Rethinking False Spring Risk

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1 Introduction

Plants that grow in temperate environments are at risk of being exposed to late spring freezes, which can be detrimental to plant growth. According to Gu et al. 2008, there are two phases involved in late spring freezing: rapid vegetative growth prior to the freeze and the post freeze setback. This combined process is known as a false spring. Freeze and thaw fluctuations can cause xylem embolism and decreased xylem conductivity which can result in crown dieback (Gu *et al.*, 2008). More frequently, plants that have been exposed to a false spring will experience leaf loss and slower canopy development (Hufkens *et al.*, 2012). With anthropogenic climate change, the severity of damage incurred from a false spring phenomena is predicted to be heightened due to earlier spring onset and greater fluctuations in temperatures. Temperate forest species around the world are initiating leaf out about 4.6 days earlier per degree Celsius (Polgar *et al.*, 2014; Wolkovich *et al.*, 2012). Spring frosts during the vegetative growth phases impose the greatest freezing threat to deciduous tree species (Sakai & Larcher, 1987). It is anticipated that there will be a decrease in false spring frequency overall but the severity of temperature variation is likely to increase, therefore amplifying the expected intensity of false spring events (Allstadt *et al.*, 2015). In 2012, a false spring event in Michigan resulted in half a billion dollars worth of fruit tree damage (Ault *et al.*, 2013; Knudson, 2012). Due to these reasons, it is crucial for researchers to properly evaluate the effects of false spring events on not only agricultural crops but in temperate forests as well.

Different species respond differently to late spring freezing events. The level of damage sustained by plants from a false spring also varies across phenophases. Generally, reproductive phases are more sensitive to false spring events than vegetative phases and developing leaves are more susceptible to damage than opening buds or expanding shoots (Lenz *et al.*, 2013; Augspurger, 2009) . However, trees that suffer severe vegetative growth damage from a false spring event will suffer greater long-term effects from the loss of photosynthetic tissue than trees that lose one year of reproductive growth. False spring events put seedling and sapling trees at greater risk to damage than adult trees (Vitasse *et al.*, 2014). Younger trees are more likely to incur lastly damage to the leaf buds and vegetative growth, whereas adult trees are at risk of xylem embolism. In order for xylem embolism to occur, extreme cavitation must first occur. This would require more intensive freezing events than it would take to damage seedling and sapling leaf buds. Especially strong freezing events (i.e. $>$-8.6°C), could result in meristemic tissue, wood parenchyma and phloem damage (Lenz *et al.*, 2013; Augspurger, 2011; Sakai & Larcher, 1987). In a study performed by Augspurger 2009, it was noted that some individuals of the same life stage but were exhibiting different phenophases during a freezing event suffered varying degrees of damage, indicating that phenophase is a greater indicator for level of risk than life stage. Warm temperatures earlier in the year (i.e. in February) do not seem to affect species, most likely because it is too soon for budburst to take place and sufficient chilling has not yet occurred. Frost damage usually occurs when there is a warmer than average March, a freezing April, and enough growing days between the high temperatures and the last freeze date (Augspurger, 2013). In a study performed by Peterson and Abatzoglou 2014, it had been determined that 7 days between budburst and last freeze date is a significant parameter. During this time, it was determined that leaf buds will have enough growing degree days to begin budburst but the leaves won't have reached full maturation yet. There is much debate over the definition of freezing temperatures, which has thus resulted in two types of freezes: a ”hard” freeze at -2.2°C and a ”soft” freeze at -1.7°C (Augspurger, 2013; Kodra *et al.*, 2011; Vavrus *et al.*, 2006).

At this time false spring studies fail to incorporate all potential factors that could affect the level of frost damage risk. A False Spring Index (FSI) signifies the likelihood of a damage to occur from a late spring freeze. 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).

$$FSI = JulianDate(LastSpringFreeze) - JulianDate(Budburst)$$

If FSI is a positive number and greater than 7, then crown dieback is more likely to occur. In this study, we aim to integrate a more thorough model for predicting false spring risk, which would ideally incorporate 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), and freeze duration/intensity. Another highly crucial factor to consider is the rate of budburst and the length of time between budburst through leaf out, which will we refer to as the duration of vegetative risk. Temperate trees are most susceptible to damage during leaf out and expansion (Vitasse *et al.*, 2014). We will use the BBCH Scale Phase 09 to define budburst and Phase 15 to define leaf out and leaf unfolding (Meier, 2001). In a study by Lenz et al. 2016, it was determined that elevation is not a key indicator for determining the level of risk from false springs. Likewise, wood density is also not a significant parameter (Augspurger, 2009). For these reasons, elevation and wood density will be excluded from the suggested model.

2 Climatic Implications: How climate change is affecting spring freezing events

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). In a study performed by Vitasse et al. , environmental effects (i.e. temperature) had a greater effect on seedling flushing than genetic effects. However, different species will respond differently to anthropogenic climate change. Most species are expected to begin leaf out earlier in the season with warming spring temperatures but some species may have the opposite response (Xin, 2016; Cleland *et al.*, 2006; Yu *et al.*, 2010).

Studies indicate that species growing at more northern latitudes tend to respond greater to photoperiod than species growing further south (Caffarra & Donnelly, 2011). Similarly, late successional species exhibit greater photoperiod sensitivities than pioneer species (Basler & Körner, 2012). Based on this information, we downloaded Daily Summary climate data sets from the NOAA Climate Data Online tool for two latitudinal gradients to measure frequency of false spring events at 8-10 latitudes for each transect (Menne *et al.*, 2012; Menne *et al.*). False springs were tallied by first calculating the number of Growing Degree Days (GDD) using the equation formulated by Michigan State University (Nugent, J., 2005). If there were 40 GDDs before a hard freeze occurred in the spring (-2.2°C), then a false spring occurred in that year. Each location includes 30 years of climate data and each transect fell within 3 degrees longitude. Table 1 shows the results from the European transect investigated. False spring occurrence ranged from 0 to 8 and increased southward.

Table 1: Number of False Springs along a Latitudinal Gradient in Western Europe

Station	Elevation	Latitude	Longitude	False Springs
Kempten, Germany	705m	47.724	10.336	8
Augsburg, Germany	461m	48.426	10.943	8
Bamberg, Germany	210m	49.875	10.921	7
Jena, Germany	155m	50.927	11.584	4
Hannover, Germany	55.0m	52.466	9.679	6
Bremen, Germany	4.00m	53.046	8.799	5
Hamburg, Germany	11.0m	53.635	9.99	4
Schleswig, Germany	43.0m	54.529	9.549	0
Flyvestation, Denmark	3.00m	57.093	9.849	0
Oslo, Norway	94.0m	59.943	10.721	0

Table 2 shows the results from the American transect. False spring occurrence ranged from 0 to 13 and exhibited an inverse relationship with latitude.

Table 2: Number of False Springs along a Latitudinal Gradient in North America

Station	Elevation	Latitude	Longitude	False Springs
Anthony, Kansas	415m	37.155	-98.028	13
Hastings, Nebraska	587m	40.583	-98.350	7
West Point, Nebraska	399m	41.845	-96.714	5
Yankton, South Dakota	360m	42.883	-97.350	5
Brookings, South Dakota	497m	44.325	-96.769	0
Aberdeen, South Dakota	395m	45.443	-98.413	2
Grand Forks, North Dakota	253m	47.933	-97.083	0
Pembina, North Dakota	241m	48.971	-97.242	1

Table 3 shows the results from the linear regression models performed for both transects. Latitude (1) represents the European transect and Latitude (2) is the American transect.

Table 3

	Dependent variable:	
	Latitude	
	(1)	(2)
False.Springs	-1.064^{***}	-0.801^{***}
	(0.180)	(0.148)
Constant	57.235^{***}	46.946^{***}
	(0.936)	(0.865)
Observations	10	8
R^2	0.813	0.830
Adjusted R^2	0.790	0.801
Residual Std. Error	1.743 (df = 8)	1.732 (df = 6)
F Statistic	34.885^{***} (df = 1; 8)	29.251^{***} (df = 1; 6)
Note:		*p<0.1; **p<0.05; ***p<0.01

As seen in above tables, as latitude increased the frequency of false spring events decreased. These results may indicate why species with a more northern range may have greater photoperiod sensitivities and also indicate that certain latitudes should be prioritized for future false spring studies.

3 Determining Spring Onset

Before a suitable model for determining false spring risk can be established, an appropriate determination of spring onset is crucial. There are many methods that can be used to determine first day of spring and there also many definitions. In order to test the best method for calculating spring onset (or budburst), we gathered data using three different methodologies. The first method for collecting budburst was from observational data recorded for 33 tree species by Dr. John O'Keefe at Harvard Forest from 1990 to 2014 (O'Keefe, 2014). Dr. O'Keefe defines budburst as 50% leaf emergence. We subsetted this data set down to include only the tree species that were most consistently observed, which ended up being eight species.The second data set was provided from PhenoCam data, which are field cameras, placed in Harvard Forest, take real-time images of plant growth and are programmed to record initial green up. The final set was collected through the USA National Phenology Network (USA-NPN), using their Data Visualization tool to gather Extended Spring Index values (SI-x) by accessing the "Spring Indices, Historic Annual" gridded layer and looking specifically at "First Leaf - Spring Onset" (USA-NPN, 2016a). The SI-x value is the time of leaf out was monitored from historical dates of budburst using honeysuckle and lilac clones around the U.S. and combining that information with daily recordings from local weather stations (USA-NPN, 2016b; Ault *et al.*, 2015b,a; Schwartz *et al.*, 2013; Schwartz, 1997). Through assessing past years' weather and budburst, scientists are able to determine general weather trends that subsequently lead to leaf out. Based on these trends, SI-x values can be calculated from daily weather data (USA-NPN, 2016b).

The date of last spring freeze was gathered from the Fisher Meteorological Station which was downloaded from the Harvard Forest web page (data available online[1]). The Tmin values were used and the Last Spring Freeze was determined from the latest Julian date that the temperature reached -1.7°C or below.

PhenoCam data is not available for Harvard Forest until 2008 and observation data is only recorded through 2014, so this evaluation assesses FSI values from 2008 through 2014. The FSI values were calculated for each methodology using the formula based on the study performed by Marino et al. (2011). Table 2 shows that the Observed and PhenoCam FSI values are all negative from 2008 through 2014. The FSI values from the USA-NPN are, on average, much higher in comparison to the other two methods.

A graphical representation of the FSI values compared across the three methodologies can be seen in Figure 1. In 2008 and 2012, FSI is higher than the significant parameter given of 7 for the NPN data, indicating a

[1] http://harvardforest.fas.harvard.edu/meteorological-hydrological-stations

possibly damaging false spring event. However, the PhenoCam data did not indicate a false spring in either of the two years and the FSI value for 2012 found through the observed data was not significant. The NPN data always had the highest FSI values.

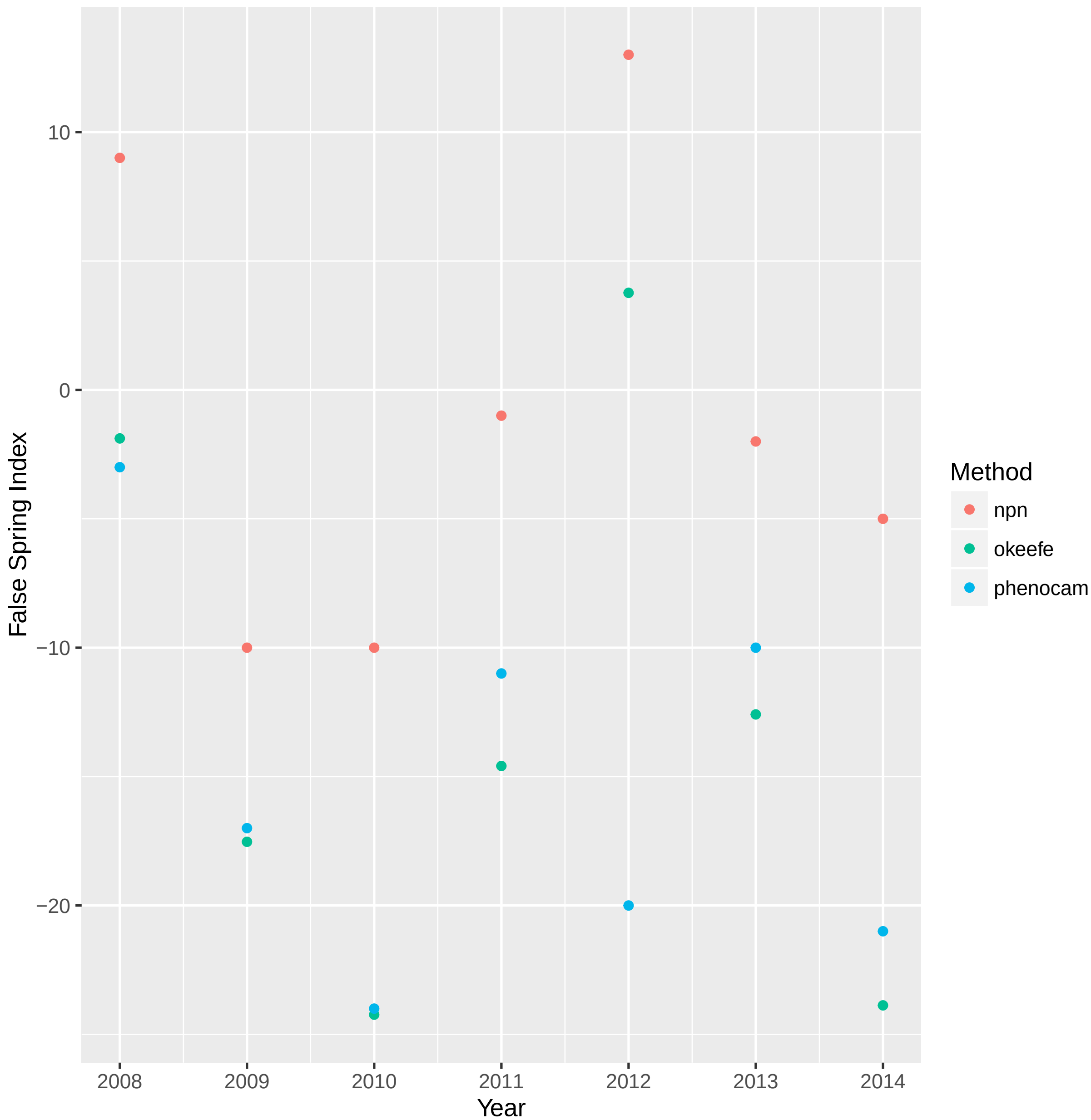

Figure 1: A scatterplot indicating FSI values from 2008 to 2014 for each methdology used in this study. PhenoCam FSI values are red, Observed FSI values are blue, and USA-NPN FSI values are green.

A Pearson Correlation was used to determine the strength of association between the three methods used in the study. As indicated in Table 1, the FSI values from the observed data and the SI-x NPN data are strongly correlated (r=0.9395), whereas the FSI values calculated using the PhenoCam data is not as strongly correlated to either the observed FSI values (r=0.4680) or the NPN FSI values (r=0.4242). Although, according to the pearson correlation, all results were similar.

Table 4: Pearson Correlation Coefficients indicating the strength of association between the FSI values calculated across all three methodologies.

	year	npn	okeefe	phenocam
year	1.00	-0.03	-0.20	-0.37
npn	-0.03	1.00	0.94	0.42
okeefe	-0.20	0.94	1.00	0.47
phenocam	-0.37	0.42	0.47	1.00

Our projections indicate that observational FSI values are highly comparable to the USA-NPN FSI values, rendering both justifiable methods for determining potential risk involved in late spring freezes. Even though budburst is defined differently between Dr. O'Keefe, USA-NPN, and the PhenoCam, the dates of budburst are similar. The spring onset dates gathered from the PhenoCam data set are different from the other two methods, which is likely due to fact that the PhenoCam data is assessing budburst for the forest canopy. Through the use of USA-NPN data, researchers could gather dates of budburst across multiple locations at once in order to determine False Spring risk, making it a more effective method than observational data. Although, all three methods are viable. Various studies have shown that understory species will initiate budburst earlier in the season 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 (Xin, 2016; Richardson & O'Keefe, 2009). So, the methodology used for determing spring onset should largely be dependent on the functional group of interest: researchers should use the USA-NPN data set for understory species, the PhenoCam data for late successional species, and observational data for a wide array of plant functional types.

4 Determining the Duration of Vegetative Risk

4.1 Tree Spotters Data

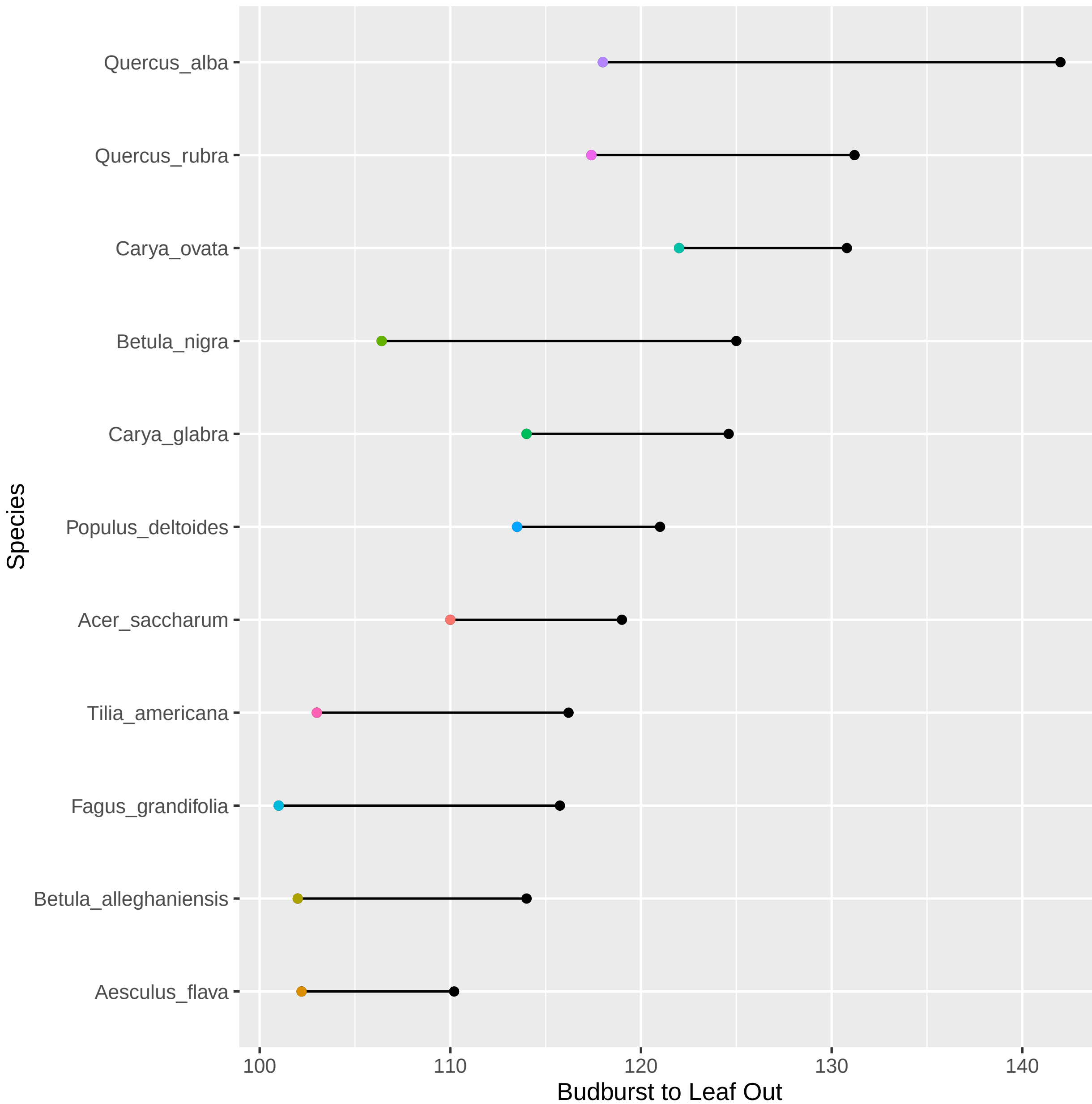

Figure 2: A timeline plot indicating the duration of vegetative risk for each species studied at the Arnold Arboretum in 2016.

4.2 Dan's Data

It is possible, that with anthropogenic climate change progressing, leaf out timing may be delayed. As winter seasons begin to warm and chilling requirements are not met, more warming in the spring must first occur for budburst to begin (Polgar *et al.*, 2014; Fu *et al.*, 2012; Morin *et al.*, 2009; McCreary *et al.*, 1990)

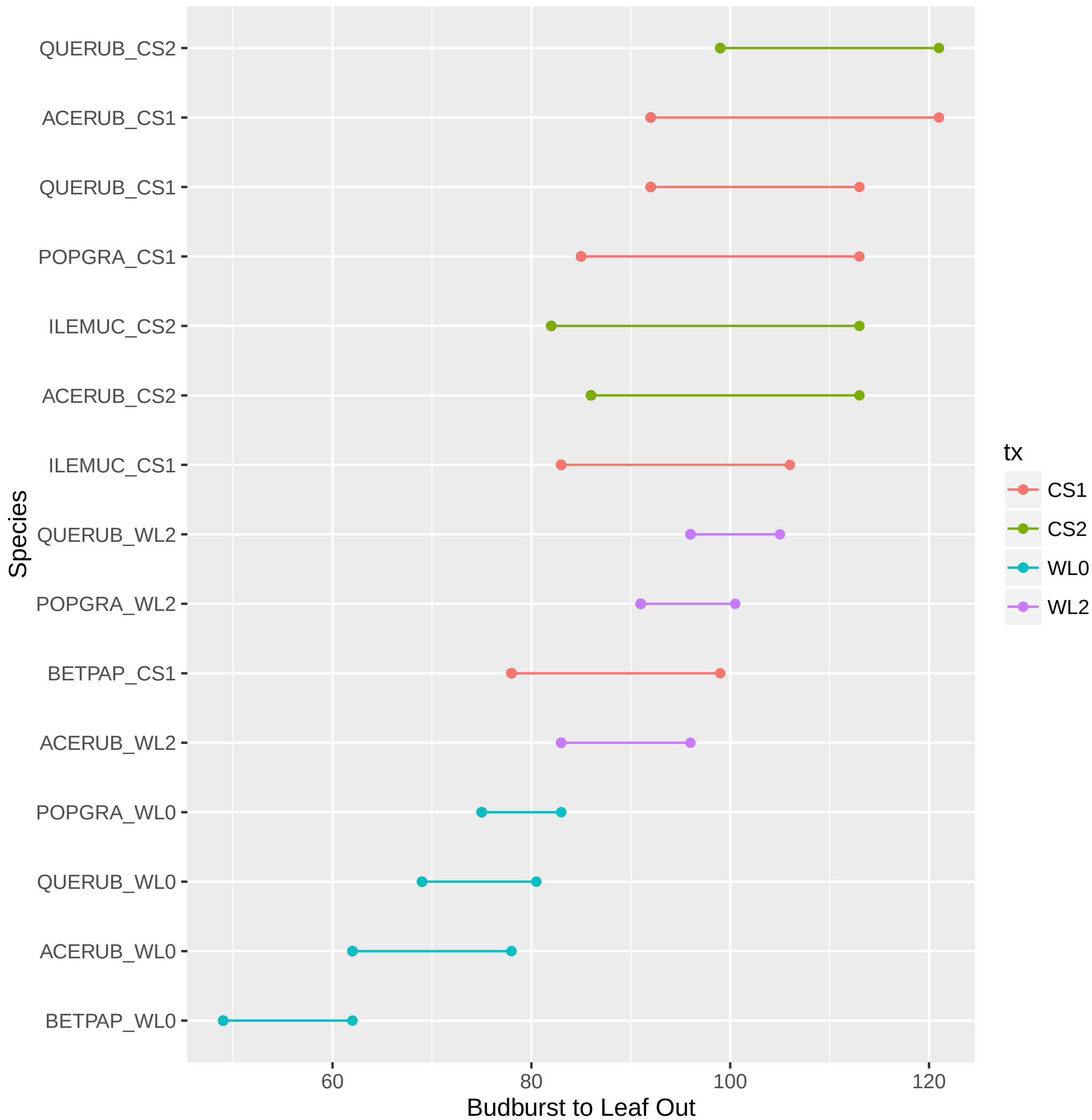

Figure 3: A timeline plot indicating the duration of vegetative risk for each species from experimental chilling study.

4.3 Dan's Data

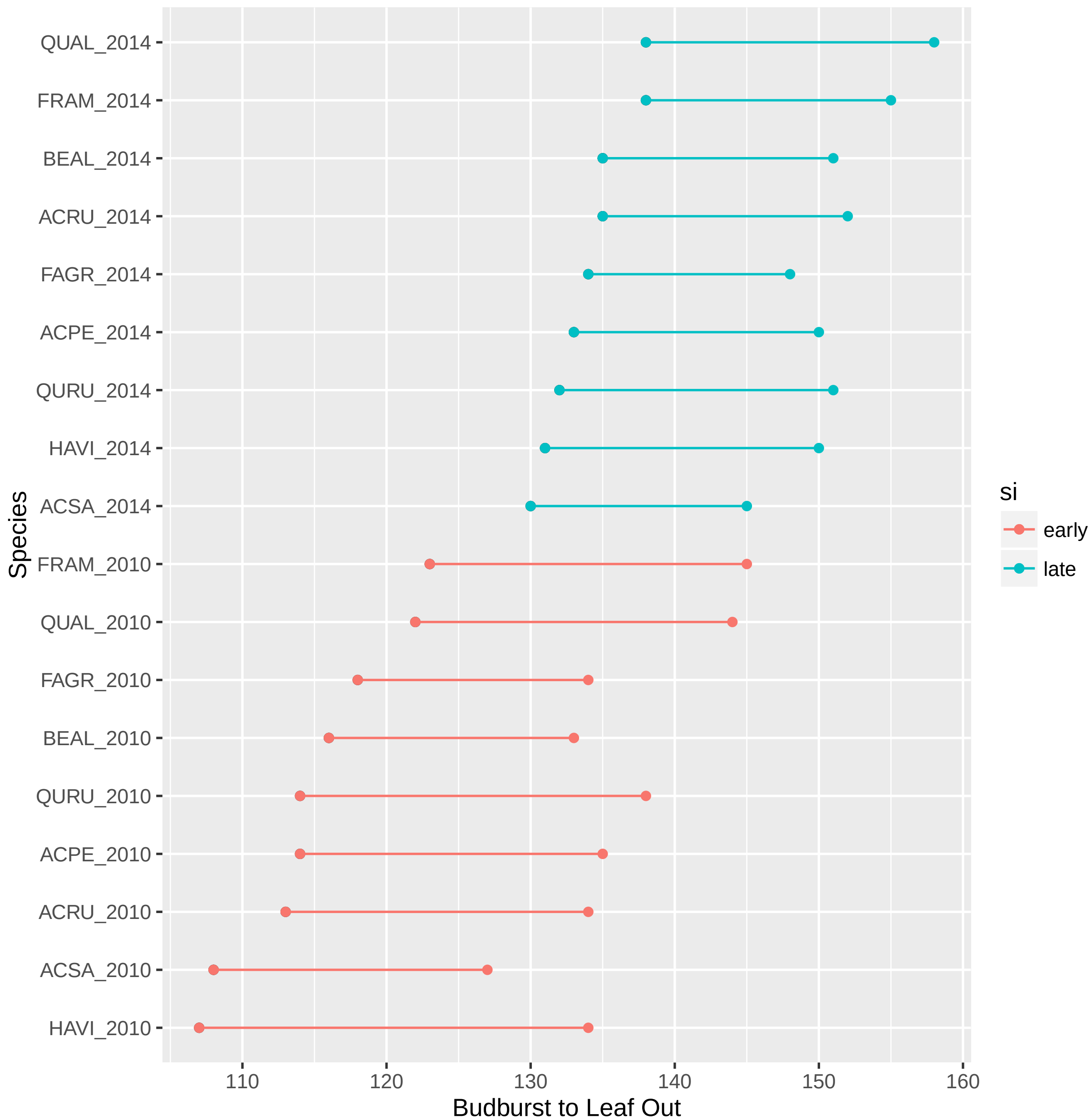

Figure 4: A timeline plot indicating the duration of vegetative risk for each species from collected from Harvard Forest.

5 Conclusion

With anthropogenic climate change, spring frost risk is higher and the level of damage expected to result is also greater. On top of that, habitat fragmentation is increasing, by understanding the impact of false springs on forest communities, a greater understanding of these detrimental impacts, especially along forest edges, would be invaluable.

Box 1: Indicators for Modeling False Spring Risk and Damage

In order to properly evaluate the expected level of damage sustained from a false spring event key indicators should be included in the model.

I. Life Stage of the Individual(s) (Caffarra & Donnelly, 2011)

  (i) Seedlings and saplings will begin budburst earlier than adults

  (ii) The duration of vegetative risk may vary between life stages

  (iii) Long-term effects may vary

II. Location Within a Forest or Canopy (Augspurger, 2013)

  (i) Individuals along the forest edge are more likely to experience a false spring

  (ii) Level of damage is likely to be higher

III. Amount of Winter Chilling (Flynn & Wolkovich, 2017?)

  (i) Will affect the timing of budburst in the spring

  (ii) Will affect the durationg of vegetative risk

IV. Proximity to Water

  (i) Large bodies of water are expected to act as a buffer to spring freezes

V. Precipitation Prior to Budburst (Anderegg *et al.*, 2013)

  (i) Will a drought increase cavitation and heighten damage from a false spring?

  (ii) Or will a drought decrease the risk of damage due to a lower chance of intercellular frost damage?

VI. Freeze Duration and Intensity

  (i) How should we define freezing temperatures?

  (ii) At what point is a freezing event severely damaging and xylem embolism occurs?

  (iii) How long must a false spring be to cause xylem embolism?

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