Regional Risk Outline

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Introduction

1. Temperate tree and shrub species are at risk of damage from late spring freezing events, also known as false springs.
   (a) However, the extent of damage and the frequency and intensity of false spring events is still largely unknown.
   (b) Individuals that initiate budburst and have not fully leafed out before the last spring freeze are at risk of leaf tissue loss, damage to the xylem, and slowed canopy development (Gu *et al.*, 2008; Hufkens *et al.*, 2012).
   (c) Temperate plants are exposed to freezing temperatures numerous times throughout the year, however, individuals are most at risk to damage from stochastic spring frosts, when frost tolerance is lowest (Sakai & Larcher, 1987).
   (d) The growing season is lengthening across many regions in the northern hemisphere (Chen *et al.*, 2005; Liu *et al.*, 2006; Kukal & Irmak, 2018), but last spring frosts still pose a threat in many of these regions (Wypych *et al.*, 2016).
   (e) False spring events can result in photosynthetic tissue loss, which could potentially impact multiple years of growth and, with the growing season extending, individuals could be exposed to more frosts in the future (Liu *et al.*, 2018).
   (f) For these reasons, episodic frosts are one of the largest limiting factors in species range limits (Kollas *et al.*, 2014).

2. Plant phenology, which is defined as the timing of recurring life-history events such as budburst, strongly tracks shifts in climate (Cleland *et al.*, 2007; Wolkovich *et al.*, 2012).

   (a) Trees and shrubs in temperate regions optimize growth by using three cues to initiate budburst: low winter temperatures, warm spring temperatures, and increasing spring daylengths.

   (b) With climate change advancing, this interaction of cues may shift spring phenologies both across and within species.

   (c) Due to the changing climate, spring onset is advancing and many temperate tree and shrub species are initiating leafout 4-6 days earlier per °C of warming (Wolkovich *et al.*, 2012; IPCC, 2015).

   (d) However, last spring freeze dates are not predicted to advance at the same rate as spring onset in some regions of the world (Inouye, 2008; Martin *et al.*, 2010; Labe *et al.*, 2016; Sgubin *et al.*, 2018), potentially amplifying the effects of false spring events in these regions.

   (e) (Too redundant??) In Germany, for example, the last freeze date has advanced by 2.6 days per decade since 1955 (Zohner *et al.*, 2016).

   (f) Major false spring events have been recorded in recent years and have found it can take 16-38 days for trees to refoliate (Gu *et al.*, 2008; Augspurger, 2009, 2013; Menzel *et al.*, 2015), which can detrimentally affect crucial processes such as carbon updake and nutrient cycling (Hufkens *et al.*, 2012; Richardson *et al.*, 2013; Klosterman *et al.*, 2018).

3. Temperate plants have evolved to minimize false spring damage through a myriad of strategies, with the most effective being avoidance: plants must exhibit flexible spring phenologies in order to maximize growth and minimize frost risk by timing budburst effectively (Polgar & Primack, 2011; Basler & Korner, 2014).

   (a) Plants growing in forest systems tend to exhibit staggered days of budburst.

   (b) Lower canopy species typically initiate budburst earlier in the season in order to utilize available resources such as light, whereas larger canopy species usually initiate budburst later in the season.

   (c) Thus, there is a trade-off between growing season length and frost risk.

   (d) Frost tolerance greatly diminishes once individuals exit the dormancy phase (i.e. processes leading to budburst) through full leaf expansion (Vitasse *et al.*, 2014; Lenz *et al.*, 2016).

   (e) Individuals that initiate budburst earlier in the season are more frost resistant (Körner *et al.*, 2016), however, as climate change advances, less frost resistant individuals may start initiating budburst before the last freeze date.

4. Many studies have assessed the interplay between cue interactions and budburst dates by investigating potenital latitudinal effects (Partanen, 2004; Vihera-aarnio *et al.*, 2006; Caffarra & Donnelly, 2011; Zohner *et al.*, 2016; Gauzere *et al.*, 2017).

    (a) However, recent studies have demonstrated regional effects may be more closely related to false spring risk: whether via altitudinal variation (Vitra *et al.*, 2017) or distance from the coast (Wypych *et al.*, 2016).

    (b) By better understanding these regional climatic implications, we may be able to determine which regions may be at risk currently and which regions may become more at risk in the future.

5. There is large debate over whether or not spring freeze damage will increase (Hänninen, 1991; Augspurger, 2013; Labe *et al.*, 2016), remain the same (Scheifinger *et al.*, 2003) or even decrease (Kramer, 1994) with climate change.

    (a) Some research suggests false spring incidence has declined in many regions (i.e. across parts of North America and Asia), however the prevalence of spring frosts has consistently increased across Europe since 1982 (Liu *et al.*, 2018).

    (b) The North Atlantic Ossilation (NAO) index is often used to describe winter and spring circulation across Europe.

    (c) More positive NAO phases tend to result in higher than average winter and early spring temperatures, and with climate change, higher NAO phases has correlated to even earlier budburst dates in some regions (Chmielewski & Rötzer, 2001), however it is unclear if more positive NAO phases also translates to more false springs.

    (d) By improving and identifying budburst and climate trends in recent years, we could potentially amplify our predictability of future projections in false springs.

    (e) For this purpose, we assessed the number of false springs that occured across 11,684 sites around Europe, spanning altitudinal and coastal gradients, using observed phenological data (857,004 observations) for six temperate, deciduous trees and combined that with daily gridded climate data for each site that extended from 1950-2016.

    (f) In this study, a false spring was tallied when temperatures fell below -2.2° (Schwartz, 1993) between budburst and leafout (CITE Rethinking here?)

    (g) We predicted that: (1) Earlier budburst species would experience more false springs, especially after 1983 and (2) there would be different regional effects on false spring incidence and those trends would shift when coupled with the effects of climate change.

Methods

Phenological Data

1. Phenological data was obtained from the Pan European Phenology network (PEP725, www.pep725.edu), which provides open access phenology records across Europe (Templ *et al.*, 2018).

2. Since plants are most susceptible to damage from frost between budburst and full leafout, we selected only leafout data (i.e., in Meier, 2001, BBCH 11, which is defined as the point of leaf unfolding and the first visible leaf stalk) from the PEP725 dataset.

3. We then subtracted 12 days from the leafout date to determine day of budburst (Donnelly *et al.*, 2017).

4. The species used in the study were *Aesculus hippocastanum L.*, *Alnus glutinosa* (L.) Gaertn., *Betula pendula* Roth., *Fagus sylvatica* Ehrh., *Fraxinus excelsior* L., *Quercus robur* L.

5. Selection criteria for the species were as follows: (1) to be temperate, deciduous species that were not cultivars or used for crops, (2) there were at least 100,000 observations of BBCH 11, (3) to represent over half of the total number of sites available (11,684), and (4) there were observations for each year used in the study (1950-2016).

Climate Data

1. We collected daily gridded climate data from the European Climate Assessment & Dataset (ECA&D) and used the E-OBS 0.25 degree regular latitude-longitude grid from version 16.

2. We used the daily minimum temperature dataset to determine if a false spring occurred, which was defined as -2.2°C (Schwartz, 1993)

3. In order to capture regional climatic effects we calculated the mean spring temperature by using the daily mean temperature from February 1 through April 30.

4. Mean spring temperature was calculated – after chilling was accummulated – to incorporate spring forcing temperatures in our Bayesian hierarchichal model and to compare differences in spring across sites (Basler & Körner, 2012).

5. We collected NAO-index data from the KNMI Climate Explorer annual NAO time series (Trouet *et al.*, 2009).

6. Since the primary aim of the study is to predict false spring incidence in a changing climate, we split our data to before and after 1983 to capture reported temporal shifts in temperature trends (Stocker *et al.*, 2013; Kharouba *et al.*, 2018).

Data Analysis

1. We used a Bayesian hierarchical model approach to analyze our data to best estimate the number of false springs across-species levels.

2. A false spring was determined if temperatures fell below -2.2°C at least once between budburst and leafout.

3. We fit a mixed-effects model using mean spring temperature, NAO, elevation, space, and climate change as predictors (fixed effects) and species as modeled groups (random effects).

4. We scaled the elevation predictor by dividing it by 100 to be consistent with the other predictors in the model.

5. We used a space parameter rather than a more traditional latitude parameter to adjust for spatial autocorrelation issues using a minimization of Moran's I of the residuals (David *et al.*, 2017) (Figure S1).

6. We then took the calculated eigenvectors determined from the MIR approach and regressed these against the number of false springs for each datapoint to establish a spatial parameter (space).

7. The Bayesian hierarchical model was fit using the brms package (Bürkner, Paul-Christian , 2017), version 2.3.1, in R (R Development Core Team, 2017), version 3.3.1, and was written as follows:

$$y_i \sim N(\alpha_(i) + \beta_{MeanSpringTemp_{sp_{(i)}}} + \beta_{NAO_{sp_{(i)}}} + \beta_{elevation_{sp_{(i)}}} + \beta_{space_{sp_{(i)}}} \beta_{ClimateChange_{sp_{(i)}}} \sigma_{sp_{(i)}} \quad (1)$$

8. The β coefficients and α were modeled at the species level:

   1. $\beta_{MeanSpringTemp_{sp}} \sim N(\mu_{MeanSpringTemp}, \sigma^2{}_{MeanSpringTemp})$

   ...

   5. $\beta_{ClimateChange_{sp}} \sim N(\mu_{ClimateChange}, \sigma^2{}_{ClimateChange})$

9. We ran two chains, each with 4,000 warm-up iterations and 2,500 sampling iterations for a total of 10,000 posterior samples for each predictor.

10. We evaluated our model performance on $\hat{R}$ values that were close to 1 and assessed chain convergence and posterior predictive checks (Gelman & Hill, 2006).

Results

Discussion & Conclusion

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Tables and Figures

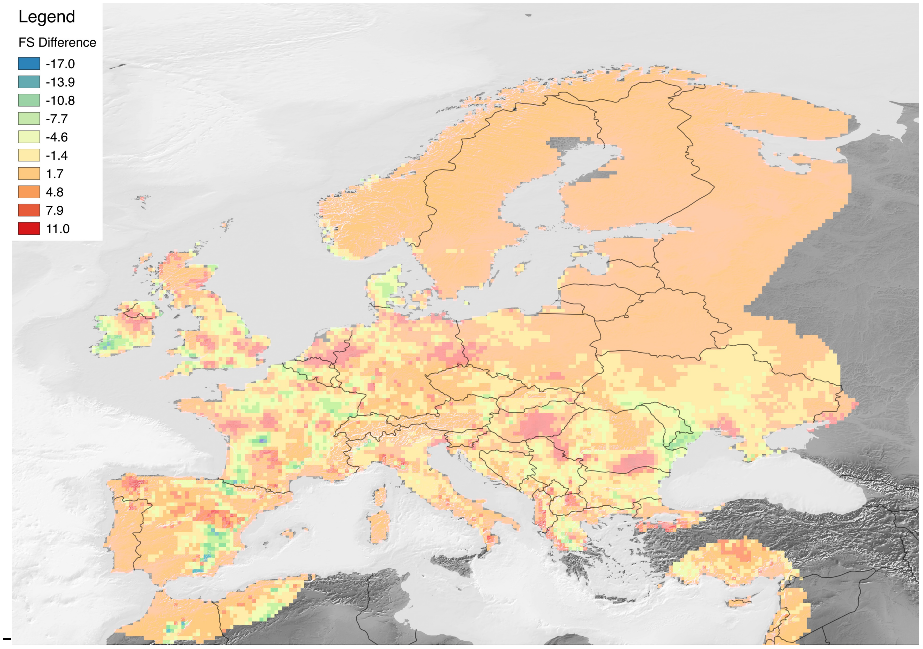

Figure 1: Number of years with freezing events that occured before temperature shifts related to climate change began (1951-1983) as compared to after reported climate shifts (1984-2016). If temperatures fell below -2°C between March 1 and June 30, a year with a spring freeze was tallied. Some regions experienced more years with spring freezes after climate change began, whereas other years experienced the same number or even fewer years with spring freezes. Regions that had more years with spring freezes after climate change began are blue and green and regions that had fewer freezes are depicted in red.

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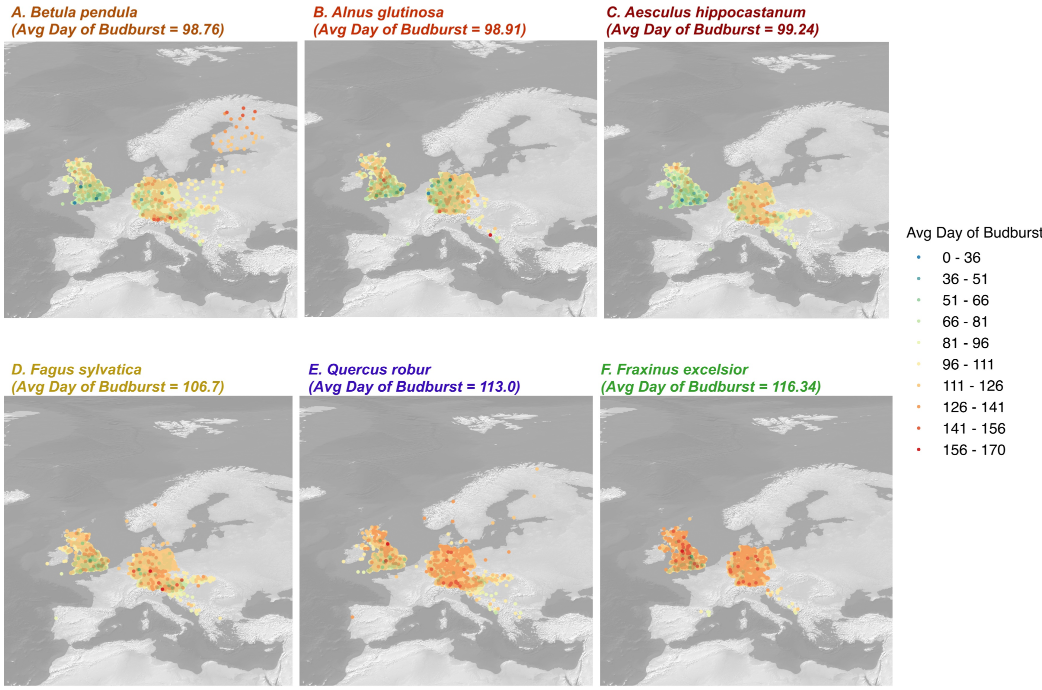

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Figure 2: The average day of budburst is mapped by site for each species. Species are ordered by day of budburst starting with *Betula pendula* as the earliest budburst date to *Fraxinus excelsior*. Earlier budburst dates are blue and later budburst dates are in red.

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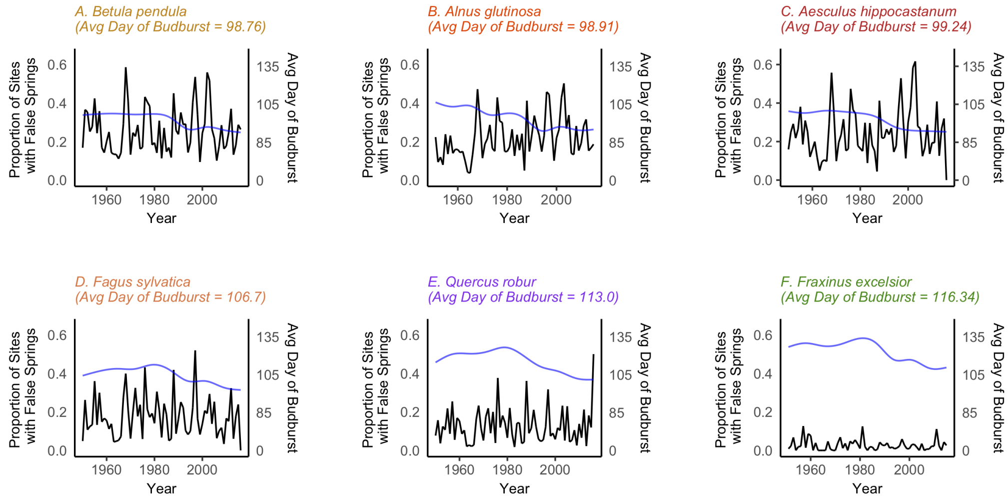

Figure 3: The black line indicates the proportion of sites that had false spring conditions for each year across all species. The blue line is a smoothing spline, indicating the trend of average day of budburst for each year for each species. Species are ordered by average day of budburst, with the earliest being *Betula pendula* and the latest being *Fraxinus excelsior*.