

Rethinking False Spring Risk

C. J. Chamberlain ^{1,2}, E. M. Wolkovich ^{1,2}, B. I. Cook ³, I. Garcia de Cortazar Atauri ⁴

June 8, 2017

Introduction

1. Introduce False Spring Concept

- (a) Plants growing in temperate environments are at risk of being exposed to late spring freezes, which can be detrimental to growth.
- (b) Individuals that leaf out before the last frost are at risk of leaf loss, damaging wood tissue, and slowed or stalled canopy development (Gu *et al.*, 2008; Hufkens *et al.*, 2012).
- (c) Therefore, temperate deciduous tree species must have plastic phenological responses in the spring in order to optimize photosynthesis and minimize frost or drought risk (Polgar & Primack, 2011).
- (d) These late spring freezing events are known as false springs. False spring events can result in highly adverse ecological and economic consequences (Knudson, 2012; Ault *et al.*, 2013).

2. Introduce Climate Change and Importance of False Spring Studies

- (a) Climate change is expected to increase damage from false spring events around the world due to earlier spring onset and greater fluctuations in temperature (Cannell & Smith, 1986; Inouye, 2008; Martin *et al.*, 2010).
- (b) Temperate forest species around the world are initiating leaf out about 4.6 days earlier per degree Celsius (Wolkovich *et al.*, 2012; Polgar *et al.*, 2014).
- (c) It is anticipated that there will be a decrease in false spring frequency overall but the magnitude of temperature variation is likely to increase, therefore amplifying the expected intensity of false spring events (Kodra *et al.*, 2011; Allstadt *et al.*, 2015).
- (d) Multiple studies have documented false spring events in recent years (Gu *et al.*, 2008; Augspurger, 2009; Knudson, 2012; Augspurger, 2013) and some have linked this to climate change (Ault *et al.*, 2013; Allstadt *et al.*, 2015; Muffler *et al.*, 2016; Xin, 2016).

- (e) Due to these reasons, it is crucial for researchers to properly evaluate the effects of false spring events on temperate forests and agricultural crops in order to make more accurate predictions on future trends.

3. Introduce Current False Spring Index Equation

- (a) Different species respond differently to late spring freezing events.
- (b) The level of damage sustained by plants from a false spring also varies across phenophases.
- (c) Various studies have assessed the risk of damage or the intensity of particular false spring events but at this time false spring studies fail to incorporate all potential factors that could affect the level of frost damage risk.
- (d) A False Spring Index (FSI) signifies the likelihood of a damage to occur from a late spring freeze.
- (e) Currently, FSI evaluates day of budburst, number of growing degree days, and day of last spring freeze through a simple equation as seen below (Marino *et al.*, 2011).

$$FSI = JulianDate(LastSpringFreeze) - JulianDate(Budburst) \quad (1)$$

- (f) False spring studies largely simplify the various ecological elements that could predict the level of plant damage from late spring freezing events.
- (g) In contrast to these simplifications, we argue that a wealth of factors greatly impacts plants' frost spring risk such that simple indices will most likely lead to inaccurate predictions and ultimately do little to advance the field.

4. State the Purpose of the Paper

- (a) In this paper we aim to highlight the complexity of factors driving a plant's false spring risk.
- (b) We outline in particular how life stage of the individual (Caffarra & Donnelly, 2011), location within a forest or canopy (Augspurger, 2013), winter chilling hours (Flynn & Wolkovich 2017?), proximity to water (Gu *et al.*, 2008), level of precipitation prior to the freezing event (Anderegg *et al.*, 2013), freeze duration/intensity, and range limits of the species (Martin *et al.*, 2010) unhinge simple metrics of false spring.
- (c) The ultimate intent is to demonstrate how an integrated view of false spring that incorporates these factors would rapidly advance progress in this field.

Defining False Spring

1. Definition and Threat

- (a) Temperate forest plants are most at risk to frost damage from episodic spring frosts (Sakai & Larcher, 1987).
- (b) Abnormally warm conditions in the late winter or early spring can cause budburst to initiate early in trees and shrubs.
- (c) Freezing temperatures following a warm spell could result in plant damage or even death (Ludlum, 1968; Mock *et al.*, 2007).
- (d) False springs are defined by two phases: rapid vegetative growth prior to a freeze and a post freeze setback (Gu *et al.*, 2008).
- (e) Freeze and thaw fluctuations can cause defoliation, xylem embolism and decreased xylem conductivity which can result in crown dieback (Gu *et al.*, 2008).
- (f) Species that are better able to phenologically track the shifts in spring advancement due to climate change are more likely to sustain damaging events such as false springs (Scheifinger *et al.*, 2003).

2. Define Chilling requirements to specify timing of damaging false spring events

- (a) Deciduousness and the evolution of two dormancy phases (i.e. endodormancy and ecodormancy) in temperate forest trees has permitted species to occupy more northern ecological niches (Samish, 1954).
- (b) Endodormancy is the period of winter when temperate trees are inhibited from growing, regardless of the outdoor environment.
- (c) Ecodormancy is the period of time when growth can occur but the external environment is not conducive to growth (e.g. too cold) (Basler & Körner, 2012).
- (d) Therefore, warm temperatures earlier in the year (i.e. in February) do not seem to affect species, most likely because trees have not yet left the endodormancy phase.
- (e) Frost damage usually occurs when there is a warmer than average March, a freezing April, and enough growing degree days between budburst and the last freeze date (Augspurger, 2013).
- (f) A damaging false spring is currently defined as having 7 or more days between budburst and the last freeze date (Equation 1) (Peterson & Abatzoglou, 2014).
- (g) The 7 day parameter exposes less resistant foliate phenophases to a false spring, thus putting the plant at a higher risk of damage.
- (h) Once budburst has initiated, buds cannot respond to cold temperatures and freeze resistance is greatly reduced (Taschler *et al.*, 2004; Lenz *et al.*, 2013; Vitasse *et al.*, 2014).
- (i) There are two types of freezes: a “hard freeze” at -2.2°C and a “soft freeze” at -1.7°C (Vavrus *et al.*, 2006; Kodra *et al.*, 2011; Augspurger, 2013).

- (j) However, the definition is still largely under debate.

3. Damage and drought

- (a) Freezing damage can occur directly via intracellular ice formation or indirectly via freezing dehydration (Pearce, 2001; Beck *et al.*, 2004; Hofmann & Bruelheide, 2015).
- (b) Intracellular ice formation often results in defoliation and increased xylem cavitation or embolism in the stem.
- (c) Freezing tolerance in plants is usually against extracellular freezing or freezing dehydration (Burke *et al.*, 1976).
- (d) Drought and desiccation within the xylem mimic the adverse effects of false spring events (Cavender-Bares *et al.*, 2015).
- (e) Dry winters typically result in new, frost-tolerant shoots due to the decreased water content and osmotic potential from the reduced number of accumulated solutes (Morin *et al.*, 2007; Hofmann & Bruelheide, 2015).
- (f) Therefore, it is hypothesized that increased bud dehydration results in increased frost hardiness (Beck *et al.*, 2007; Norgaard Nielsen & Rasmussen, 2009; Poirier *et al.*, 2010; Kathke & Bruelheide, 2011; Hofmann & Bruelheide, 2015).
- (g) However, more studies are needed to investigate the interplay between false spring events and precipitation and how that relationship impacts the level of damage a plant sustains.

Determining Spring Onset

1. Elucidate the difference between spring onset and study species

- (a) Spring forest phenology essentially progresses through successional stages: understory species, seedlings and saplings typically initiate budburst first in order to exploit open canopies and early growth, whereas late successional species may start later in the season to avoid frost or drought risk (Richardson & O’Keefe, 2009; Xin, 2016).
- (b) Therefore, habitat type plays a large role in the overall spring onset of a specific ecological region.
- (c) Pure grasslands or young forest will, overall, have earlier budburst dates than large stands of canopy trees and mixed forests may have a spring onset date somewhere between the two.
- (d) False spring studies should first assess the forest demographics and functional groups of the study species in order to effectively estimate the date of spring onset.

2. Methodologies

- (a) A suitable methodology for determining spring onset is crucial in order to establish an effective model for false spring risk, especially since the current false spring equation only uses two inputs: date of spring onset and date of last freeze (Equation 1).
- (b) If the date of spring onset is inaccurate, the level of risk determined by the current equation (Equation 1) could render erroneous results.
- (c) There are many methods available to ascertain the first day of spring.
- (d) Spring onset can be calculated through observational data, PhenoCam or remote-sensing data, or through the USA National Phenology Network's (USA-NPN) Extended Spring Index (SI-x) tool (USA-NPN, 2016).
- (e) Studies often use observation data to evaluate spring onset to target budburst more precisely, however, it can be difficult or even impossible for large-scale studies.
- (f) PhenoCam and remote-sensing data is suitable for canopy tree species, whereas USA-NPN SI-x is more applicable for understory species.
- (g) The three methodologies to determine spring onset were compared using observational data from Harvard Forest (O'Keefe, 2014), PhenoCam data from Harvard Forest (Richardson, 2015), and USA-NPN SI-x (USA-NPN, 2016) and then inputted into the FSI equation (Equation 1) to calculate FSI values from 2008 to 2014 (Figure 1).

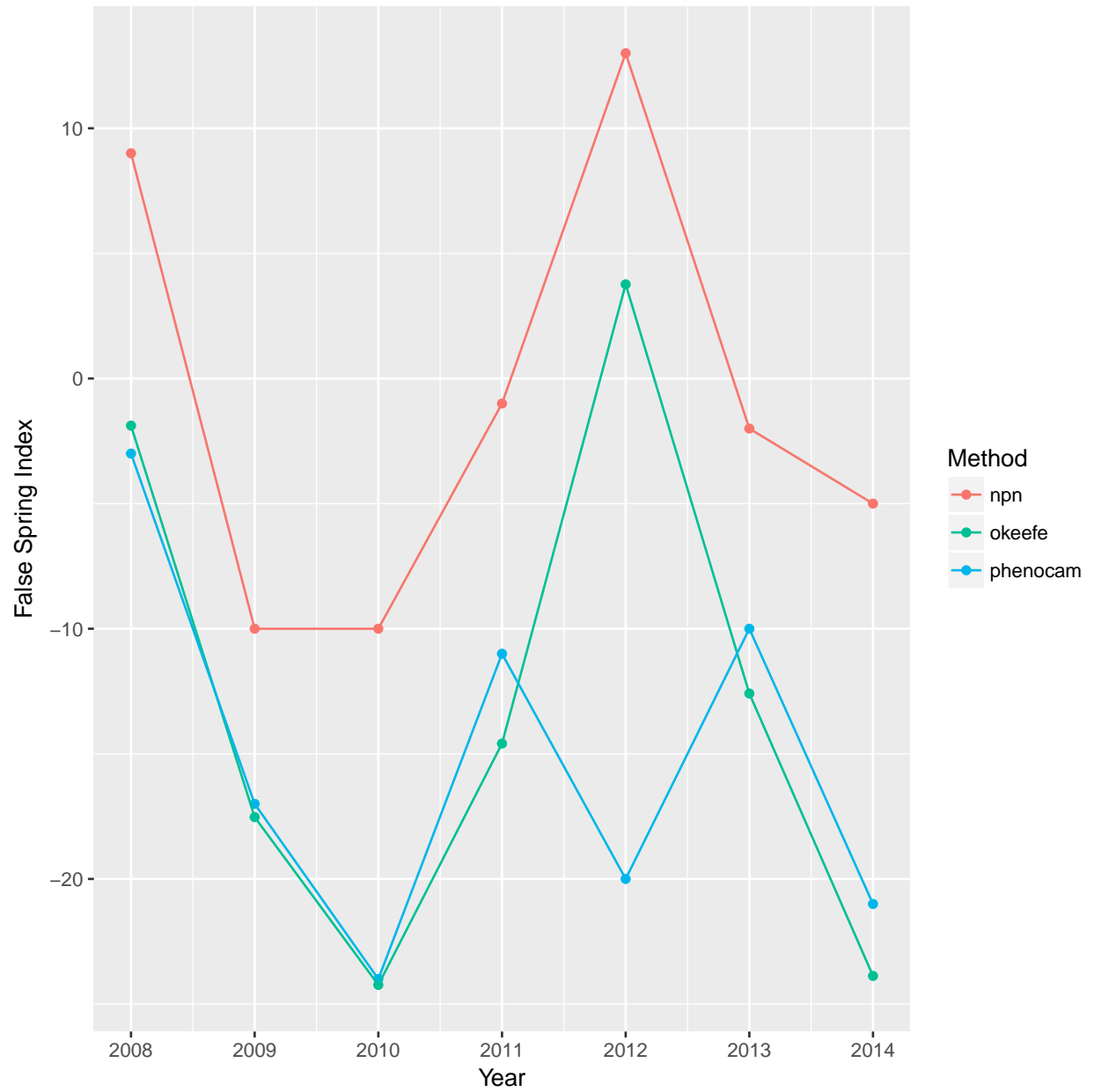


Figure 1: A scatterplot indicating FSI values from 2008 to 2014 for each methodology used in this study. PhenoCam FSI values are red, Observed FSI values are blue, and USA-NPN FSI values are green.

- (h) Observational FSI values and USA-NPN FSI values are highly comparable and are justifiable methods for determining potential false spring risk.
- (i) PhenoCam data is also comparable to the other two methods, however, it would be more useful for canopy species, which is evident from the results seen in 2012 (Figure 1).
- (j) In 2012, a false spring event was reported through many regions of the US due to warm tempera-

tures occurring in March (Ault *et al.*, 2015).

- (k) These high temperatures would most likely be too early for larger canopy species to initiate budburst but they would affect smaller understory species as is seen by the discrepancy in results for 2012 (Figure 1).
- (l) Researchers should use the USA-NPN dataset for understory species, PhenoCam or remote-sensing data for late successional species, and observational data for a wide array of plant functional types.

Defining Vegetative Risk

1. Define Vegetative Risk

- (a) Plants at certain vegetative phenophases (i.e. before full leafout of the entire plant) are more likely to sustain damage from a false spring than individuals past the leafout phenophase.
- (b) Frost tolerance steadily decreases after budburst begins until the leaf is fully unfolded, with leafout being the most susceptible to frost damage (Lenz *et al.*, 2016).
- (c) The rate of budburst and the length of time between budburst and leafout is essential for predicting level of damage from a false spring event.
- (d) We will refer to the timing of these collective phenophases (i.e. budburst to leafout) as the duration of vegetative risk.

2. Phenophases and Life Stage

- (a) Reproductive phases are generally more sensitive to false spring events than vegetative phases and developing leaves are more susceptible to damage than opening buds or expanding shoots (Augspurger, 2009; Lenz *et al.*, 2013).
- (b) However, trees that suffer severe vegetative growth damage will suffer greater long-term effects from the loss of photosynthetic tissue than trees that lose one year of reproductive growth.
- (c) Spring freezing events that occur during the vegetative growth phenophases impose the greatest freezing threat to deciduous tree and shrub species (Sakai & Larcher, 1987).
- (d) Therefore, phenophase is a crucial indicator for how much damage a plant will sustain from a freezing event.
- (e) Seedlings and saplings initiate budburst before canopy closure in order to benefit from the increased light levels (Augspurger, 2008), which puts them at greater risk to false spring damage than adult trees (Vitasse *et al.*, 2014).

- (f) Younger plants are more likely to sustain lasting damage to the leaf buds and vegetative growth, whereas adult trees are at risk of xylem embolism.
- (g) For xylem embolism to occur, extreme cavitation must first be present.
- (h) Extensive cavitation in the xylem requires more intensive freezing events than freezing events that damage seedling and sapling leaf buds.
- (i) Especially strong freezing events (i.e. $> -8.6^{\circ}\text{C}$), could result in meristematic tissue, wood parenchyma and phloem damage (Sakai & Larcher, 1987; Augspurger, 2011; Lenz *et al.*, 2013).

3. Species Differences

- (a) Different species respond differently to anthropogenic climate change.
- (b) Most species are expected to begin leafout earlier in the season with warming spring temperatures but some species may have the opposite response (Cleland *et al.*, 2006; Yu *et al.*, 2010; Xin, 2016).
- (c) Studies indicate that species growing at more northern latitudes tend to respond greater to photoperiod than species growing further south (Partanen, 2004; Vihera-aarnio *et al.*, 2006; Caffarra & Donnelly, 2011).
- (d) Similarly, late successional species exhibit greater photoperiod sensitivities than pioneer or under-story species (Basler & Körner, 2012) and they also require more chilling in the winter and greater forcing temperatures in the spring to initiate budburst (Laube *et al.*, 2013).
- (e) It is anticipated that these more opportunistic individuals that initiate budburst earlier in the spring with the shifts in climate would attempt to limit freezing risk by decreasing the duration of vegetative risk and progress to full leaf expansion faster.
- (f) The duration of vegetative risk is usually extended if a freezing event occurs during the phenophases between budburst and full leafout and species with short durations of vegetative risk often sustain higher levels of damage (Augspurger, 2009).
- (g) It is hypothesized that if the duration of vegetative risk is longer, then the buds and leaves will be heartier against frosts, however this still has yet to be tested thoroughly.
- (h) We assess the interaction between duration of vegetative risk and false spring events using two datasets: from a growth chamber chilling experiment and long-term observational data.

4. Data

- (a) Deciduous trees and shrubs require a certain number of chilling units in order to leave the endodormancy phase.

- (b) This helps protect temperate plants against stochastic warm spells in the winter so that they do not break dormancy too early in the season.
- (c) Chilling units differ across species and across habitats.
- (d) Species growing at higher latitudes are more likely to have lower chilling requirements to break dormancy (Myking & Heide, 1995; Howe *et al.*, 2003) due to the shorter growing season and selective pressure to initiate budburst as soon as temperatures are conducive to growth (Prev  y *et al.*, 2017).
- (e) With anthropogenic climate change, it is possible that certain species will have insufficient winter chilling (especially at lower latitudes) resulting in higher spring forcing requirements (McCreary *et al.*, 1990; Morin *et al.*, 2009; Fu *et al.*, 2012; Polgar *et al.*, 2014; Chuine, 2010).
- (f) Similarly, spring forcing temperature and photoperiod length requirements for budburst to occur vary among species and habitats.
- (g) This is evident through the high levels of genetic diversity for spring budburst to occur across temperate forest tree species (Chuine *et al.*, 2001).
- (h) Data from a growth chamber experiment were used to compare 9 temperate forest species between two treatments: high chilling hours, long photoperiod and high forcing temperatures (WL1) against no additional chilling, short photoperiod and low forcing temperatures (CS0) (Flynn and Wolkovich, 2017?).

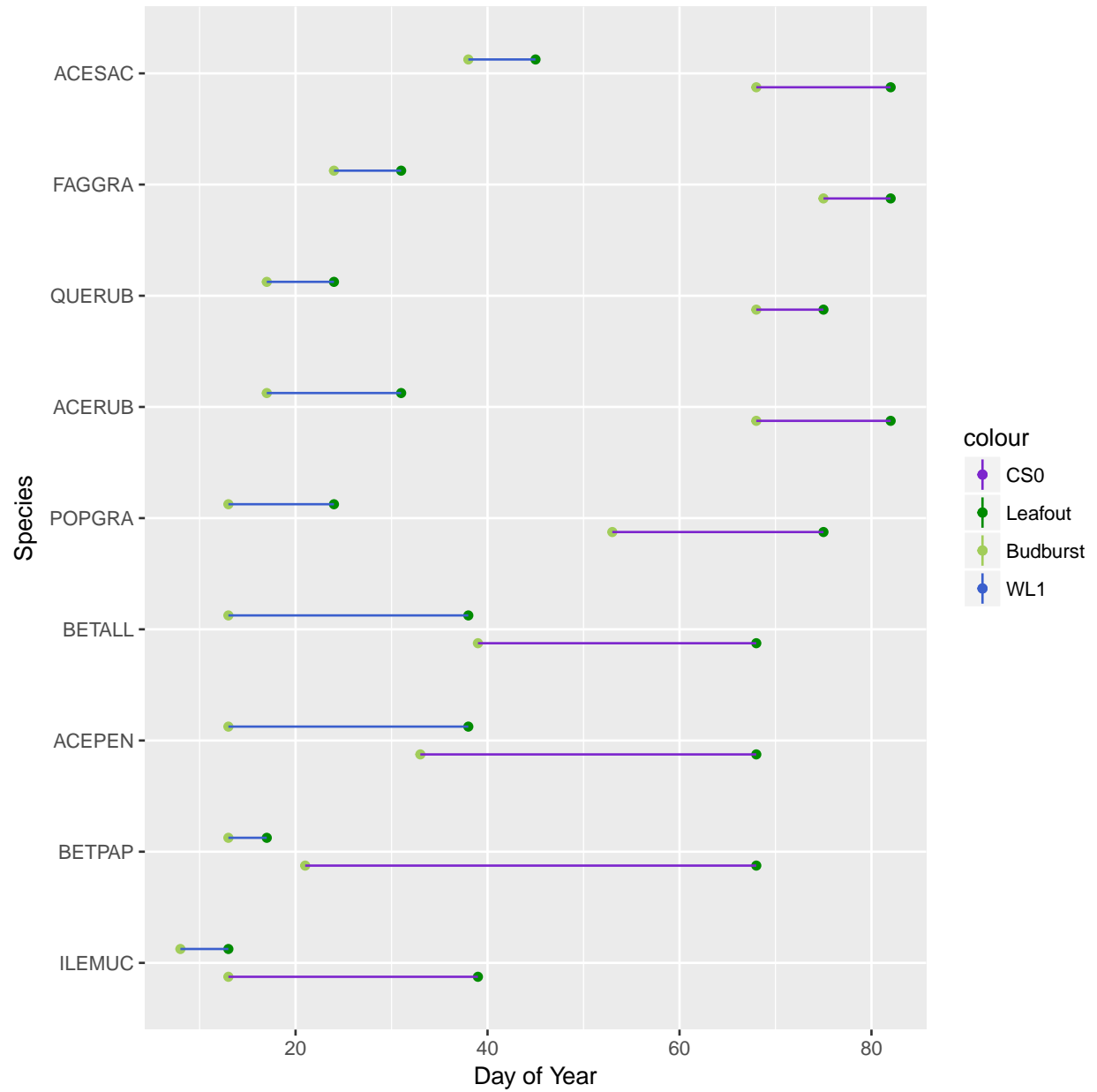


Figure 2: Day of budburst and the day of leaf out for native tree species in New England. Data was collected from a growth chamber experiment using any combination of two photoperiod treatments, two forcing treatments, and three chilling treatments. The standard deviation is represented in blue for budburst and green for leaf out.

- (i) According to the results, individuals that initiate budburst earlier in the season (i.e. *Betula papyrifera* (Marsh.) and *Ilex mucronata* (L.)) tend to begin budburst early regardless of treatment, but the treatment does affect the duration of vegetative risk significantly (Figure 2).

- (j) As the season progresses, treatment does not affect the duration of vegetation as much, however, the day of budburst tends to initiate later in the season with the weaker treatment effects (i.e. CS0).
- (k) Anova results indicate forcing temperatures and photoperiod length determine the duration of vegetative risk more than chilling requirements, which may be due to studying species within similar latitudinal range limits.
- (l) Further studies are essential to investigate the interplay between chilling, forcing, and photoperiod effects on the duration of vegetative risk, especially for species occupying habitats more susceptible to false spring events.

5. Harvard Forest Data

- (a) Forcing temperatures in the spring affect the duration of vegetative risk: years with lower forcing temperatures and fewer growing degree days will have longer durations of vegetative risk (Donnelly *et al.*, 2017).
- (b) It is therefore expected that high variation in spring temperatures may result in longer durations of vegetative risk.
- (c) Using observational data from Harvard Forest (O’Keefe, 2014), we compared two years of data: one year that had an unusually early spring onset (2010) and another year that an unusually late spring onset (2014).
- (d) By comparing the durations of vegetative risk to the average daily temperatures for each year, we found that...

References

- Allstadt, A.J., Vavrus, S.J., Heglund, P.J., Pidgeon, A.M., Wayne, E. & Radeloff, V.C. (2015) Spring plant phenology and false springs in the conterminous U. S. during the 21st century. *Environmental Research Letters (submitted)* **10**, 104008.
- Anderegg, W.R.L., Plavcová, L., Anderegg, L.D.L., Hacke, U.G., Berry, J.A. & Field, C.B. (2013) Drought’s legacy: Multiyear hydraulic deterioration underlies widespread aspen forest die-off and portends increased future risk. *Global Change Biology* **19**, 1188–1196.
- Augspurger, C.K. (2008) Early spring leaf out enhances growth and survival of saplings in a temperate deciduous forest. *Oecologia* **156**, 281–286.

- Augspurger, C.K. (2009) Spring 2007 warmth and frost: Phenology, damage and refoliation in a temperate deciduous forest. *Functional Ecology* **23**, 1031–1039.
- Augspurger, C.K. (2011) Frost damage and its cascading negative effects on *aesculus glabra*. *Plant Ecology* **212**, 1193–1203.
- Augspurger, C.K. (2013) Reconstructing patterns of temperature, phenology, and frost damage over 124 years: Spring damage risk is increasing. *Ecology* **94**, 41–50.
- Ault, T.R., Henebry, G.M., de Beurs, K.M., Schwartz, M.D., Betancourt, J.L. & Moore, D. (2013) The False Spring of 2012, Earliest in North American Record. *Eos, Transactions American Geophysical Union* **94**, 181–182.
- Ault, T.R., Zurita-Milla, R. & Schwartz, M.D. (2015) A Matlab{©} toolbox for calculating spring indices from daily meteorological data. *Computers {&} Geosciences* **83**, 46–53.
- Basler, D. & Körner, C. (2012) Photoperiod sensitivity of bud burst in 14 temperate forest tree species. *Agricultural and Forest Meteorology* **165**, 73–81.
- Beck, E.H., Fettig, S., Knake, C., Hartig, K. & Bhattarai, T. (2007) Specific and unspecific responses of plants to cold and drought stress. *Journal of Biosciences* **32**, 501–510.
- Beck, E.H., Heim, R. & Hansen, J. (2004) Plant resistance to cold stress: Mechanisms and environmental signals triggering frost hardening and dehardening. *Journal of Biosciences* **29**, 449–459.
- Burke, M., Gusta, L., Quamme, H., Weiser, C. & Li, P. (1976) Freezing and injury in plants. *Annual Review of Plant Physiology* **27**, 507–528.
- Caffarra, A. & Donnelly, A. (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.
- Cannell, M. & Smith, R. (1986) Climatic Warming , Spring Budburst and Forest Damage on Trees Author (s): M . G . R . Cannell and R . I . Smith Published by : British Ecological Society Stable URL : <http://www.jstor.org/stable/2403090> JSTOR is a not-for-profit service that helps schol. *Journal of Applied Ecology* **23**, 177–191.
- Cavender-Bares, J., González-Rodríguez, A., Eaton, D.A.R., Hipp, A.A.L., Beulke, A. & Manos, P.S. (2015) Phylogeny and biogeography of the american live oaks (*quercus subsection virentes*): a genomic and population genetics approach. *Molecular Ecology* **24**, 3668–3687.
- Chaine, I. (2010) Why does phenology drive species distribution? *Philosophical Transactions of the Royal Society B: Biological Sciences* **365**, 3149–3160.

- Chuine, I., Aitken, S.N. & Ying, C.C. (2001) Temperature thresholds of shoot elongation in provenances of *Pinus contorta*. *Canadian Journal of Forest Research* **31**, 1444–1455.
- Cleland, E., Chiariello, N., Loarie, S., Mooney, H. & Field, C. (2006) Diverse responses of phenology to global changes in a grassland ecosystem. *PNAS* **103**, 13740–13744.
- Donnelly, A., Yu, R., Caffarra, A., Hanes, J.M., Liang, L., Desai, A.R., Liu, L. & Schwartz, M.D. (2017) Interspecific and interannual variation in the duration of spring phenophases in a northern mixed forest. *Agricultural and Forest Meteorology* **243**, 55–67.
- Fu, Y.H., Campioli, M., Van Oijen, M., Deckmyn, G. & Janssens, I.A. (2012) *Bayesian comparison of six different temperature-based budburst models for four temperate tree species*, vol. 230.
- Gu, L., Hanson, P.J., Post, W.M., Kaiser, D.P., Yang, B., Nemani, R., Pallardy, S.G. & Meyers, T. (2008) The 2007 Eastern US Spring Freeze: Increased Cold Damage in a Warming World. *BioScience* **58**, 253.
- Hofmann, M. & Bruehlheide, H. (2015) Frost hardiness of tree species is independent of phenology and macro-climatic niche. *Journal of Biosciences* **40**, 147–157.
- Howe, G.T., Aitken, S.N., Neale, D.B., Jermstad, K.D., Wheeler, N.C. & Chen, T.H. (2003) From genotype to phenotype: unraveling the complexities of cold adaptation in forest trees. *Canadian Journal of Botany* **81**, 1247–1266.
- Hufkens, K., Friedl, M.A., Keenan, T.F., Sonnentag, O., Bailey, A., O’Keefe, J. & Richardson, A.D. (2012) Ecological impacts of a widespread frost event following early spring leaf-out. *Global Change Biology* **18**, 2365–2377.
- Inouye, D.W. (2008) Effects of climate change on phenology, frost damage, and floral abundance of montane wildflowers. *Ecology* **89**, 353–362.
- Kathke, S. & Bruehlheide, H. (2011) Differences in frost hardiness of two Norway spruce morphotypes growing at Mt. Brocken, Germany. *Flora - Morphology, Distribution, Functional Ecology of Plants* **206**, 120–126.
- Knudson, W. (2012) The economic impact of the spring’s weather on the fruit and vegetable sectors. *The Strategic Marketing Institute Working Paper* .
- Kodra, E., Steinhäuser, K. & Ganguly, A.R. (2011) Persisting cold extremes under 21st-century warming scenarios. *Geophysical Research Letters* **38**, 1–5.
- Laube, J., Sparks, T.H., Estrella, N., Höfler, J., Ankerst, D.P. & Menzel, A. (2013) Chilling outweighs photoperiod in preventing precocious spring development. *Global Change Biology* **20**, 170–182.

- Lenz, A., Hoch, G., Körner, C. & Vitasse, Y. (2016) Convergence of leaf-out towards minimum risk of freezing damage in temperate trees. *Functional Ecology* pp. 1–11.
- Lenz, A., Hoch, G., Vitasse, Y. & Körner, C. (2013) European deciduous trees exhibit similar safety margins against damage by spring freeze events along elevational gradients. *New Phytologist* **200**, 1166–1175.
- Ludlum, D.M. (1968) *Early American Winters: 1604-1820*. 3, American Meteorological Society.
- Marino, G.P., Kaiser, D.P., Gu, L. & Ricciuto, D.M. (2011) Reconstruction of false spring occurrences over the southeastern United States, 1901–2007: an increasing risk of spring freeze damage? *Environmental Research Letters* **6**, 24015.
- Martin, M., Gavazov, K., Körner, C., Hattenschwiler, S. & Rixen, C. (2010) Reduced early growing season freezing resistance in alpine treeline plants under elevated atmospheric CO₂. *Global Change Biology* **16**, 1057–1070.
- McCreary, D.D., Lavender, D.P. & Hermann, R.K. (1990) Predicted global warming and Douglas-fir chilling requirements. *Annales des Sciences Forestieres* **47**, 325–330.
- Mock, C.J., Mojzisek, J., McWaters, M., Chenoweth, M. & Stahle, D.W. (2007) The winter of 1827–1828 over eastern north america: a season of extraordinary climatic anomalies, societal impacts, and false spring. *Climatic Change* **83**, 87–115.
- Morin, X., Ameglio, T., Ahas, R., Kurz-Besson, C., Lanta, V., Lebourgeois, F., Miglietta, F. & Chuine, I. (2007) Variation in cold hardiness and carbohydrate concentration from dormancy induction to bud burst among provenances of three european oak species. *Tree Physiology* **27**, 817–825.
- Morin, X., Lechowicz, M.J., Augspurger, C., O’keefe, J., Viner, D. & Chuine, I. (2009) Leaf phenology in 22 North American tree species during the 21st century. *Global Change Biology* **15**, 961–975.
- Muffler, L., Beierkuhnlein, C., Aas, G., Jentsch, A., Schweiger, A.H., Zohner, C. & Kreyling, J. (2016) Distribution ranges and spring phenology explain late frost sensitivity in 170 woody plants from the northern hemisphere. *Global Ecology and Biogeography* **25**, 1061–1071.
- Myking, T. & Heide, O.M. (1995) Dormancy release and chilling requirement of buds of latitudinal ecotypes of *Betula pendula* and *B. pubescens*. *Tree Physiology* **15**, 697–704.
- Norgaard Nielsen, C.C. & Rasmussen, H.N. (2009) Frost hardening and dehardening in *Abies procera* and other conifers under differing temperature regimes and warm-spell treatments. *Forestry* **82**, 43–59.
- O’Keefe, J. (2014) Phenology of Woody Species at Harvard Forest since 1990. Tech. rep.

- Partanen, J. (2004) Dependence of photoperiodic response of growth cessation on the stage of development in *picea abies* and *betula pendula* seedlings. *Forest Ecology and Management* **188**, 137–148.
- Pearce, R. (2001) Plant freezing and damage. *Annals of Botany* **87**, 417–424.
- Peterson, A.G. & Abatzoglou, J.T. (2014) Observed changes in false springs over the contiguous United States. *Geophysical Research Letters* **41**, 2156–2162.
- Poirier, M., Lacointe, A. & Ameglio, T. (2010) A semi-physiological model of cold hardening and dehardening in walnut stem. *Tree Physiology* **30**, 1555–1569.
- Polgar, C., Gallinat, A. & Primack, R.B. (2014) Drivers of leaf-out phenology and their implications for species invasions: Insights from Thoreau’s Concord. *New Phytologist* **202**, 106–115.
- Polgar, C.A. & Primack, R.B. (2011) Leaf-out phenology of temperate woody plants: From trees to ecosystems. *New Phytologist* **191**, 926–941.
- Prevéy, J., Velland, M., Rüger, N., Hollister, R., Bjorkman, A., Myers-Smith, I., Elmendorf, S., Clark, K., Cooper, E., Elberling, B., Fosaa, A., Henry, G., Høye, T., Jónsdóttir, I., Klanderua, K., Lévesque, E., Mauritz, M., Molau, U., Natali, S., Oberbauer, S., Panchen, Z., Post, E., Rumpf, S., Schmidt, N., Schuur, E., Semechuk, P., Troxler, T., Welker, J. & Rixen, C. (2017) Greater temperature sensitivity of plant phenology at colder sites: implications for convergence across northern latitudes. *Global Change Biology* **23**, 2660–2671.
- Richardson, A. & O’Keefe, J. (2009) *Phenological differences between understory and overstory: a case study using the long-term harvard forest records*, pp. 87–117. Springer.
- Richardson, A.D. (2015) Phenocam images and canopy phenology at harvard forest since 2008.
- Sakai, A. & Larcher, W. (1987) *Frost Survival of Plants*. Springer-Verlag.
- Samish, R. (1954) Dormancy in woody plants. *Annual Review of Plant Physiology and Plant Molecular Biology* **5**, 183–204.
- Scheifinger, H., Menzel, A., Koch, E. & Peter, C. (2003) Trends of spring time frost events and phenological dates in central europe. *Theoretical and Applied Climatology* **74**, 41–51.
- Taschler, D., Beikircher, B. & Neuner, G. (2004) Frost resistance and ice nucleation in leaves of five woody timberline species measured in situ during shoot expansion. *Tree Physiology* **24**, 331–337.
- USA-NPN (2016) USA National Phenology Network Extended Spring Indices.

- Vavrus, S., Walsh, J.E., Chapman, W.L. & Portis, D. (2006) The behavior of extreme cold air outbreaks under greenhouse warming. *International Journal of Climatology* **26**, 1133–1147.
- Vihera-aarnio, A., Hakkinen, R. & Junttila, O. (2006) Critical night length for bud set and its variation in two photoperiodic ecotypes of *betula pendula*. *Tree Physiology* **26**, 1013–1018.
- Vitasse, Y., Lenz, A., Hoch, G. & Körner, C. (2014) Earlier leaf-out rather than difference in freezing resistance puts juvenile trees at greater risk of damage than adult trees. *Journal of Ecology* **102**, 981–988.
- Wolkovich, E.M., Cook, B.I., Allen, J.M., Crimmins, T.M., Betancourt, J.L., Travers, S.E., Pau, S., Regetz, J., Davies, T.J., Kraft, N.J.B., Ault, T.R., Bolmgren, K., Mazer, S.J., McCabe, G.J., McGill, B.J., Parmesan, C., Salamin, N., Schwartz, M.D. & Cleland, E.E. (2012) Warming experiments underpredict plant phenological responses to climate change. *Nature* **485**, 18–21.
- Xin, Q. (2016) A risk-benefit model to simulate vegetation spring onset in response to multi-decadal climate variability: Theoretical basis and applications from the field to the Northern Hemisphere. *Agriculture and Forest Meteorology* pp. 139–163.
- Yu, H., Luedeling, E. & Xu, J. (2010) Winter and spring warming result in delayed spring phenology on the tibetan plateau. *Proc Natl Acad Sci U S A* **107**, 22151–6.

Supplemental Information

ACEPEN	Sum.Sq	Df	F value	Pr(>F)
chilling	149.41	2	1.20	0.30
forcing	4909.59	1	78.94	0.00
photoperiod	1309.59	1	21.06	0.00
Residuals	6654.56	107		

ACERUB	Sum.Sq	Df	F value	Pr(>F)
chilling	0.62	2	0.00	1.00
forcing	1731.00	1	25.92	0.00
photoperiod	462.78	1	6.93	0.01
Residuals	6611.17	99		

ACESAC	Sum.Sq	Df	F value	Pr(>F)
chilling	65.41	2	0.46	0.64
forcing	259.14	1	3.61	0.06
photoperiod	231.41	1	3.22	0.08
Residuals	4524.88	63		

BETALL	Sum.Sq	Df	F value	Pr(>F)
chilling	525.95	2	5.00	0.01
forcing	1463.30	1	27.81	0.00
photoperiod	632.83	1	12.03	0.00
Residuals	6944.50	132		

BETPAP	Sum.Sq	Df	F value	Pr(>F)
chilling	6.00	2	0.04	0.96
forcing	1776.23	1	21.47	0.00
photoperiod	1105.08	1	13.35	0.00
Residuals	10509.00	127		

FAGGRA	Sum.Sq	Df	F value	Pr(>F)
chilling	144.41	2	1.66	0.20
forcing	611.20	1	14.04	0.00
photoperiod	1.05	1	0.02	0.88
Residuals	2829.78	65		

ILEMUC	Sum.Sq	Df	F value	Pr(>F)
chilling	26.49	2	0.54	0.59
forcing	2262.34	1	91.61	0.00
photoperiod	1035.85	1	41.94	0.00
Residuals	3334.05	135		

POPGRA	Sum.Sq	Df	F value	Pr(>F)
chilling	54.63	2	0.39	0.68
forcing	2405.73	1	34.52	0.00
photoperiod	1019.78	1	14.63	0.00
Residuals	6760.98	97		

QUERUB	Sum.Sq	Df	F value	Pr(>F)
chilling	35.61	2	0.45	0.64
forcing	680.83	1	17.34	0.00
photoperiod	369.53	1	9.41	0.00
Residuals	4946.29	126		

ACEPEN	Sum.Sq	Df	F value	Pr(>F)
chilling	104.66	2	0.87	0.42
forcing	4745.38	1	79.18	0.00
photoperiod	1306.03	1	21.79	0.00
chilling:forcing	63.31	2	0.53	0.59
chilling:photoperiod	181.96	2	1.52	0.22
forcing:photoperiod	257.63	1	4.30	0.04
Residuals	6113.18	102		

ACERUB	Sum.Sq	Df	F value	Pr(>F)
chilling	1.53	2	0.01	0.99
forcing	1721.25	1	26.13	0.00
photoperiod	381.81	1	5.80	0.02
chilling:forcing	358.58	2	2.72	0.07
chilling:photoperiod	37.69	2	0.29	0.75
forcing:photoperiod	17.35	1	0.26	0.61
Residuals	6191.98	94		

ACESAC	Sum.Sq	Df	F value	Pr(>F)
chilling	65.78	2	0.45	0.64
forcing	204.31	1	2.83	0.10
photoperiod	267.24	1	3.70	0.06
chilling:forcing	76.27	2	0.53	0.59
chilling:photoperiod	164.28	2	1.14	0.33
forcing:photoperiod	0.05	1	0.00	0.98
Residuals	4194.28	58		

BETALL	Sum.Sq	Df	F value	Pr(>F)
chilling	526.41	2	5.57	0.00
forcing	1463.33	1	30.95	0.00
photoperiod	632.83	1	13.38	0.00
chilling:forcing	66.32	2	0.70	0.50
chilling:photoperiod	226.18	2	2.39	0.10
forcing:photoperiod	612.56	1	12.95	0.00
Residuals	6005.50	127		

BETPAP	Sum.Sq	Df	F value	Pr(>F)
chilling	6.07	2	0.04	0.96
forcing	1765.57	1	21.22	0.00
photoperiod	1101.18	1	13.24	0.00
chilling:forcing	71.38	2	0.43	0.65
chilling:photoperiod	62.92	2	0.38	0.69
forcing:photoperiod	233.62	1	2.81	0.10
Residuals	10148.80	122		

FAGGRA	Sum.Sq	Df	F value	Pr(>F)
chilling	145.37	2	1.64	0.20
forcing	595.26	1	13.40	0.00
photoperiod	0.42	1	0.01	0.92
chilling:forcing	39.45	2	0.44	0.64
chilling:photoperiod	83.56	2	0.94	0.40
forcing:photoperiod	35.33	1	0.80	0.38
Residuals	2665.38	60		

ILEMUC	Sum.Sq	Df	F value	Pr(>F)
chilling	28.03	2	0.60	0.55
forcing	2277.73	1	97.37	0.00
photoperiod	1033.49	1	44.18	0.00
chilling:forcing	16.09	2	0.34	0.71
chilling:photoperiod	106.28	2	2.27	0.11
forcing:photoperiod	171.89	1	7.35	0.01
Residuals	3041.00	130		

POPGRA	Sum.Sq	Df	F value	Pr(>F)
chilling	50.56	2	0.37	0.69
forcing	2390.66	1	35.16	0.00
photoperiod	1016.39	1	14.95	0.00
chilling:forcing	45.72	2	0.34	0.72
chilling:photoperiod	152.02	2	1.12	0.33
forcing:photoperiod	296.37	1	4.36	0.04
Residuals	6254.69	92		

QUERUB	Sum.Sq	Df	F value	Pr(>F)
chilling	35.70	2	0.46	0.63
forcing	668.59	1	17.39	0.00
photoperiod	364.39	1	9.48	0.00
chilling:forcing	174.11	2	2.26	0.11
chilling:photoperiod	110.91	2	1.44	0.24
forcing:photoperiod	15.92	1	0.41	0.52
Residuals	4652.62	121		