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, and this risk may shift with climate change
   (a) The growing season is lengthening (mainly due to earlier springs) 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).
   (b) Spring onset is advancing with temperate tree and shrub species initiating leafout 4-6 days on average earlier per °C of warming (Wolkovich *et al.*, 2012; IPCC, 2015).
   (c) Last spring freeze dates are not predicted to advance at the same rate (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.
   (d) In Germany, for example, the last freeze date has advanced by 2.6 days per decade since 1955 (Zohner *et al.*, 2016) but leafout is advancing around twice as fast.
   (e) 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).
2. Episodic frosts are one of the largest limiting factors in species range limits and have shaped plant life history strategies (Kollas *et al.*, 2014).

(a) 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).

(b) 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).

(c) 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).

(d) Individuals and species 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.

(e) Despite the importance of false spring events, the extent of damage and the frequency and intensity of false spring events is still largely unknown.

3. Plant phenology and climate are tightly intertwined (Pau *et al.*, 2011), thus understanding major climate oscillation patterns is essential for predicting budburst and, ultimately, false spring risk.

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

(b) More positive NAO phases tend to result in higher than average winter and 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.

4. 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; Vitra *et al.*, 2017) with climate change and there is also great variation within studies.

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

(c) By better understanding these regional climatic implications and which factors are most crucial for predicting risk, 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. The majority of false spring studies assess the effects of one predictor (e.g. temperature, elevation or distance from the coast) on false spring prevalence but most fail to incorporate multiple effects.
    (a) Our primary aim is to investigate the known regional factors on false spring risk and compare the effect of them and their interaction with climate change. The key regional factors we identify for this study are: mean spring temperature, NAO index, elevation and distance from the coast.
6. By refining and identifying budburst and climate trends in recent years, we could improve future projections in false springs.
    (a) For this purpose, we assessed the number of false springs that occured across 11,648 sites around Europe, spanning altitudinal and coastal gradients, using observed phenological data (754,786 observations) for six temperate, deciduous trees and combined that with daily gridded climate data for each site that extended from 1951-2016.
    (b) In this study, a false spring was tallied when temperatures fell below -2.2° (Schwartz, 1993) between budburst and leafout (CITE Rethinking here?).
    (c) 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).
    (d) We predicted that: (1) Earlier budburst species would experience more false springs, especially after 1983 and (2) there would be different regional effects (i.e. mean spring temperature, NAO index, elevation, distance from the coast) on false spring incidence and those trends would shift when coupled with the effects of climate change.

Methods

Phenological Data and Calculating Vegetative Risk

1. We obtained phenological data 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 establish a rough estimate for day of budburst (Donnelly *et al.*, 2017).

4. The species used in the study were *Aesculus hippocastanum* Poir., *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 90,000 observations of BBCH 11, (3) to represent over half of the total number of sites available (11,684), (4) there were observations for at least 65 out of the 66 years of the study (1951-2016).

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.

3. False springs in this study were defined as temperatures at or below -2.2°C (Schwartz, 1993).

4. In order to capture regional climatic effects we calculated the mean spring temperature by using the daily mean temperature from March 1 through May 30.

5. Mean spring temperature was calculated – likely after chilling was accummulated – in an attempt to incorporate the general effects of spring forcing temperatures in our Bayesian hierarchichal model and to compare differences in spring across sites (Basler & Körner, 2012; Körner *et al.*, 2016).

6. We collected NAO-index data from the KNMI Climate Explorer annual NAO time series and selected the NAO indices from November until April to best capture the effects of NAO on budburst for each region (Trouet *et al.*, 2009).

7. Since the primary aim of the study is to predict fals spring incidence in a changing climate, we split the data: before temperature trends increased (1951-1983) and after trends increased (1984-2016, Stocker *et al.*, 2013; Kharouba *et al.*, 2018).

Data Analysis

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

   (a) We scaled all of the predictors and found a z-score following the binary predictor approach in order to best compare the effects of each climate variable to each other (Gelman & Hill, 2006).

(b) 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).

(c) 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).

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

(a) We fit a bernoulli distribution model using mean spring temperature, NAO, elevation, distance from the coast, space, and climate change as predictors and all two-way interactions (fixed effects) and species as two-way interactions to simulate modeled groups on the main effects.

(b) 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: (subject to change as per above, this is just the ideal model)

$$
\begin{aligned}
y_i \sim N(\alpha_(i)) &+ \beta_{MeanSpringTemp_{(i)}} + \beta_{NAO_{(i)}} + \beta_{Elevation_{(i)}} + \beta_{DistanceCoast_{(i)}} + \beta_{Space_{(i)}} \\
&+ \beta_{ClimateChange_{(i)}} + \beta_{MeanSpringTemp \times Species_{(i)}} + \beta_{NAO \times Species_{(i)}} + \beta_{Elevation \times Species_{(i)}} \\
&+ \beta_{DistanceCoast \times Species_{(i)}} + \beta_{Space \times Species_{(i)}} + \beta_{ClimateChange \times Species_{(i)}} \\
&+ \beta_{MeanSpringTemp \times ClimateChange_{(i)}} + \beta_{NAO \times ClimateChange_{(i)}} + \beta_{Elevation \times ClimateChange_{(i)}} \\
&+ \beta_{DistanceCoast \times ClimateChange_{(i)}} + \beta_{Space \times ClimateChange_{(i)}} + \sigma_{sp_{(i)}}
\end{aligned}
$$

(c) 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.

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

Results

Species variation in budburst and false spring incidence

1. There is variation in day of budburst across the six species and across space (Figure 1).

(a) The top three species (*Betula pendula*, *Alnus glutinosa*, *Aesculus hippocastenum*) generally initiated budburst earlier than the bottom three species (*Fagus sylvatica*, *Quercus robur*, *Fraxinus excelsior*).

   (b) Across all species, certain regions tended to initiate budburst earlier than others (i.e. United Kingdom was earlier than parts of Austria).

2. All species initiated budburst earlier after 1983 (Figure 2) and the minimum temperature between budburst and leafout was, on average, higher after 1983.

3. Species that initiated budburst early were not always at a higher risk of false springs (Figure 2), as is evident by *Alnus glutinosa*.

   (a) As seen in Figure (3), mean spring temperature for most species ranged from -5°C to 12°C, but for *Alnus glutinosa* and *Fraxinus excelsior* the mean spring temperature rarely dropped below 0°C.

   (b) The average minimum temperature between budburst and leafout, however, varied across the six species with *Betula pendula* and *Aesculus hippocastenum* experiencing the lowest minimum temperatures.

The effects of climatic regional variation on false spring incidence

1. The effects of the predictors varied in both direction and magnitude (Figure 5).

   (a) Mean spring temperature had the biggest effect on the number of false springs, with warmer spring temperatures resulting is fewer false springs.

   (b) More positive NAO indices, higher elevations, and sites further from the coast all increased the likelihood of false springs.

   (c) Overall, there were fewer false springs after 1983.

2. Most of the interactions with increasing temperatures (i.e. the Climate Change predictor), demonstrate a decreased risk in false springs, however, the rate of false spring risk increased at sites further from the coast after 1983 (Figure 6).

The effects of changing the temperature threshold

1. By changing the temperature threshold for defining a false spring — from -2.2°C to -5°C — many of the predictors changed in both magnitude and direction but overall there were fewer false springs (Figure 7).

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Tables and Figures

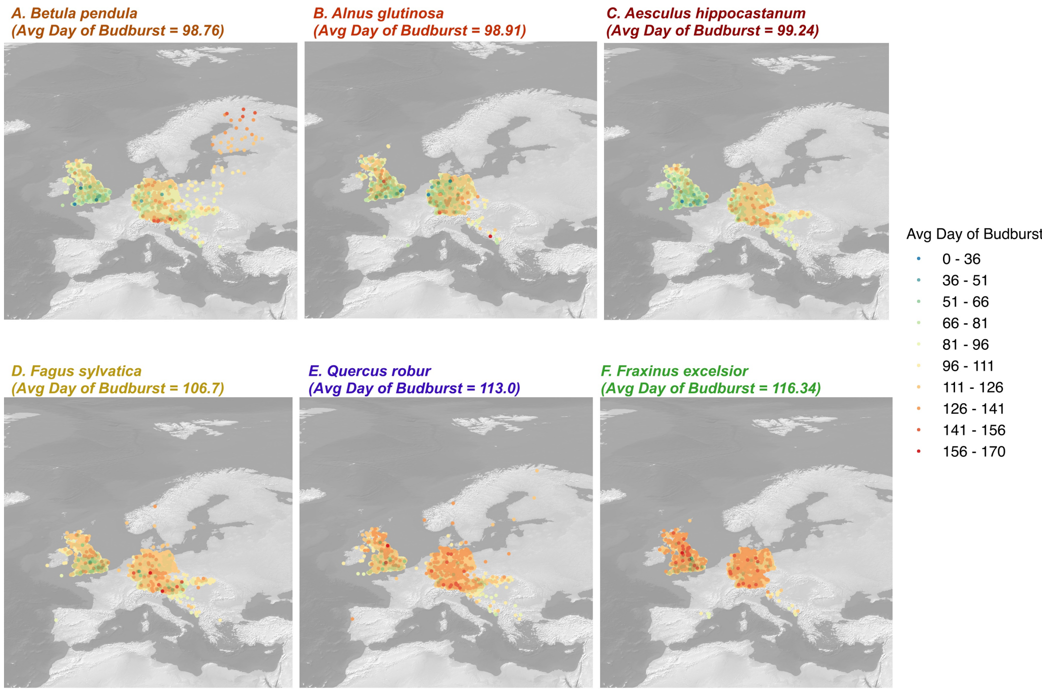

Figure 1: The average day of budburst is mapped by site for each species. Species are ordered by day of budburst starting with *Betula pendula* as the earliest budburst date to *Fraxinus excelsior*. Earlier budburst dates are blue and later budburst dates are in red.

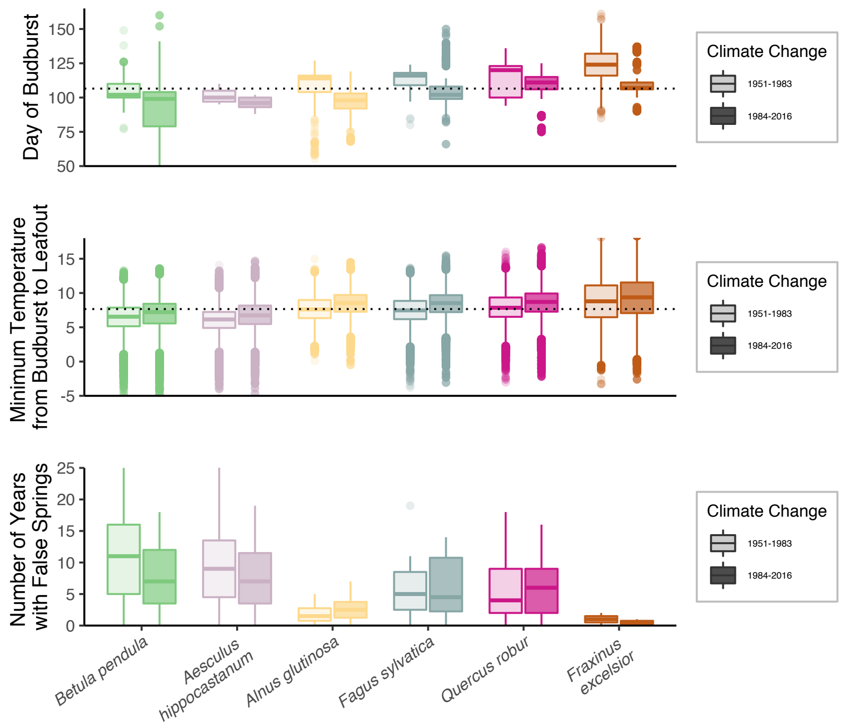
Day of Budburst
150
125
100
75
50
Minimum Temperature
from Budburst to Leafout
15
10
5
0
-5
Number of Years
with False Springs
25
20
15
10
5
0
Climate Change
1951-1983
1984-2016
Betula pendula
Aesculus hippocastanum
Alnus glutinosa
Fagus sylvatica
Quercus robur
Fraxinus excelsior

Figure 2

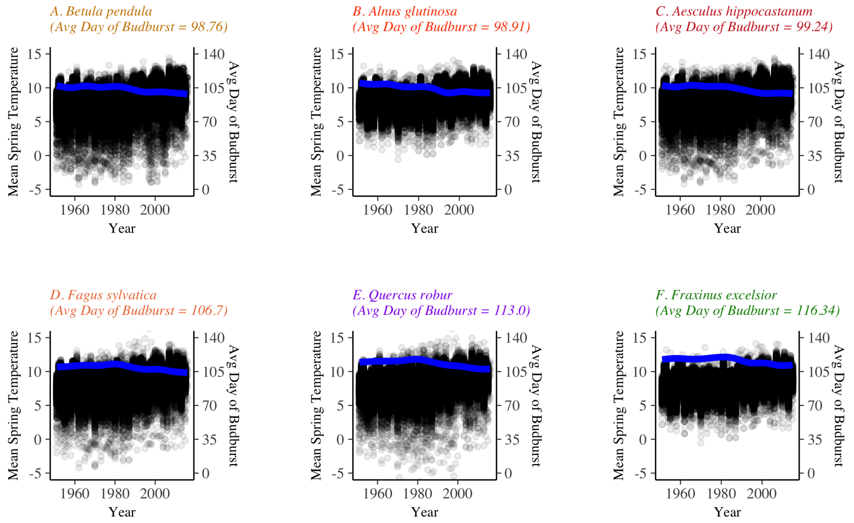

Figure 3

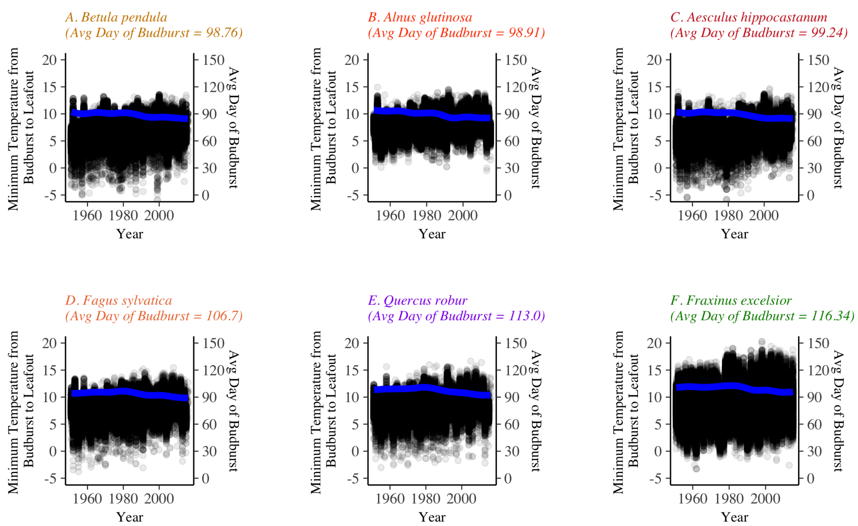

Figure 4

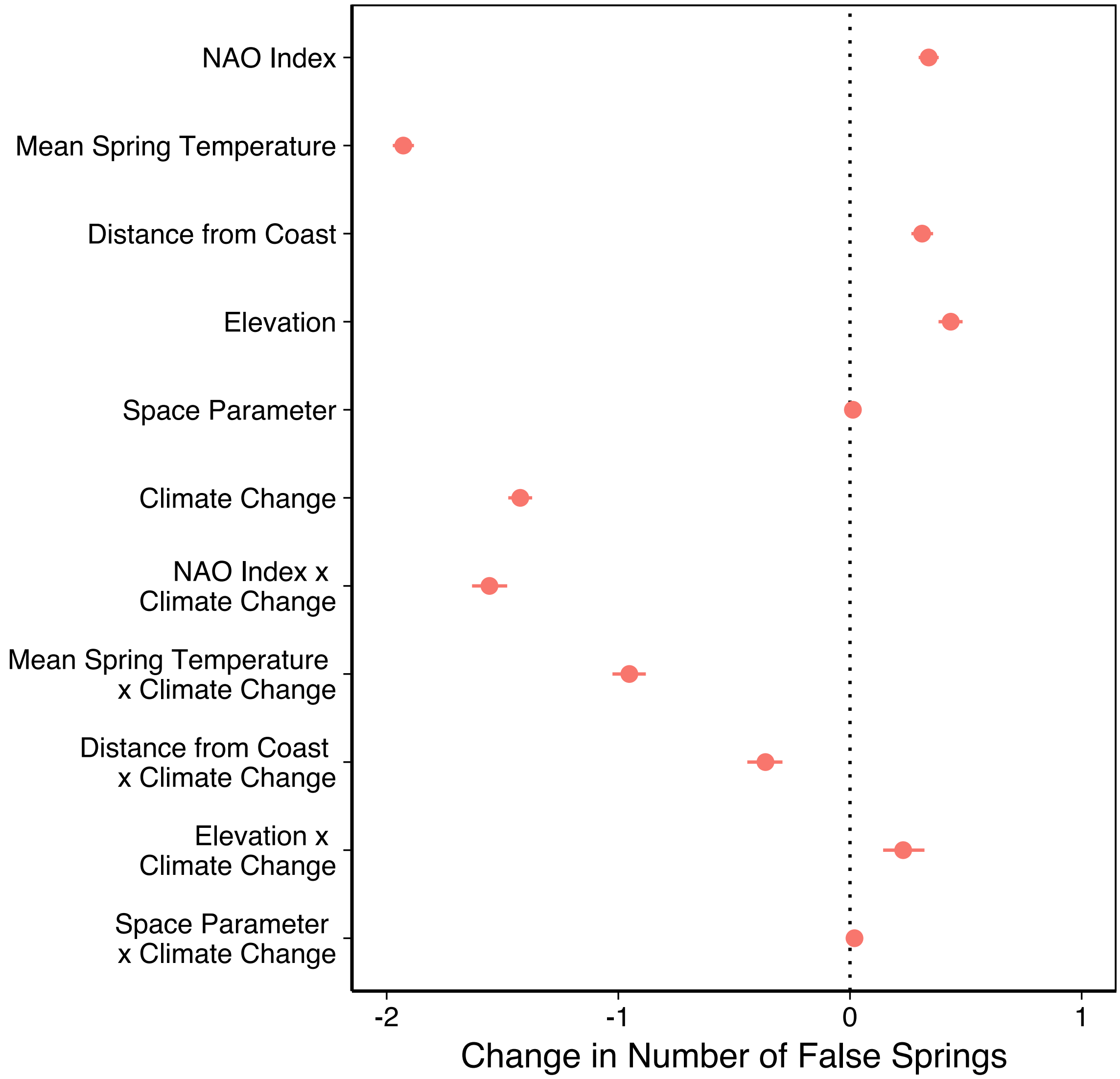
NAO Index
Mean Spring Temperature
Distance from Coast
Elevation
Space Parameter
Climate Change
NAO Index x Climate Change
Mean Spring Temperature x Climate Change
Distance from Coast x Climate Change
Elevation x Climate Change
Space Parameter x Climate Change
-2
-1
0
1
Change in Number of False Springs

Figure 5

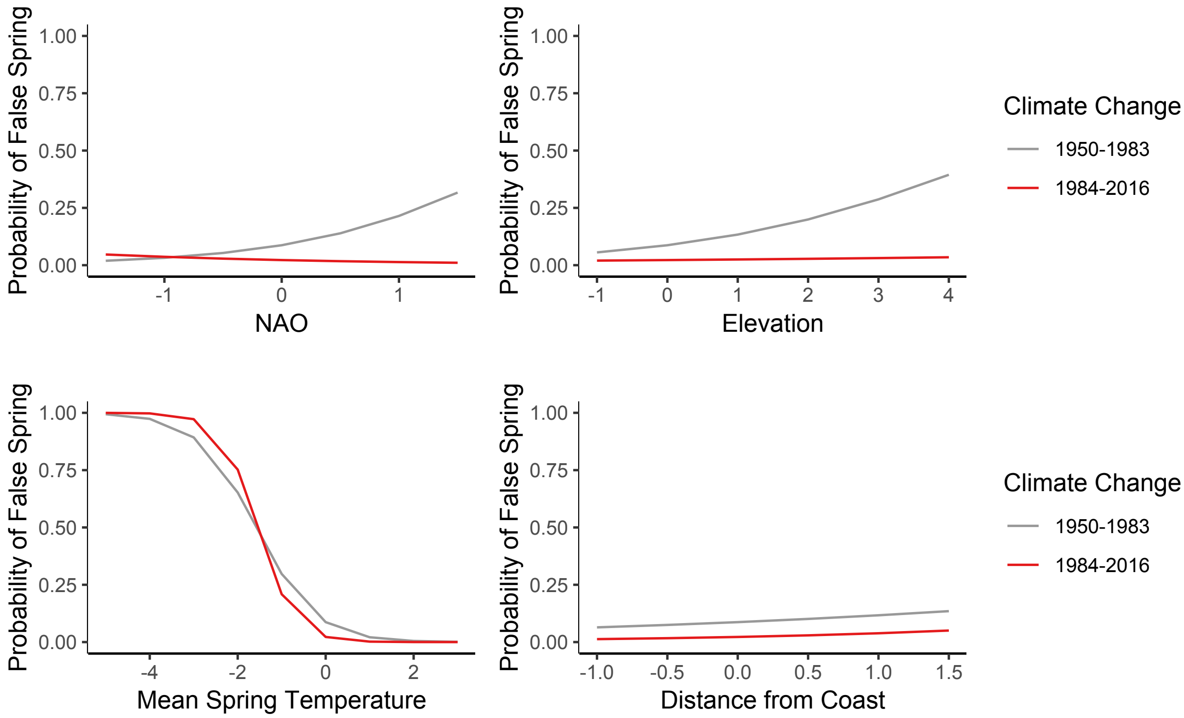
Probability of False Spring
1.00
0.75
0.50
0.25
0.00
NAO
Elevation
Mean Spring Temperature
Distance from Coast
Climate Change
1950-1983
1984-2016

Figure 6

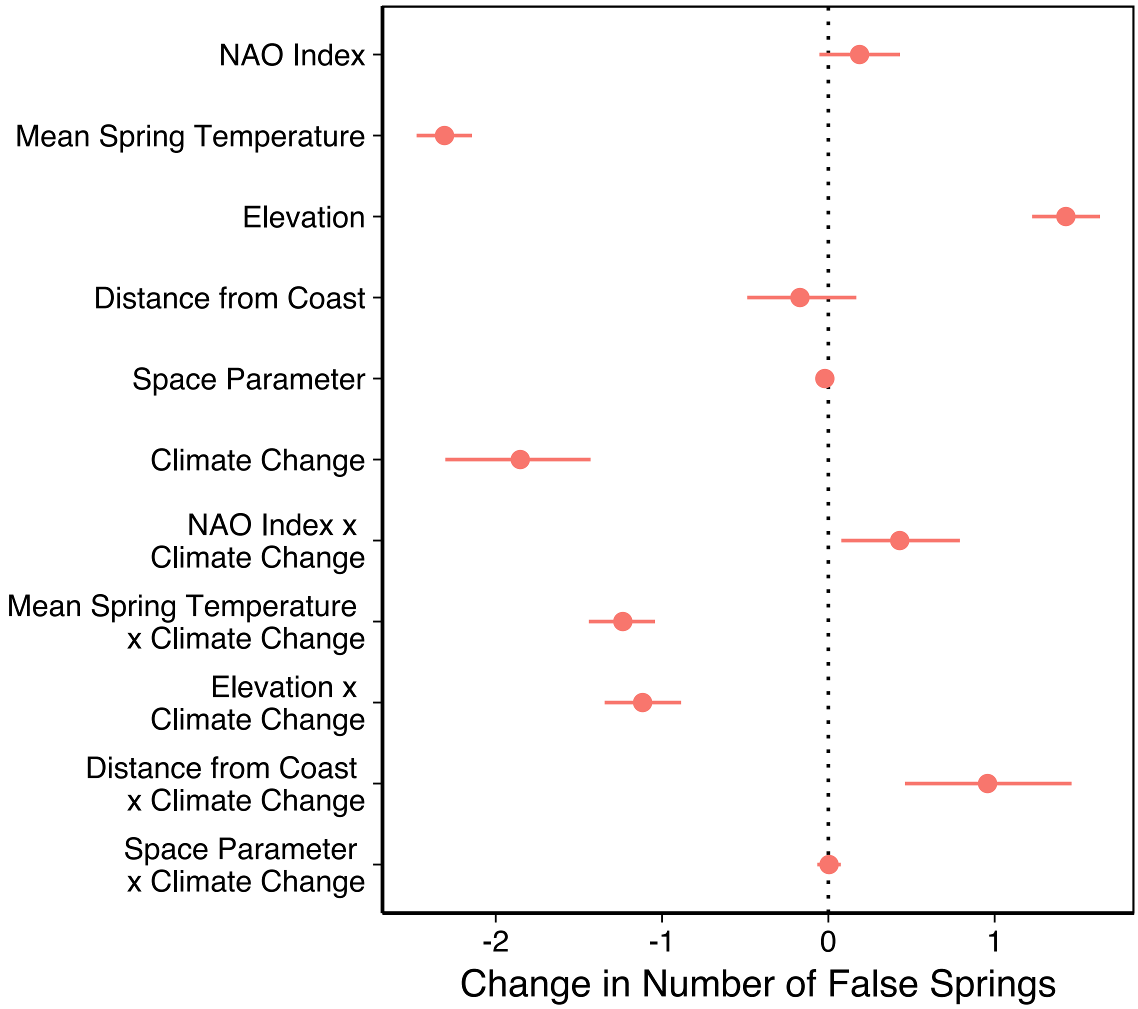

Figure 7

Supplement: Tables and Figures

Table 1: Data points collected for each species

Species	Num. of Observations	Num. of Sites	Num. of Years
Aesculus hippocastanum	156836	10158	66
Alnus glutinosa	91182	6775	66
Betula pendula	155251	10139	66
Fagus sylvatica	129133	9099	66
Fraxinus excelsior	92665	7327	65
Quercus robur	131635	8811	66

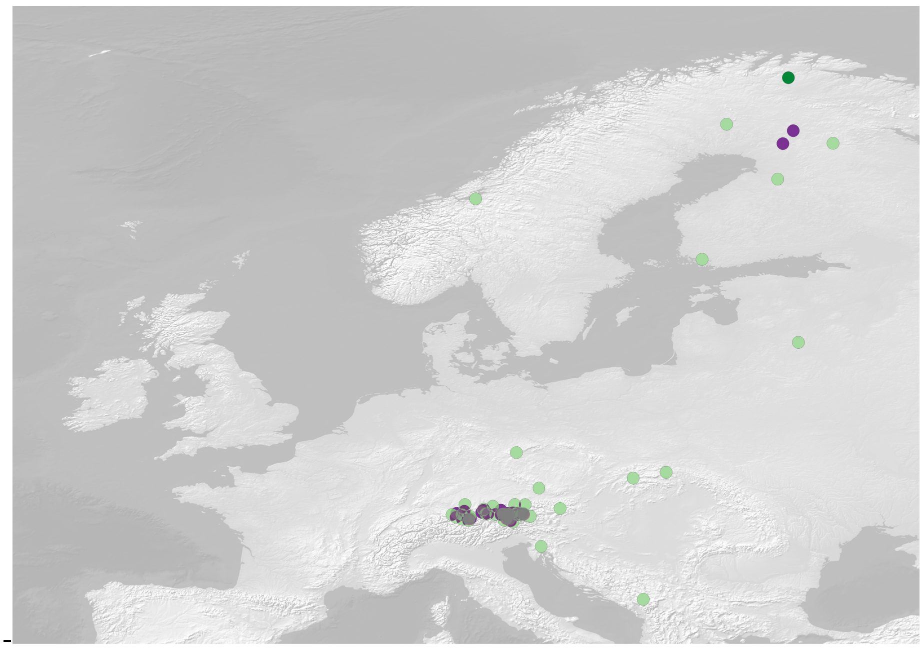

Figure 8: Space parameter values are mapped for each location to elucidate patterns in the parameter values.