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 1951-2016.

   (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 establish a rough estimate for 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 140,000 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 February 1 through April 30.

5. Mean spring temperature was calculated – likely after chilling was accummulated – in an attempt to incorporate a 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 (Trouet *et al.*, 2009).

7. 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 and all two-way interactions (fixed effects) and species as modeled groups on the main effects (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. (Although, we may find that space and elevation are collinear and may decide to take space out and use elevation instead - unless space is picking up more of the distance from the coast then we'll use the space parameter instead of elevation)

8. 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)

$$
\begin{aligned}
y_i \sim N(\alpha_(i) + &\beta_{MeanSpringTemp_{sp_{(i)}}} + \beta_{NAO_{sp_{(i)}}} + \beta_{elevation_{sp_{(i)}}} + \beta_{space_{sp_{(i)}}} + \beta_{ClimateChange_{sp_{(i)}}} \\
&+ \beta_{MeanSpringTemp \times ClimateChange_{(i)}} + \beta_{NAO \times ClimateChange_{(i)}} \\
&+ \beta_{elevation \times ClimateChange_{(i)}} + \beta_{space \times ClimateChange_{(i)}} + \sigma_{sp_{(i)}}
\end{aligned}
$$

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

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

       ...

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

10. 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.

11. 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

Species variation in budburst and false spring incidence

1. There is variation in day of budburst across the six species and across space - BB maps Fig (should I include a small model here to demonstrate this? (i.e. fs cc + (cc|species)))
    (a) Earlier budbursting species experienced more false spring conditions - proportion of sites Fig
    (b) Our data supports evidence that day of budburst is advancing earlier over time, especially after the early 1980s

The effects of climatic regional variation on false spring incidence - potentially! still waiting on final model results!

1. The relationship between the main effects and false spring as compared before and after 1983 (Fig. Main effects)
    (a) As elevation increases, plants are exposed to more frequent false spring conditions and the rate of increase is greater under climate change.
    (b) As mean spring temperature increases, there are fewer false springs and the rate of decrease is greater after 1983.
    (c) NAO-index does not seem to be a strong predictor of false spring, (discussion: which may mean that even though budburst is earlier, late spring freezes are less likely to occur in high NAO years.)
    (d) As the space parameter increases (which captures distance from the coast and shifts in elevation), false spring incidence increased.

Discussion & Conclusion - jumbles of thoughts right now...

1. Some regions are more susceptible to false spring risk than others and, with climate change, some regions that are low risk now, may become more at risk.
   (a) The rate false spring risk is increasing at higher elevations but decreasing in regions with warmer mean spring temperatures.
   (b) Regions that are less at risk to false spring conditions may be more at risk to drought as climate change advances.
   (c) Thus, plants must exhibit even more flexible spring phenologies in order to keep up with the rate of change and the different types of potential risks.
2. Individuals from more Northern provenances tend to be more susceptible to spring frost damage, whereas more Southern individuals are more sensitive to fall frosts (Montwé *et al.*, 2018).
   (a) With regional shifts in climate, will fall frosts become more damaging than spring frosts?

References

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. (2013) Reconstructing patterns of temperature, phenology, and frost damage over 124 years: Spring damage risk is increasing. *Ecology* **94**, 41–50.

Basler, D. & Körner, C. (2012) Photoperiod sensitivity of bud burst in 14 temperate forest tree species. *Agricultural and Forest Meteorology* **165**, 73–81.

Basler, D. & Korner, C. (2014) Photoperiod and temperature responses of bud swelling and bud burst in four temperate forest tree species. *Tree Physiology* **34**, 377–388.

Bürkner, Paul-Christian (2017) brms: An R Package for Bayesia Multilevel Models. *Journal of Statistical Software* **80**, 1–28.

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.

Chen, X., Hu, B. & Yu, R. (2005) Spatial and temporal variation of phenological growing season and climate change impacts in temperate eastern china. *Global Change Biology* **11**, 1118–1130.

Chmielewski, F.M. & Rötzer, T. (2001) Response of tree phenology to climate change across europe. *Agricultural and Forest Meteorology* **108**, 101 – 112.

Cleland, E.E., Chuine, I., Menzel, A., Mooney, H.A. & Schwartz, M.D. (2007) Shifting plant phenology in response to global change. *Trends in Ecology and Evolution* **22**, 357–365.

David, B., Thomas, D., Stéphane, D. & Jason, V. (2017) Disentangling good from bad practices in the selection of spatial or phylogenetic eigenvectors. *Ecography* **0**.

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.

Gauzere, J., Delzon, S., Davi, H., Bonhomme, M., Garcia de Cortazar-Atauri, I. & Chuine, I. (2017) Integrating interactive effects of chilling and photoperiod in phenological process-based models. A case study with two European tree species: *Fagus sylvatica* and *Quercus petraea*. *Agricultural and Forest Meteorology* pp. 9–20.

Gelman, A. & Hill, J. (2006) *Data analysis using regression and multilevel/hierarchical models*. Cambridge university press.

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.

Hänninen, H. (1991) Does climatic warming increase the risk of frost damage in northern trees? *Plant, Cell & Environment* **14**, 449–454.

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.

IPCC (2015) *Climate change 2014: mitigation of climate change*, vol. 3. Cambridge University Press.

Kharouba, H.M., Ehrlén, J., Gelman, A., Bolmgren, K., Allen, J.M., Travers, S.E. & Wolkovich, E.M. (2018) Global shifts in the phenological synchrony of species interactions over recent decades. *Proceedings of the National Academy of Sciences* **115**, 5211–5216.

Klosterman, S., Hufkens, K. & Richardson, A.D. (2018) Later springs green-up faster: the relation between onset and completion of green-up in deciduous forests of north america. *International Journal of Biometeorology* .

Kollas, C., Körner, C. & Randin, C.F. (2014) Spring frost and growing season length co-control the cold range limits of broad-leaved trees. *Journal of Biogeography* **41**, 773–783.

Körner, C., Basler, D., Hoch, G., Kollas, C., Lenz, A., Randin, C.F., Vitasse, Y. & Zimmermann, N.E. (2016) Where, why and how? explaining the low-temperature range limits of temperate tree species. *Journal of Ecology* **104**, 1076–1088.

Kramer, K. (1994) A modelling analysis of the effects of climatic warming on the probability of spring frost damage to tree species in the netherlands and germany. *Plant, Cell & Environment* **17**, 367–377.

Kukal, M.S. & Irmak, S. (2018) U.s. agro-climate in 20th century: Growing degree days, first and last frost, growing season length, and impacts on crop yields. *Scientific Reports* **8**.

Labe, Z., Ault, T. & Zurita-Milla, R. (2016) Identifying anomalously early spring onsets in the cesm large ensemble project. *Climate Dynamics* **48**, 3949–3966.

Lenz, A., Hoch, G., Körner, C. & Vitasse, Y. (2016) Convergence of leaf-out towards minimum risk of freezing damage in temperate trees. *Functional Ecology* **30**, 1–11.

Liu, Q., Piao, S., Janssens, I.A., Fu, Y., Peng, S., Lian, X., Ciais, P., Myneni, R.B., Peñuelas, J. & Wang, T. (2018) Extension of the growing season increases vegetation exposure to frost. *Nature Communications* **9**.

Liu, X., Yin, Z., Shao, X. & Qin, N. (2006) Temporal trends and variability of daily maximum and minimum, extreme temperature events, and growing season length over the eastern and central tibetan plateau during 1961–2003. *Journal of Geophysical Research: Atmospheres* **111**.

Martin, M., Gavazov, K., Körner, C., Hattenschwiler, S. & Rixen, C. (2010) Reduced early growing season freezing resistance in alpine treeline plants under elevated atmospheric CO_2. *Global Change Biology* **16**, 1057–1070.

Meier, U. (2001) Growth stages of mono-and dicotyledonous plants BBCH Monograph Edited by Uwe Meier Federal Biological Research Centre for Agriculture and Forestry. *Agriculture* **12**, 141—-147 ST —- Geochemical study of the organic mat.

Menzel, A., Helm, R. & Zang, C. (2015) Patterns of late spring frost leaf damage and recovery in a european beech (fagus sylvatica l.) stand in south-eastern germany based on repeated digital photographs. *Frontiers in Plant Science* **6**, 110.

Montwé, D., Isaac-Renton, M., Hamann, A. & Spiecker, H. (2018) Cold adaptation recorded in tree rings highlights risks associated with climate change and assisted migration. *Nature Communications* **9**.

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.

Polgar, C.A. & Primack, R.B. (2011) Leaf-out phenology of temperate woody plants: From trees to ecosystems. *New Phytologist* **191**, 926–941.

R Development Core Team (2017) R: A language and environment for statistical computing. *R Foundation for Statistical Computing, Vienna, Austria* .

Richardson, A.D., Keenan, T.F., Migliavacca, M., Ryu, Y., Sonnentag, O. & Toomey, M. (2013) Climate change, phenology, and phenological control of vegetation feedbacks to the climate system. *Agricultural and Forest Meteorology* **169**, 156 – 173.

Sakai, A. & Larcher, W. (1987) *Frost Survival of Plants*. Springer-Verlag.

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.

Schwartz, M.D. (1993) Assessing the onset of spring: A climatological perspective. *Physical Geography* **14(6)**, 536–550.

Sgubin, G., Swingedouw, D., Dayon, G., de Cortázar-Atauri, I.G., Ollat, N., Pagé, C. & van Leeuwen, C. (2018) The risk of tardive frost damage in french vineyards in a changing climate. *Agricultural and Forest Meteorology* **250-251**, 226 – 242.

Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. & Midgley, P.M. (2013) Climate change 2013: The physical science basis. contribution of working group i to the fifth assessment report of the intergovernmental panel on climate change, 1535 pp.

Templ, B., Koch, E., Bolmgren, K., Ungersböck, M., Paul, A., Scheifinger, H., Rutishauser, T., Busto, M., Chmielewski, F.M., Hájková, L., Hodzić, S., Kaspar, F., Pietragalla, B., Romero-Fresneda, R., Tolvanen, A., Vučetič, V., Zimmermann, K. & Zust, A. (2018) Pan european phenological database (pep725): a single point of access for european data. *International Journal of Biometeorology* **62**, 1109–1113.

Trouet, V., Esper, J., Graham, N., Baker, A., Scourse, J. & Frank, D. (2009) Persistent positive north atlantic oscillation mode dominated the medieval climate anomaly. *Science* .

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. & KÃÂűrner, C. (2014) The interaction between freezing tolerance and phenology in temperate deciduous trees. *Frontiers in Plant Science* **5**.

Vitra, A., Lenz, A. & Vitasse, Y. (2017) Frost hardening and dehardening potential in temperate trees from winter to budburst. *New Phytologist* **216**, 113–123.

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.

Wypych, A., Ustrnul, Z., Sulikowska, A., Chmielewski, F.M. & Bochenek, B. (2016) Spatial and temporal variability of the frost-free season in central europe and its circulation background. *International Journal of Climatology* **37**, 3340–3352.

Zohner, C.M., Benito, B.M., Svenning, J.C. & Renner, S.S. (2016) Day length unlikely to constrain climate-driven shifts in leaf-out times of northern woody plants. *Nature Climate Change* **6**, 1120–1123.

Tables and Figures

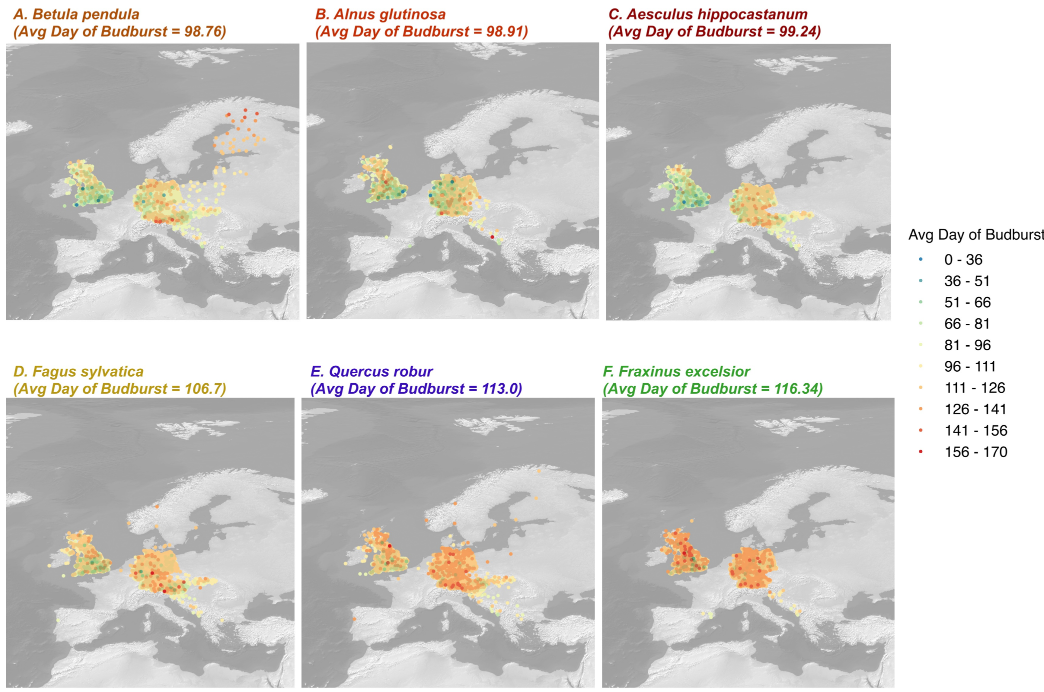

Figure 1: The average day of budburst is mapped by site for each species. Species are ordered by day of budburst starting with *Betula pendula* as the earliest budburst date to *Fraxinus excelsior*. Earlier budburst dates are blue and later budburst dates are in red.

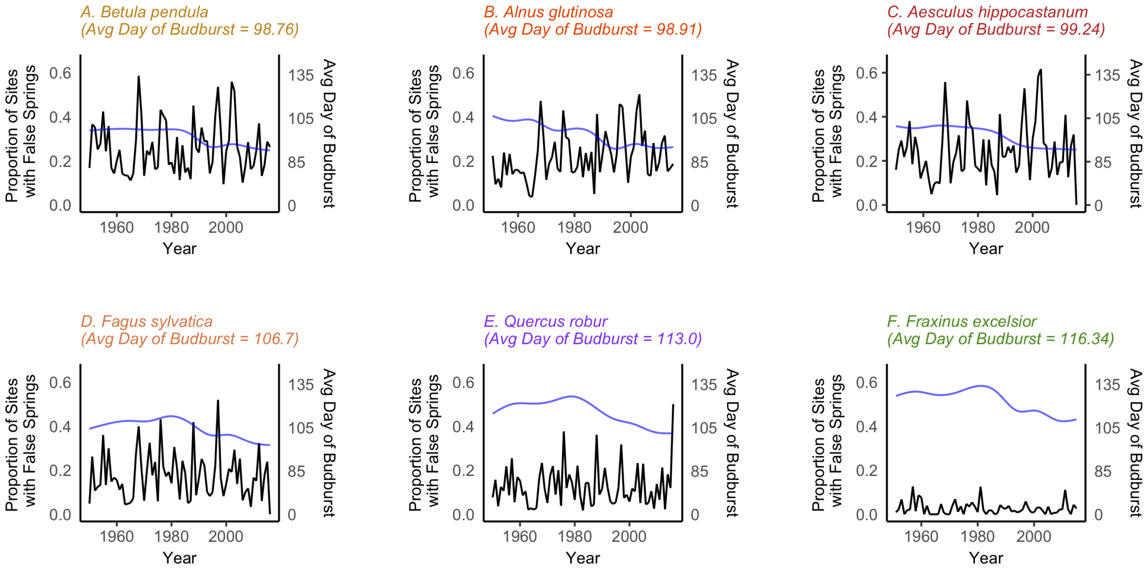

Figure 2: The black line indicates the proportion of sites that had false spring conditions for each year across all species. The blue line is a smoothing spline, indicating the trend of average day of budburst for each year for each species. Species are ordered by average day of budburst, with the earliest being *Betula pendula* and the latest being *Fraxinus excelsior*.

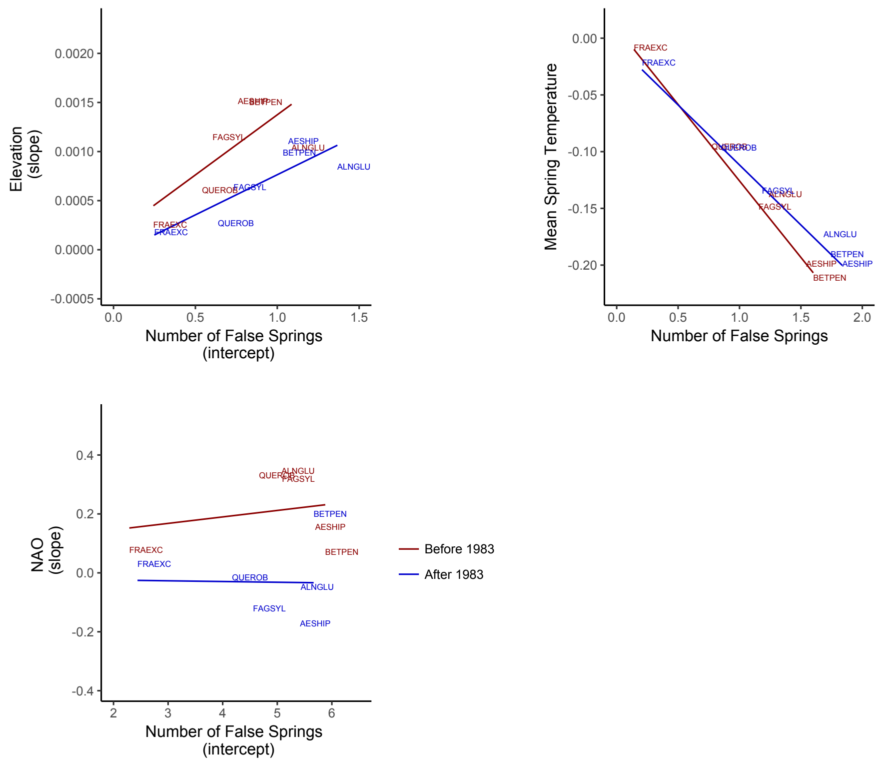

Figure 3: Model output graphed with intercept on the x-axis and the slope of the main effect on the y-axis. Data was first pooled by species and before and after 1983. (A) Shows the effects of mean spring temperature. As temperature increases, the number of false springs decreases and, before 1983, that rate of decline was more rapid. (B) As elevation increases, there are more false springs, but after 1983, the rate of increase is less. (C) There is no strong relationship between NAO-index and number of false springs, with very little change in slope with number of false springs.

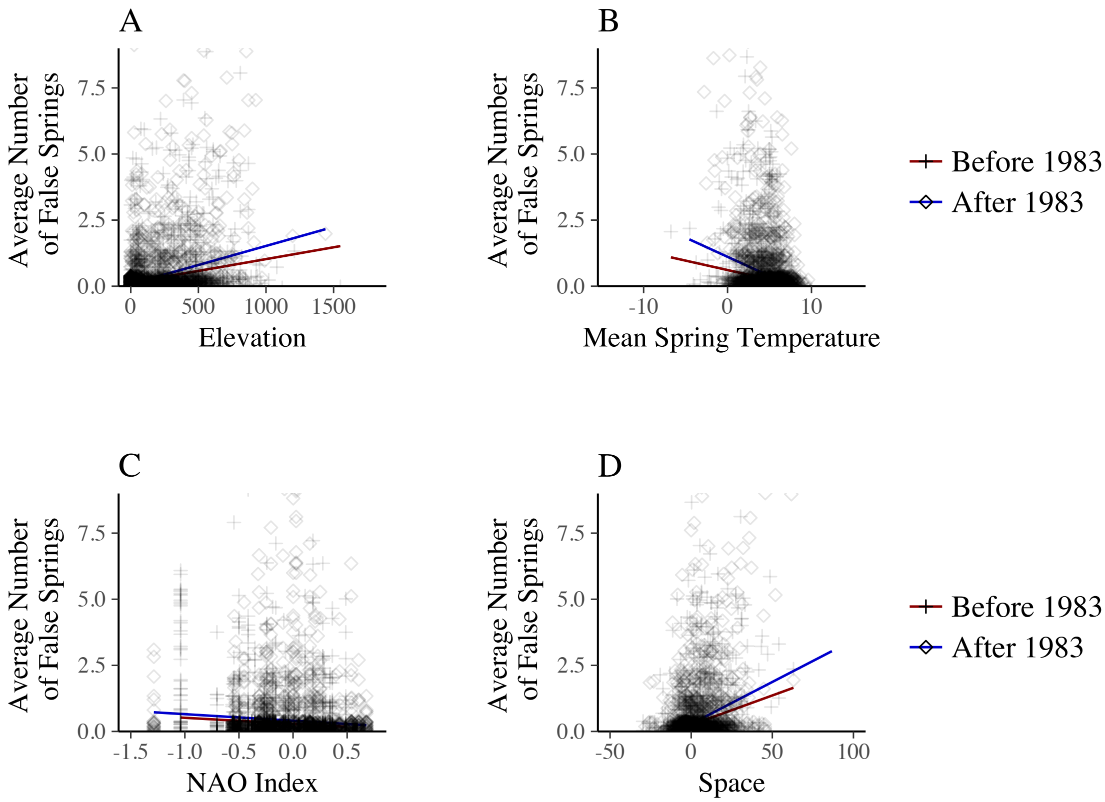

Figure 4: Series of plots showing the main effects in the model for a subset of the data. (A) As elevation increases, the number of false springs tends to increase and the rate of increase is greater after 1983. (B) As mean spring temperature increases, the number of false springs decreases and the rate of decrease is great after 1983. (C) There is no strong relationship between NAO-index and number of false springs. (D) As the space parameter increases (i.e. distance from the coast or the elevation changes) the number of false springs increases and the rate of increase is slightly greater after 1983.

Supplement: Tables and Figures

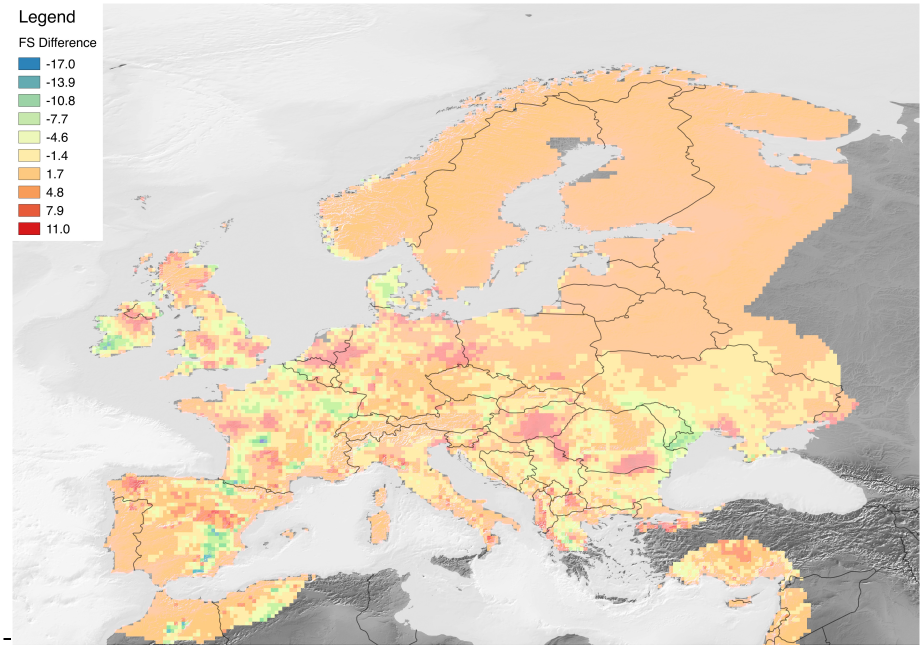

Figure 5: Number of years with freezing events that occured before temperature shifts related to climate change began (1951-1983) as compared to after reported climate shifts (1984-2016). If temperatures fell below -2°C between March 1 and June 30, a year with a spring freeze was tallied. Some regions 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.

Table 1: Data points collected for each species

Species	**Num. of Observations**	**Num. of Sites**	**Num. of Years**
Aesculus hippocastanum	232279	10158	66
Alnus glutinosa	148295	6775	66
Betula pendula	232042	10139	66
Fagus sylvatica	199848	7327	66
Fraxinus excelsior	154370	9099	65
Quercus robur	198600	8811	66

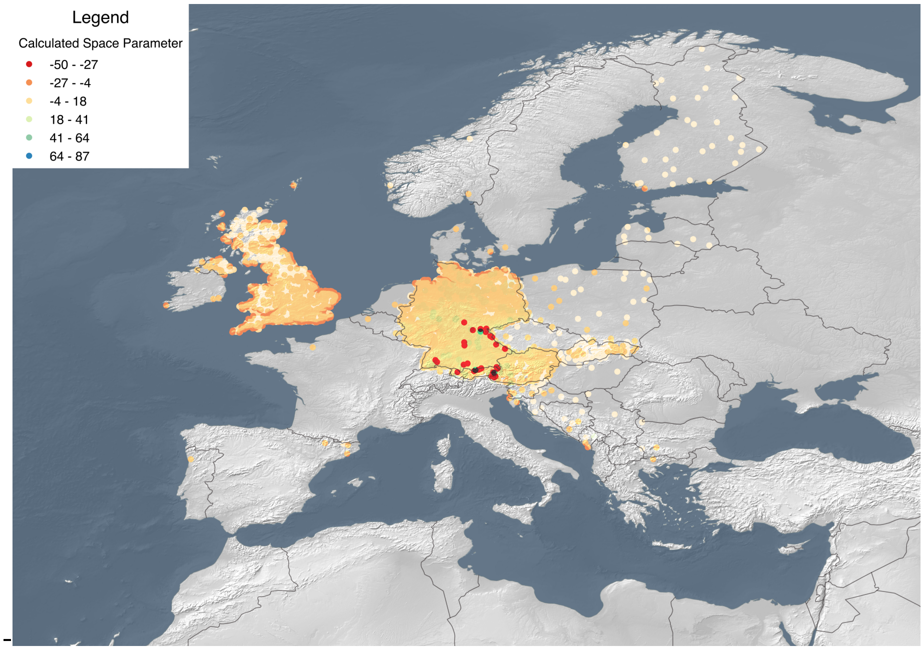

Figure 6: Space parameter values are mapped for each location to elucidate patterns in the parameter values.