year longitudinal study suggest that earlier budburst, coincident with global warming, may occur very rapidly, especially in the seldom-studied lower-latitude deciduous forests.

Acknowledgements

The author wishes to thank Christopher Moretti for preparing the graphs, and Carol Augspurger, Mark Schwartz, and Richard Primack for helpful discussion.

References

Augspurger, Carol K. 2013. Reconstructing patterns of temperature, phenology, and frost damage over 124 years: Spring damage risk is increasing. *Ecology* 94: 41-50.

Basara, Jeffrey B., Heather G. Basara, Bradley G. Illston, and Kenneth C. Crawford. The impact of the urban heat island during an intense heat wave in Oklahoma City. *Advances in Meteorology* Volume 2010, Article ID 230365, 10 pages doi:10.1155/2010/230365.

Basler, David, and Christian Körner 2012. Photoperiod sensitivity of bud burst in 14 temperate forest tree species. *Agricultural and Forest Meteorology* 165: 73-81.

Caffarra, Amelia, and Alison Donnelly 2011. The ecological significance of phenology in four different tree species: effects of light and temperature on bud burst. *International Journal of Biometeorology* 55: 711-721.

Cole, Ella F., and Ben C. Sheldon 2017. The shifting phenological landscape: Within- and between-species variation in leaf emergence in a mixed-deciduous woodland. *Ecology and Evolution* 7: 1,135-1,147.

Fu, Yongshuo H., et al. 2014. Unexpected role of winter precipitation in determining heat requirement for spring vegetation green-up at northern, middle, and high latitudes. *Global Change Biology* 20: 3,743-3,755.

Fu, Yongshuo H., et al. 2015. Declining global warming effects on the phenology of spring leaf unfolding. *Nature* 526: 104-107.

GLOBE Program. Tree and shrub green-up. Available online. URL: <https://www.globe.gov/get-trained/protocol-ettraining/etraining-modules/16867717/3099387>. Accessed November 8, 2022.

Gunderson, Carla A., Nelson T. Edwards, Ashley V. Walker, Keiran H. O'Hara, Christina M. Campion, and Paul J. Hanson 2012. Forest phenology and a warmer climate—growing season extension in relation to climatic provenance. *Global Change Biology* 18: 2,008-2,025.

Hufkens, Koen, Mark A. Friedl, Trevor F. Keenan, Oliver Sonnentag, Amey Bailey, John O'Keefe, and Andrew D. Richardson. Ecological impacts of a widespread frost event following early spring leaf-out. *Global Change Biology* 18: 2,365-2,377.

Ibáñez, Inés, Richard B. Primack, Abraham J. Miller-Rushing, Elizabeth Ellwood, Hiroyoshi Higuchi, Sang Don Lee, Hiromi Kobori, and John A. Silander 2010. Forecasting phenology under global warming. *Philosophical Transactions of the Royal Society B* 365: 3,247-3,260.

IBM.com 2022. IBM SPSS Advanced Statistics 28. Available online. URL: https://www.ibm.com/docs/en/SSLVMB_28.0.0/pdf/IBM_SPSS_Advanced_Statistics.pdf. Accessed October 20, 2022.

Kim, Jongho, Sujong Jeong, Chang-Eui Park, Hoonyoung Park, Sungwon Son, and Sang Yong Kim 2021. Regional and species variations in spring and autumn phenology of 25 temperate species in South Korea. *Asia-Pacific Journal of Atmospheric Science*. <https://doi.org/10.1007/s13143-021-00247-0>.

Linkosalo, Tapio, Risto Häkkinen, Juhani Terhivuo, Heikki Tuomenvirta, and Pertti Hari 2009. The time series of flowering and leaf bud burst of boreal trees (1846-2005) support the direct temperature observations of climatic warming. *Agricultural and Forest Meteorology* 149: 453-461.

Luo, Xiangzhong, Xiaoqiu Chen, Lingzhiao Wang, Lin Xu, and Youhua Tian 2014. Modeling and predicting spring land surface phenology of the deciduous broadleaf forest in northern China. *Agricultural and Forest Meteorology* 198: 33-41.

- Marino, Garret P., Dale P. Kaiser, Lianhong Gu, and Daniel M. Ricciuto 2011. Reconstruction of false spring occurrences over the southeastern United states, 1901-2007: an increasing risk of spring freeze damage? *Environmental Research Letters* 6: 024015. Available online. URL: <https://iopscience.iop.org/article/10.1088/1748-9326/6/2/024015/meta>. Accessed November 8, 2022.
- McCabe, Gregory J., Toby R. Ault, Benjamin I. Cook, Julio L. Betancourt, and Mark D. Schwartz 2012. Influences of the El Nino Southern Oscillation and the Pacific Decadal Oscillation on the timing of the North American spring. *International Journal of Climatology* 32: 2,301-2,310.
- Menzel, Annette, et al. 2006. European phenological response to climate change matches the warming pattern. *Global Change Biology* 12: 1,969-1,976.
- Menzel, A., Estrella, N., and Fabian, P. 2008. Spatial and temporal variability of the phenological seasons in Germany from 1951 to 1996. *Global Change Biology* 7: 657-666.
- Messinck, Jennifer 2017. Buds, Leaves, Shoots, and Flowers: Analysis of Plant Phenology Across an Environmental Gradient. Ph.D. dissertation, University of Oklahoma. Available at <https://shareok.org/handle/11244/50746>.
- Miller-Rushing, Abraham J., Richard B. Primack, Daniel Primack, and Sharda Mukunda 2006. Photographs and herbarium specimens as tools to document phenological changes in response to global warming. *American Journal of Botany* 93: 1,667-1,674.
- Morin, Xavier, Martin J. Lechowicz, Carol Augspurger, John O'Keefe, David Viner, and Isabel Chiune 2009. Leaf phenology in 22 North American tree species during the 21st century. *Global Change Biology* 15: 961-975.
- Nanninga, Claudia, Chris R. Buyarski, Andrew M. Pretorius, and Rebecca A. Montgomery 2017. Increased exposure to chilling advances the time to budburst in North American tree species. *Tree Physiology* 37: 1,727-1,738. Available online. URL: <https://academic.oup.com/treephys/article/37/12/1727/4583663?login=true>. Accessed November 8, 2022.
- National Weather Service Climate Prediction Center 2021. Cold & Warm Episodes by Season. Available online. URL: https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php. Accessed November 8, 2022.
- Oklahoma Climatological Survey 2022a. Station monthly summaries. Available online: http://www.mesonet.org/index.php/weather/station_monthly_summaries. Accessed November 8, 2022.

Oklahoma Climatological Survey 2022b. Oklahoma climate: Long-term averages and extremes. Available online. URL: <https://climate.ok.gov/index.php/climate>. Accessed November 8, 2022.

Park, Hoonyoung, Su-JongJeong, Chang-HoiHo, Jinwon Kim, Molly E.Brown, and Michael E.Schaepman 2015. Nonlinear response of vegetation green-up to local temperature variations in temperate and boreal forests in the Northern Hemisphere. *Remote Sensing of Environment* 165: 100-108.

Parmesan, Camille 2006. Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology, Evolution, and Systematics* 37: 637-669.

Polgar, Caroline A., and Richard B. Primack 2011. Leaf-out phenology of temperate woody plants: From trees to ecosystems. *New Phytologist*. doi: 10.1111/j.1469-8137.2011.03803.x.

Polgar, Caroline A., Amanda Gallinat, and Richard B. Primack 2014. Drivers of leaf-out phenology and their implications for species invasions: insights from Thoreau's Concord. *New Phytologist* 202: 106-115.

Primack, Richard B. 2014. *Walden Warming: Climate Change Comes to Thoreau's Woods*. University of Chicago Press.

Primack, Richard B., and Amanda S. Gallinat 2016. Spring budburst in a changing climate. *American Scientist* 104: 102-109.

Rice, Stanley A., 2003. South with the Spring: A story of evolution and tree buds. *National Center for Science Education Reports* 23: 27-32.

Rice, Stanley A., and Sonya L. Ross 2014. Oklahoma deciduous trees differ in chilling enhancement of budburst. *Oklahoma Native Plant Record* 14: 43-49.

Richardson, Andrew D., Amey Schenck Bailey, Ellen G. Denny, C. Wayne Martin, and John O'Keefe 2006. Phenology of a northern hardwood forest canopy. *Global Change Biology* 12: 1,174-1,188.

Rousi, Matti and Jaakko Heinonen 2007. Temperature sum accumulation effects on within-population variation and long-term trends in date of bud burst of European white birch (*Betula pendula*). *Tree Physiology* 27: 1,019-1,025.

Schieber, B. 2006. Spring phenology of European beech (*Fagus sylvatica* L.) in a submountain beech stand with different stocking in 1995–2004. *Journal of Forest Science* 52: 208-216.

Schwartz, Mark D. 1994. Monitoring global change with phenology: The case of the spring green wave. *International Journal of Biometeorology* 38: 18-22.

Schwartz, Mark D., ed. 2013. *Phenology: An Integrative Environmental Science*. Springer.

Schwartz, Mark D., Ahas, Rhein, and Aasa, Anto 2006. Onset of spring starting earlier across the Northern Hemisphere. *Global Change Biology* 12: 343-351.

Schwartz, Mark D., Toby R. Ault, and Julio L. Betancourt 2013. Spring onset variations and trends in the continental United States: past and regional assessment using temperature-based indices. *International Journal of Climatology* 33: 2,917-2,922.

Schwartz, Mark D., and Jonathan M. Hanes 2010. Continental-scale phenology: warming and chilling. *International Journal of Climatology* 30: 1,595-1,598.

Sparks, T. H., and Carey, P. D. 1995. The responses of species to climate over two centuries: An analysis of the Marsham phenological record, 1936-1947. *Journal of Ecology* 83: 321-329.

Sparks, T. H., E. P. Jeffree, and C. E. Jeffree 2000. An examination of the relationship between flowering times and temperature at the national scale using long-term phenological records from the UK. *International Journal of Meteorology* 44: 82-87.

Wang, Huanjiong, Hui Wang, Quansheng Ge, and Junhu Dai 2020. The interactive effects of chilling, photoperiod, and forcing temperature on flowering phenology of temperate woody plants. *Frontiers in Plant Science* 16. Available online. URL: <https://www.frontiersin.org/articles/10.3389/fpls.2020.00443/full>. Accessed November 8, 2022.

Webb, Campbell O., David D. Ackerly, Mark A. McPeck, and Michael J. Donoghue 2002. Phylogenies and community ecology. *Annual Review of Ecology and Systematics* 33: 475-505.

Xie, Yingying, Kazi F. Ahmed, Jenica M. Allen, Adam M. Wilson, and John A. Silander 2015. Green-up of deciduous forest communities of northeastern North America in response to climate variation and climate change. *Landscape Ecology* 30: 109-123.

Ye, Hua-Lin, Qun-Ying Jin, Peng Hua-Zheng, Tang-Jun Zhu, Jian-Jun Shen, Guo-shuai Huang, and Min Wang 2020. A novel sunshine duration-based photothermal time model interprets the photosensitivity of flower maturity of pecan cultivars. *International Journal of Biometeorology* 64: 17-27.

Yu, Rong, Mark D. Schwartz, Alison Donnelly, and Liang Liang 2016. An observation-based progression modeling approach to spring and autumn deciduous tree phenology. *International Journal of Biometeorology* 60: 335-349.

Zhao, Tingting, and Mark D. Schwartz 2003. Examining the onset of spring in Wisconsin. *Climate Research* 24: 59-70.