

Predicting changes in temperate forest budburst using continental-scale observations and models

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[1] A new framework for understanding the macro-scale variations in spring phenology is developed by using new data from the USA National Phenology Network. Changes in spring budburst for the United States are predicted by using Coupled Model Intercomparison Project phase 5 outputs. Macro-scale budburst simulations for the coming century indicate that projected warming leads to earlier budburst by up to 17 days. The latitudinal gradient of budburst becomes less pronounced due to spatially varying sensitivity of budburst to climate change, even in the most conservative emissions scenarios. Currently existing interspecies differences in budburst date are predicted to become smaller, indicating the potential for secondary impacts at the ecosystem level. We expect that these climate-driven changes in phenology will have large effects on the carbon budget of U.S. forests and these controls should be included in dynamic global vegetation models.

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1. Introduction

[2] Accurate prediction of changes in spring budburst in response to climate change is critical for predicting changes in ecosystem dynamics and feedbacks to climate [Piao *et al.*, 2007; Penuelas *et al.*, 2009]. Various schemes for representing temperate tree spring phenology have been developed [Chuine 2000; Arora and Boer, 2005; Jeong *et al.*, 2012]. Several of these spring phenology schemes have been embedded in Dynamic Global Vegetation Models (DGVMs) and atmospheric global climate models (GCMs) [Krinner *et al.*, 2005; Lawrence *et al.*, 2011]. Improvements to phenology schemes have been shown to contribute to more reliable simulations of atmosphere-biosphere interactions [Levis and Bonan, 2004; Jeong *et al.*, 2009].

[3] Recent model-data inter-comparison studies have shown that there exist large biases in predictions of spring budburst, indicating that further improvements in spring phenology schemes are needed [Richardson *et al.*, 2012]. Previous process-based phenology schemes have been primarily

developed from local observations from a single site and/or species. Although local models are generally able to predict spring budburst in other regions with similar climate [Chuine *et al.*, 2000], large biases occur when they are applied to different climatic regions [Chiang and Brown, 2007]. To address this problem, satellite-retrieved vegetation indices have been used to develop regional and global phenology models [Botta *et al.*, 2000]. Although satellite-based phenology indices can capture large-scale features of phenology, they exhibit large uncertainties associated with limited spatio-temporal resolution and difficulty in reconstructing species-specific phenology [Fisher *et al.*, 2006]. In particular, the uncertainties in species selection can have large implications for predictions of terrestrial carbon and water budgets [Jeong *et al.*, 2012; Migliavacca *et al.*, 2012].

[4] In this paper, our overall objective is to evaluate macro-scale variations in spring phenology in current climate and to develop predictions of changes in springtime phenology under future climates. We present a new, macro-scale framework for predicting changes in spring budburst over the continental United States (Figure S1 in Supporting Information). Whereas previous budburst models have relied entirely on observations from a single locale for parameterization [Morin *et al.*, 2009], the model developed in this paper capitalizes on observations from a new nationwide phenology monitoring network, the USA National Phenology Network (USA-NPN), that engages federal agencies, environmental networks and field stations, educational institutions, and citizen scientists [USA-NPN, 2010; Schwartz *et al.*, 2012]. After developing the model, we use it to generate future predictions driven by four climate scenarios (the representative concentration pathways or RCPs) of the Coupled Model Intercomparison Project phase 5 (CMIP5) [Taylor *et al.*, 2012]. These RCPs will be highlighted in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5). Use of these state-of-the-science climate forcings enables us to at least partially quantify budburst uncertainties owing to uncertainties in future emissions and the climate variability and change.

2. Methods

[5] We used budburst data from the USA National Phenology Network (USA-NPN). Observations are available for 2009–2010 across the United States. This data set allows, for the first time, the evaluation of large-scale features of species-specific phenology over North America. The date of leaf budburst in USA-NPN is characterized by the phenophase definition of leaves emerging. According to this definition, budburst is said to occur when emerging leaves are visible in at least three locations on a particular plant. The resulting data spanned over 196 sites across the continental United States. To apply LSB into USA-NPN sites, the model requires

All Supporting Information may be found in the online version of this article.

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location-specific temperature information. For each of the USA-NPN sites, we selected the nearest station of the National Climatic Data Center (NCDC; <http://www.ncdc.noaa.gov>), which was generally within 5 km. Because the NCDC data do not include daily average temperature, we estimated T by averaging the daily maximum and minimum temperatures.

[6] Our initial modeling approach used a Local Species-specific Budburst (LSB) model developed using Harvard Forest observations (equation 1) [Jeong et al., 2012]. The LSB model assumes that chill days reduce the growing degree day (GDD) requirement, and predicts that budburst occurs when

$$\text{GDD}(t) \geq a + b \exp[c \text{NCD}(t)]. \quad (1)$$

Here, t is day of the year and a , b , and c are species-specific parameters inferred from Harvard Forest observations (Table S1 and Jeong et al. [2012]). GDD (t) is defined by

$$\text{GDD}(t) = \sum_{\text{Jan } 1}^t \max(T - 5^{\circ}\text{C}, 0), \quad (2)$$

and $\text{NCD}(t)$ is defined as the number of chilling days (any day with daily mean temperature less than 5°C constitutes a chilling day) since January 1. The mean daily temperature is T .

[7] To address biases in the LSB (see section 3 below), we developed a new Macro-scale Species-specific Budburst (MSB) model for budburst date whereby equation 1 was replaced by

$$\text{GDD}(t) \geq a + b \exp[c \text{NCD}(t)] + d(T_{\text{Jan-Feb}} + 5.5^{\circ}\text{C}). \quad (3)$$

[8] $T_{\text{Jan-Feb}}$ represents daily mean temperature averaged over all January and February days for a specific location. The offset of 5.5°C is the $T_{\text{Jan-Feb}}$ at Harvard Forest and is included here so that equation 3 would reduce to equation 1 at Harvard Forest. The (species-specific) values of the constant d were obtained by minimizing model RMS errors with respect to data from all USA-NPN stations in 2009 (Table S1). The 2010 data were not used to calculate d and were instead used for model evaluation. The d term can be thought of as a correction to the a parameter based on winter temperature.

[9] After model development and evaluation, we predicted the future changes in spring phenology by using the newly developed budburst model (equation 3) forced by daily mean temperatures derived from seven coupled global climate models (CGCMs) and Earth system models (ESMs) in CMIP5 (Table S2). Because the CMIP5 models do not exactly reproduce the observed climate at each grid cell, future changes were taken to be relative to each model's historical climate. Prior to 2006, the budburst model was driven with CMIP5's historical simulations (there are seven of these, one for each CMIP5 model). After 2006, the budburst model was driven with each of 28 different possible forcings: four representative concentration pathways (RCPs) times seven CMIP5 models. For a given RCP, the temperature predictions of different CMIP5 models are not identical because of different representations of physics, dynamics, and biogeochemical feedbacks. They therefore lead to different thermal and chilling conditions used to drive the budburst model (equation 3). For the historical simulations and for each RCP, we calculated the ensemble mean and ensemble standard deviation of the budburst date resulting from each of the seven CMIP5 models.

3. Results

3.1. Model Evaluation

[10] Figure 1 compares LSB model predictions for budburst to observations from the USA-NPN. The LSB model gives the smallest biases for *Acer saccharum* (-2.3 days in

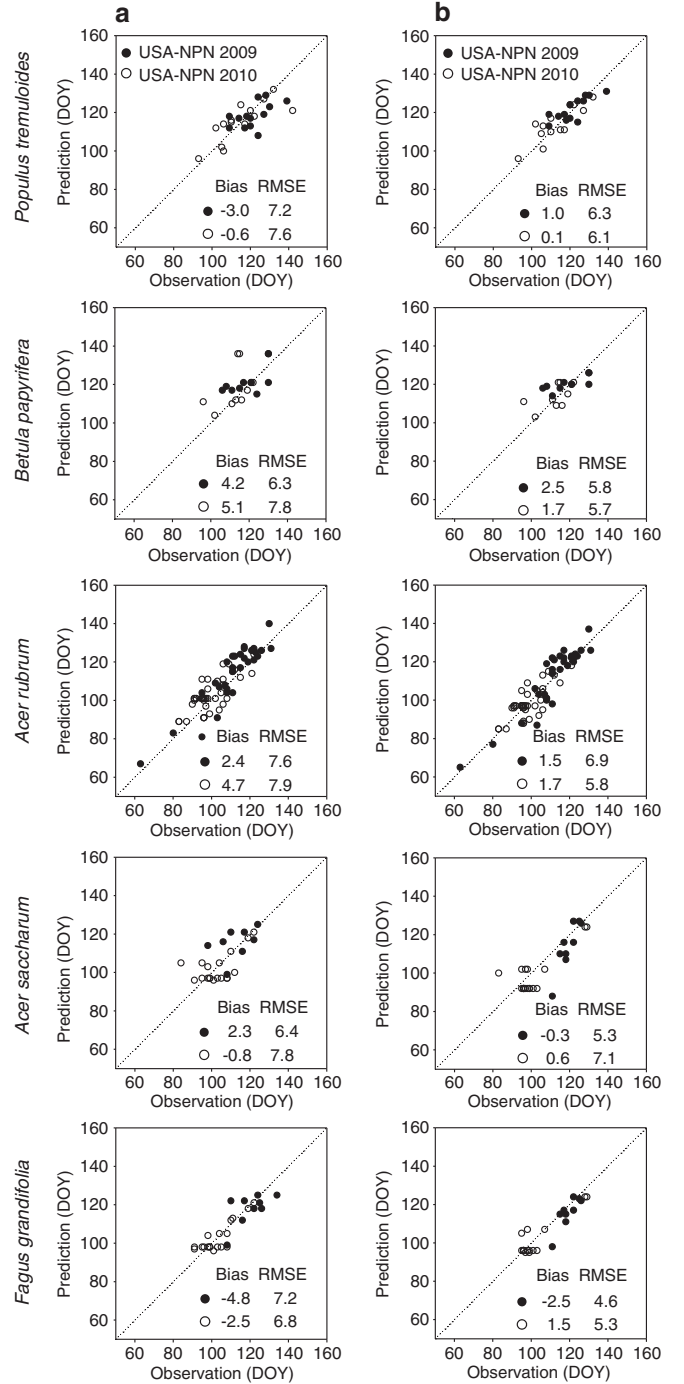


Figure 1. Comparison between observed and predicted budburst date of five deciduous tree species (*Populus tremuloides*, *Betula papyrifera*, *Acer rubrum*, *Acer saccharum*, and *Fagus grandifolia*), at each USA-NPN site in 2009 (closed circles) and 2010 (open circles): (a) predicted budburst date by LSB (local species-specific budburst) model and (b) predicted budburst date by MSB (macro-scale species-specific budburst) model.

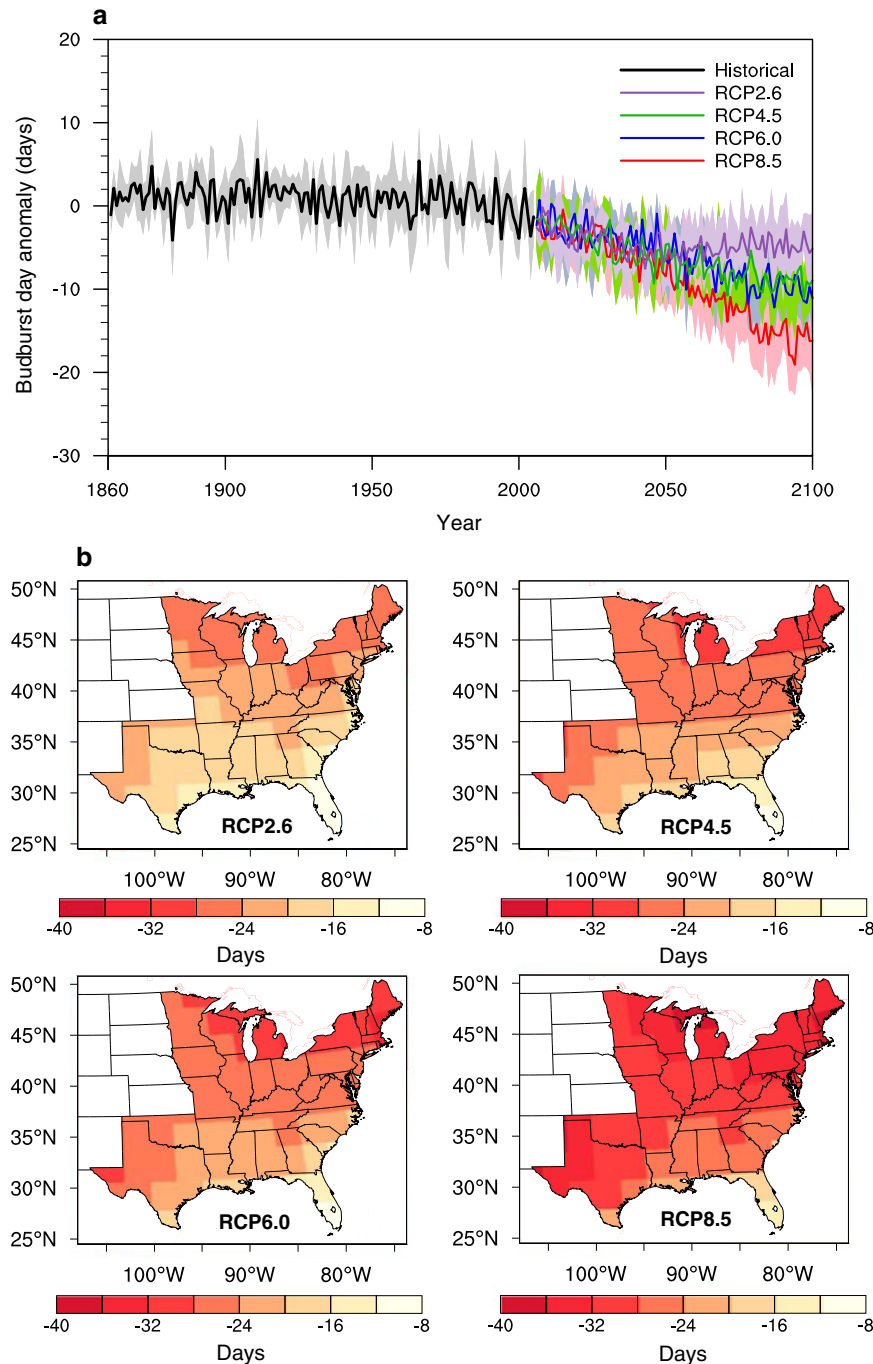


Figure 2. *Acer rubrum* (Red maple) budburst date anomalies relative to the 1980–1999 average: (a) spatially averaged budburst date anomaly for the eastern United States. The solid line in the figure indicates the ensemble mean of seven CMIP5 models, and the shading indicates the ensemble standard deviation. (b) Spatial patterns of budburst date anomaly for the 2080–2099 period. The different maps correspond to the indicated RCPs. The domain is based on the current distribution of *A. rubrum* from United States Department of Agriculture.

2009 and -0.8 days in 2010) and the largest biases for *Fagus grandifolia* (-4.2 days in 2009 and -5.2 days in 2010). We hypothesized that the biases arose because the trees at the different USA-NPN sites were adapted to a different climatology than the trees at Harvard Forest [Lechowicz, 1984]. We tested this by computing the correlation between budburst biases and (i) December, (ii) January, (iii) February, (iv) March, and (v) April monthly mean temperature

differences between individual sites and Harvard Forest, and (vi) latitude relative to Harvard Forest (Table S3). We found that winter temperatures (especially January and February) have a significant negative correlation with budburst biases, indicating that the model predicts too early of a budburst date at locations where winters are relatively warm. Compared to the LSB model (Figure 1a), the MSB model (Figure 1b) gives markedly smaller biases and RMSEs.

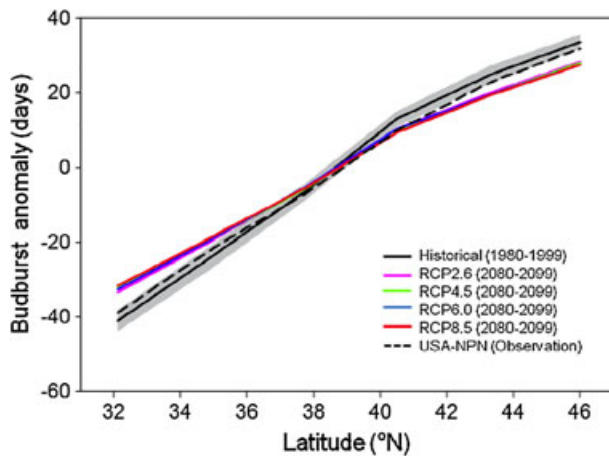


Figure 3. The spring green-wave. The budburst anomaly for each latitude band is taken with respect to the mean budburst date, defined as an equally weighted average over all latitude bands. Results are presented for the historical period (1980–1999), as well as for future (2080–2099) projections from RCP2.6, RCP4.5, RCP6.0, and RCP8.5. Gray shading indicates the ensemble standard deviation. The dashed line indicates the observed latitudinal gradient of budburst date from USA-NPN data.

[11] Our phenology model is species-specific, but many DGVMs include only one temperate broadleaf deciduous tree type (e.g., Krinner *et al.*, 2005; Lawrence *et al.*, 2012). To understand the errors that are incurred when a single phenology model is used for all species, we applied each of our five species-specific phenology models to each of the five species (Table S4). Interestingly, our results indicate that the budburst of different species may be well characterized by their successional status. Errors would remain relatively small if early successional species (*P. tremuloides* and *B. papyrifera*) were simulated with a single model and mid-to-late-successional species (*A. rubrum*, *A. saccharum*, and *F. grandifolia*) were simulated with a second model. Errors generally get much larger when an early successional species is simulated with a phenology model derived from mid-to-late-successional species, and vice-versa. These results suggest that, in terms of phenology, DGVMs and ESMs should include at least two temperate broadleaf deciduous tree types.

3.2. Budburst Predictions

[12] Figure 2 shows changes in budburst date of *A. rubrum* averaged over its current range in the eastern United States. Simulations with all RCPs result in earlier budburst (negative anomalies) during the coming century. Predicted budburst is similar for all RCPs until about 2050; however, differences are apparent by about 2080 and persist through 2100. By 2100, the largest shift toward earlier budburst occurs in RCP8.5 (16.1 days earlier relative to present), the smallest shift occurs in RCP2.6 (4.7 days earlier relative to present), and intermediate shifts occur in RCP4.5 (8.3 days earlier relative to present) and RCP6.0 (9.5 days earlier relative to present). Spatial distributions of budburst anomalies also show earlier budburst for all RCPs (Figure 2). Compared to the late 20th century, budburst becomes 8–40 days earlier by 2100. The northern parts of the United States have more pronounced changes than the southern parts of the United States, with the largest changes occurring in Maine, New York, Michigan, and Wisconsin (about –38 days in RCP8.5). The southeastern United States, including Florida, Georgia, and Alabama, show smaller changes (about –10 days in RCP8.5).

[13] The latitudinal gradient in budburst date across the United States, known as the “green-wave” [Schwartz, 1998], is shown in Figure 3 for *A. rubrum*. To illustrate the gradient, we first computed the average budburst date in each latitude band. We then carried out an equally weighted average over all latitude bands to compute a regional mean budburst. The anomalies shown in the figure are for a particular latitudinal band relative to the whole area averaged budburst. For comparing latitudinal gradient of budburst between observation and CMIP5 predictions, observed budburst dates were up-scaled to match with CMIP5 grid size. The spring green-wave is evident in observations, historical simulations, and future projections. Although the magnitude of the green-wave in the ensemble mean of the historical simulations is slightly higher than that of the observations, the differences in particular latitude bands are typically smaller than the ensemble standard deviation. This close similarity between model and observations strongly supports the use of the MSB model for evaluating future macro-scale phenology variations. Under all RCPs, we find that the spring green-wave flattens out in 2080–2099 relative to 1980–1999, suggesting the propagation speed of budburst from south to north has increased. For example, in

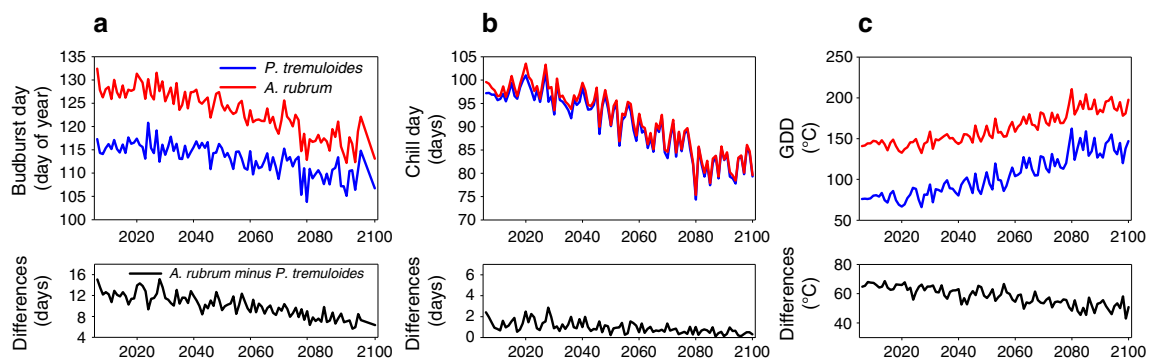


Figure 4. Comparison of changes in budburst date of *P. tremuloides* (Trembling aspen) and *A. rubrum* (Red maple) in RCP8.5: (a) changes of budburst date in each species (top) and differences in budburst date between two species (bottom). (b) Same as Figure 4a, but for chill days until budburst date. (c) Same as Figure 1a, but for growing degree days until budburst date.

the present climate normal, the spring green-wave travels from Miami to Maine in 74.7 days; however, in the future, it requires only 59.1 days. Surprisingly, we also find that the green-wave is insensitive to the choice of RCP.

[14] To evaluate how climate warming affects the budburst date of different species, we compared early and mid-successional hardwood species (*Populus tremuloides* and *Acer rubrum*, respectively) in RCP8.5 (Figure 4). Although budburst date has been shifted earlier in both species, the differences in their budburst dates have decreased with time. During the late 21st century, the interspecies differences in budburst date are reduced to only 4 days, indicating the potential impact of spring phenology at the population level. This result is primarily driven by changes in thermal forcing, suggesting that warming will contribute to differential changes in capacity adaptation (i.e., early budburst as an efficacious use of resources) between species experiencing the same climatic changes. We emphasize that our analysis is limited to spring budburst tree species. As a class, the budburst of spring-flowering species may exhibit greater temperature sensitivity than summer-flowering species [Menzel *et al.*, 2006].

4. Discussion and Conclusions

[15] In our model, it is not guaranteed that warmer climate will always lead to earlier budburst than cooler climate because the model includes both chill day and thermal forcing requirements. However, earlier budburst in the present study can be explained by the relatively larger impacts of changes in thermal forcing. We also expect that warming will trigger a speed-up of the spring green-wave across the continent and, surprisingly, this occurs to a similar degree in all emissions scenarios (Figure 3). Although previous studies have predicted regional changes in budburst dates, the models used in these studies were calibrated from data from a single site or a specific region [Morin *et al.*, 2009]. If we had used the LSB to predict budburst on continental scales, the predicted latitudinal gradient would have been flattened relative to the observations, as indicated by the sign of d in Table S3.

[16] Previous work has suggested that a locally calibrated phenology model can successfully simulate the variations of spring phenology over wide regions and that any remaining unexplained variance might be related to the genetic differentiation (or climatic adaptation) [Chuine *et al.*, 2000]. Consequently, genetic variation may hamper scaling of phenology models from local- to macro-scale because it necessitates the use of different model parameters for different regions. In tree transfer experiments that controlled for temperature, Perry and Wang [1960] showed that some species had earlier budburst when seedlings were of southern origin than when they were of northern origin. Like Perry and Wang [1960], our local model predicts too early of budburst at locations where winters are relatively warm (e.g., southern regions). The new parameter in MSB is consistent with the idea of genetic variations (or adaptation) of budburst, and its implementation in the MSB greatly reduces the latitude-dependence of model errors.

[17] In developing the MSB, we only focused on temperature as a driver for budburst variations. However, other factors, including photoperiod, may also have some influence on the budburst date, especially for late successional species such as *Fagus sylvatica*. However, the role of photoperiod is

somewhat controversial [Kramer, 1994; Schaber and Badeck, 2003; Korner and Basler, 2010]. For example, Heide [1993] reported that *F. sylvatica* required both a substantial period of chilling and a long photoperiod prior to budburst. However, Caffarra and Donnelly [2011] showed that *F. sylvatica* was able to flush when exposed to a short photoperiod provided that it was subject to artificial chilling treatments. Other studies showed slight or nonexistent influences of photoperiod on budburst of *F. sylvatica* [Falusi and Calamassi, 1996]. The discrepancy between studies might be attributed to the data and methods (e.g., whole tree in Falusi and Calamassi [1996] versus cut twigs in Caffarra and Donnelly [2011]).

[18] As next steps, both additional data and improvements in the model would help to improve model predictions. The spatial coverage of data is not complete, and our model may exaggerate budburst variations in regions where there are few observations. Ongoing USA-NPN data collection can help to reduce these remaining uncertainties. In addition, citizen science initiatives like USA-NPN can be complemented by other data sets collected by professional researchers. For example, we expect that data from regional and continental camera networks based on digital repeat photography [e.g., Sonnentag *et al.*, 2012] will lead to large improvements in our ability to construct realistic phenology models. Furthermore, additional mechanistic underpinning of phenology models should be developed [Arora and Boer, 2005]. We expect that this also will be made possible by ongoing USA-NPN and camera network data collection at a broad range of sites and for many species. One particularly interesting issue that may be investigated with a larger USA-NPN data set complemented by camera networks is how interspecies competition affects phenology. For example, the ability of an individual tree to compete for light may affect the way that its budburst date responds to temperature.

[19] This work is evidence that ongoing citizen efforts for monitoring phenology will play a key role in future predictions in climate and ecosystem change. Based on our new framework combining USA-NPN data and climate modeling, we conclude that regional and species diversity will exert critical controls on the large-scale spatial distributions of spring budburst changes, and these controls should be included in DGVM in order to improve their ability to predict land-atmosphere exchanges of carbon, energy, and water.

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