

<sup>1</sup> **Regional Risk Outline**

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<sup>10</sup>

<sup>11</sup> **Introduction**

<sup>12</sup> 1. Temperate tree and shrub species are at risk of damage from late spring freezing events, also known as  
<sup>13</sup> false springs.

<sup>14</sup> (a) However, the extent of damage and the frequency and intensity of false spring events is still largely  
<sup>15</sup> unknown.

<sup>16</sup> (b) Individuals that initiate budburst and have not fully leafed out before the last spring freeze are  
<sup>17</sup> at risk of leaf tissue loss, damage to the xylem, and slowed canopy development (Gu *et al.*, 2008;  
<sup>18</sup> Hufkens *et al.*, 2012).

<sup>19</sup> (c) Temperate plants are exposed to freezing temperatures numerous times throughout the year,  
<sup>20</sup> however, individuals are most at risk to damage from stochastic spring frosts, when frost tolerance  
<sup>21</sup> is lowest (Sakai & Larcher, 1987).

<sup>22</sup> (d) The growing season is lengthening across many regions in the northern hemisphere (Chen *et al.*,  
<sup>23</sup> 2005; Liu *et al.*, 2006; Kukal & Irmak, 2018), but last spring frosts still pose a threat in many of  
<sup>24</sup> these regions (Wypych *et al.*, 2016).

<sup>25</sup> (e) False spring events can result in photosynthetic tissue loss, which could potentially impact multiple  
<sup>26</sup> years of growth and, with the growing season extending, individuals could be exposed to more frosts  
<sup>27</sup> in the future (Liu *et al.*, 2018).

<sup>28</sup> (f) For these reasons, episodic frosts are one of the largest limiting factors in species range limits  
<sup>29</sup> (Kollas *et al.*, 2014).

- 30        2. Plant phenology, which is defined as the timing of recurring life-history events such as budburst, strongly  
31        tracks shifts in climate (Cleland *et al.*, 2007; Wolkovich *et al.*, 2012).
- 32            (a) Trees and shrubs in temperate regions optimize growth by using three cues to initiate budburst:  
33              low winter temperatures, warm spring temperatures, and increasing spring daylengths.
- 34            (b) With climate change advancing, this interaction of cues may shift spring phenologies both across  
35              and within species.
- 36            (c) Due to the changing climate, spring onset is advancing and many temperate tree and shrub species  
37              are initiating leafout 4-6 days earlier per °C of warming (Wolkovich *et al.*, 2012; IPCC, 2015).
- 38            (d) However, last spring freeze dates are not predicted to advance at the same rate as spring onset  
39              in some regions of the world (Inouye, 2008; Martin *et al.*, 2010; Labe *et al.*, 2016; Sgubin *et al.*,  
40              2018), potentially amplifying the effects of false spring events in these regions.
- 41            (e) (Too redundant??) In Germany, for example, the last freeze date has advanced by 2.6 days per  
42              decade since 1955 (Zohner *et al.*, 2016).
- 43            (f) Major false spring events have been recorded in recent years and have found it can take 16-38  
44              days for trees to refoliate (Gu *et al.*, 2008; Augspurger, 2009, 2013; Menzel *et al.*, 2015), which can  
45              detrimentally affect crucial processes such as carbon uptake and nutrient cycling (Hufkens *et al.*,  
46              2012; Richardson *et al.*, 2013; Klosterman *et al.*, 2018).
- 47        3. Temperate plants have evolved to minimize false spring damage through a myriad of strategies, with  
48        the most effective being avoidance: plants must exhibit flexible spring phenologies in order to maximize  
49        growth and minimize frost risk by timing budburst effectively (Polgar & Primack, 2011; Basler &  
50        Körner, 2014).
- 51            (a) Plants growing in forest systems tend to exhibit staggered days of budburst.
- 52            (b) Lower canopy species typically initiate budburst earlier in the season in order to utilize available  
53              resources such as light, whereas larger canopy species usually initiate budburst later in the season.
- 54            (c) Thus, there is a trade-off between growing season length and frost risk.
- 55            (d) Frost tolerance greatly diminishes once individuals exit the dormancy phase (i.e. processes leading  
56              to budburst) through full leaf expansion (Vitasse *et al.*, 2014; Lenz *et al.*, 2016).
- 57            (e) Individuals that initiate budburst earlier in the season are more frost resistant (Körner *et al.*,  
58              2016), however, as climate change advances, less frost resistant individuals may start initiating  
59              budburst before the last freeze date.

- 60        4. Many studies have assessed the interplay between cue interactions and budburst dates by investigating  
61        potential latitudinal effects (Partanen, 2004; Vihera-aarnio *et al.*, 2006; Caffarra & Donnelly, 2011;  
62        Zohner *et al.*, 2016; Gauzere *et al.*, 2017).
- 63            (a) However, recent studies have demonstrated regional effects may be more closely related to false  
64            spring risk: whether via altitudinal variation (Vitra *et al.*, 2017) or distance from the coast  
65            (Wypych *et al.*, 2016).
- 66            (b) By better understanding these regional climatic implications, we may be able to determine which  
67            regions may be at risk currently and which regions may become more at risk in the future.
- 68        5. There is large debate over whether or not spring freeze damage will increase (Hänninen, 1991; Augspurger,  
69            2013; Labe *et al.*, 2016), remain the same (Scheifinger *et al.*, 2003) or even decrease (Kramer, 1994)  
70            with climate change.
- 71            (a) Some research suggests false spring incidence has declined in many regions (i.e. across parts of  
72            North America and Asia), however the prevalence of spring frosts has consistently increased across  
73            Europe since 1982 (Liu *et al.*, 2018).
- 74            (b) The North Atlantic Oscillation (NAO) index is often used to describe winter and spring circulation  
75            across Europe.
- 76            (c) More positive NAO phases tend to result in higher than average winter and early spring tempera-  
77            tures, and with climate change, higher NAO phases has correlated to even earlier budburst dates  
78            in some regions (Chmielewski & Rötzer, 2001), however it is unclear if more positive NAO phases  
79            also translates to more false springs.
- 80            (d) By improving and identifying budburst and climate trends in recent years, we could potentially  
81            amplify our predictability of future projections in false springs.
- 82            (e) For this purpose, we assessed the number of false springs that occurred across 11,684 sites around  
83            Europe, spanning altitudinal and coastal gradients, using observed phenological data (857,004  
84            observations) for six temperate, deciduous trees and combined that with daily gridded climate  
85            data for each site that extended from 1951-2016.
- 86            (f) In this study, a false spring was tallied when temperatures fell below -2.2° (Schwartz, 1993) between  
87            budburst and leafout (CITE Rethinking here?)
- 88            (g) We predicted that: (1) Earlier budburst species would experience more false springs, especially  
89            after 1983 and (2) there would be different regional effects on false spring incidence and those  
90            trends would shift when coupled with the effects of climate change.

<sub>91</sub> **Methods**

<sub>92</sub> **Phenological Data**

- <sub>93</sub> 1. Phenological data was obtained from the Pan European Phenology network (PEP725, [www.pep725.edu](http://www.pep725.edu)),  
<sub>94</sub> which provides open access phenology records across Europe (Templ *et al.*, 2018).
- <sub>95</sub> 2. Since plants are most susceptible to damage from frost between budburst and full leafout, we selected  
<sub>96</sub> only leafout data (i.e., in Meier, 2001, BBCH 11, which is defined as the point of leaf unfolding and the  
<sub>97</sub> first visible leaf stalk) from the PEP725 dataset.
- <sub>98</sub> 3. We then subtracted 12 days from the leafout date to establish a rough estimate for day of budburst  
<sub>99</sub> (Donnelly *et al.*, 2017).
- <sub>100</sub> 4. The species used in the study were *Aesculus hippocastanum* L., *Alnus glutinosa* (L.) Gaertn., *Betula*  
<sub>101</sub> *pendula* Roth., *Fagus sylvatica* Ehrh., *Fraxinus excelsior* L., *Quercus robur* L.
- <sub>102</sub> 5. Selection criteria for the species were as follows: (1) to be temperate, deciduous species that were not  
<sub>103</sub> cultivars or used for crops, (2) there were at least 140,000 observations of BBCH 11, (3) to represent  
<sub>104</sub> over half of the total number of sites available (11,684), (4) there were observations for at least 65 out  
<sub>105</sub> of the 66 years of the study (1951-2016).

<sub>106</sub> **Climate Data**

- <sub>107</sub> 1. We collected daily gridded climate data from the European Climate Assessment & Dataset (ECA&D)  
<sub>108</sub> and used the E-OBS 0.25 degree regular latitude-longitude grid from version 16.
- <sub>109</sub> 2. We used the daily minimum temperature dataset to determine if a false spring occurred.
- <sub>110</sub> 3. False springs in this study were defined as temperatures at or below -2.2°C (Schwartz, 1993).
- <sub>111</sub> 4. In order to capture regional climatic effects we calculated the mean spring temperature by using the  
<sub>112</sub> daily mean temperature from February 1 through April 30.
- <sub>113</sub> 5. Mean spring temperature was calculated – likely after chilling was accumulated – in an attempt to  
<sub>114</sub> incorporate the general effects of spring forcing temperatures in our Bayesian hierarchical model and  
<sub>115</sub> to compare differences in spring across sites (Basler & Körner, 2012; Körner *et al.*, 2016).
- <sub>116</sub> 6. We collected NAO-index data from the KNMI Climate Explorer annual NAO time series (Trouet *et al.*,  
<sub>117</sub> 2009).

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

121   **Data Analysis**

- 122     1. We used a Bayesian hierarchical model approach to analyze our data to best estimate the number of  
 123       false springs across-species levels.
- 124     2. A false spring was determined if temperatures fell below -2.2°C at least once between budburst and  
 125       leafout.
- 126     3. We fit a mixed-effects model using mean spring temperature, NAO, elevation, space, and climate change  
 127       as predictors and all two-way interactions (fixed effects) and species as modeled groups on the main  
 128       effects (random effects).
- 129     4. We scaled the elevation predictor by dividing it by 100 to be consistent with the other predictors in the  
 130       model.
- 131     5. We used a space parameter, rather than a more traditional latitude parameter, to adjust for spatial  
 132       autocorrelation issues using a minimization of Moran's *I* of the residuals (David *et al.*, 2017) (Figure  
 133       S1).
- 134     6. We then took the calculated eigenvectors determined from the MIR approach and regressed these  
 135       against the number of false springs for each datapoint to establish a spatial parameter (space).
- 136     7. (Although, we may find that space and elevation are collinear and may decide to take space out and  
 137       use elevation instead - unless space is picking up more of the distance from the coast then we'll use the  
 138       space parameter instead of elevation)
- 139     8. The Bayesian hierarchical model was fit using the brms package (Bürkner, Paul-Christian , 2017),  
 140       version 2.3.1, in R (R Development Core Team, 2017), version 3.3.1, and was written as follows: (subject  
 141       to change as per above, this is just the ideal model)

$$y_i \sim N(\alpha(i) + \beta_{MeanSpringTemp_{sp(i)}} + \beta_{NAO_{sp(i)}} + \beta_{elevation_{sp(i)}} + \beta_{space_{sp(i)}} + \beta_{ClimateChange_{sp(i)}} \\ + \beta_{MeanSpringTemp \times ClimateChange_{(i)}} + \beta_{NAO \times ClimateChange_{(i)}} \\ + \beta_{elevation \times ClimateChange_{(i)}} + \beta_{space \times ClimateChange_{(i)}} + \sigma_{sp(i)})$$

9. The  $\beta$  coefficients and  $\alpha$  were modeled at the species level:

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

...

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

139 10. We ran two chains, each with 4,000 warm-up iterations and 2,500 sampling iterations for a total of  
140 10,000 posterior samples for each predictor.

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

## 143 Results

### 144 Species variation in budburst and false spring incidence

145 1. There is variation in day of budburst across the six species and across space - BB maps Fig (should I  
146 include a small model here to demonstrate this? (i.e. fs cc + (cc|species)))

147 (a) Earlier budbursting species experienced more false spring conditions - proportion of sites Fig

148 (b) Our data supports evidence that day of budburst is advancing earlier over time, especially after  
149 the early 1980s

### 150 The effects of climatic regional variation on false spring incidence - potentially! 151 still waiting on final model results!

152 1. The relationship between the main effects and false spring as compared before and after 1983 (Fig.  
153 Main effects)

154 (a) As elevation increases, plants are exposed to more frequent false spring conditions and the rate of  
155 increase is greater under climate change.

156 (b) As mean spring temperature increases, there are fewer false springs and the rate of decrease is  
157 greater after 1983.

158 (c) NAO-index does not seem to be a strong predictor of false spring, ( discussion: which may mean  
159 that even though budburst is earlier, late spring freezes are less likely to occur in high NAO years.)

160 (d) As the space parameter increases (which captures distance from the coast and shifts in elevation),  
161 false spring incidence increased.

<sub>162</sub> Discussion & Conclusion - jumbles of thoughts right now...

- <sub>163</sub> 1. Some regions are more susceptible to false spring risk than others and, with climate change, some  
<sub>164</sub> regions that are low risk now, may become more at risk.
- <sub>165</sub> (a) The rate false spring risk is increasing at higher elevations but decreasing in regions with warmer  
<sub>166</sub> mean spring temperatures.
- <sub>167</sub> (b) Regions that are less at risk to false spring conditions with climate change may be more at risk to  
<sub>168</sub> drought.
- <sub>169</sub> (c) Thus, plants must exhibit even more flexible spring phenologies in order to keep up with the rate  
<sub>170</sub> of change.
- <sub>171</sub> 2. Individuals from more Northern provenances tend to be more susceptible to spring frost damage,  
<sub>172</sub> whereas more Southern individuals are more sensitive to fall frosts (Montwé *et al.*, 2018).
- <sub>173</sub> (a) With regional shifts in climate, will fall frosts become more damaging than spring frosts?

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290 **Tables and Figures**

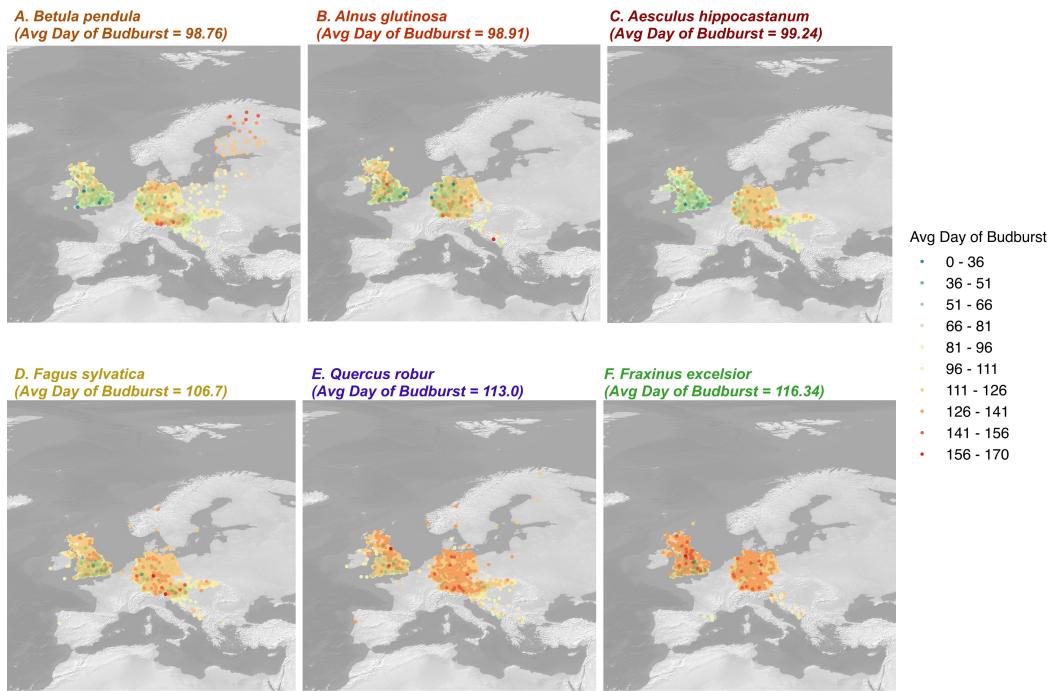


Figure 1: The average day of budburst is mapped by site for each species. Species are ordered by day of budburst starting with *Betula pendula* as the earliest budburst date to *Fraxinus excelsior*. Earlier budburst dates are blue and later budburst dates are in red.

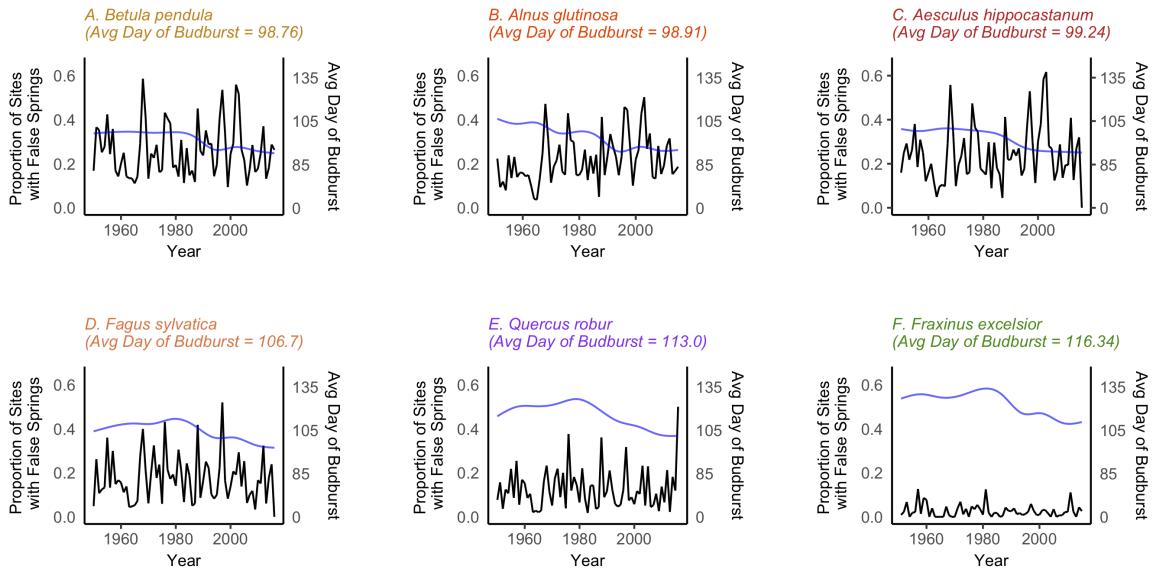


Figure 2: The black line indicates the proportion of sites that had false spring conditions for each year across all species. The blue line is a smoothing spline, indicating the trend of average day of budburst for each year for each species. Species are ordered by average day of budburst, with the earliest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

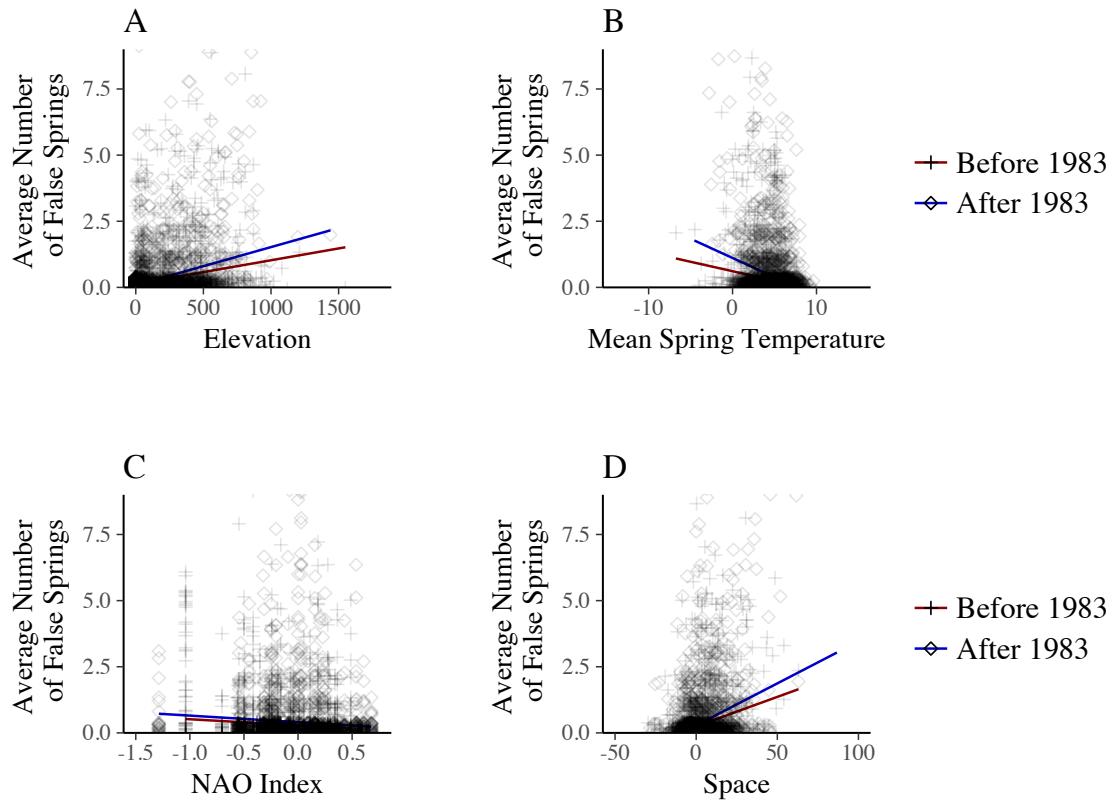


Figure 3: Series of plots showing the main effects in the model for a subset of the data. (A) As elevation increases, the number of false springs tends to increase and the rate of increase is greater after 1983. (B) As mean spring temperature increases, the number of false springs decreases and the rate 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.

<sup>291</sup> **Supplement: Tables and Figures**

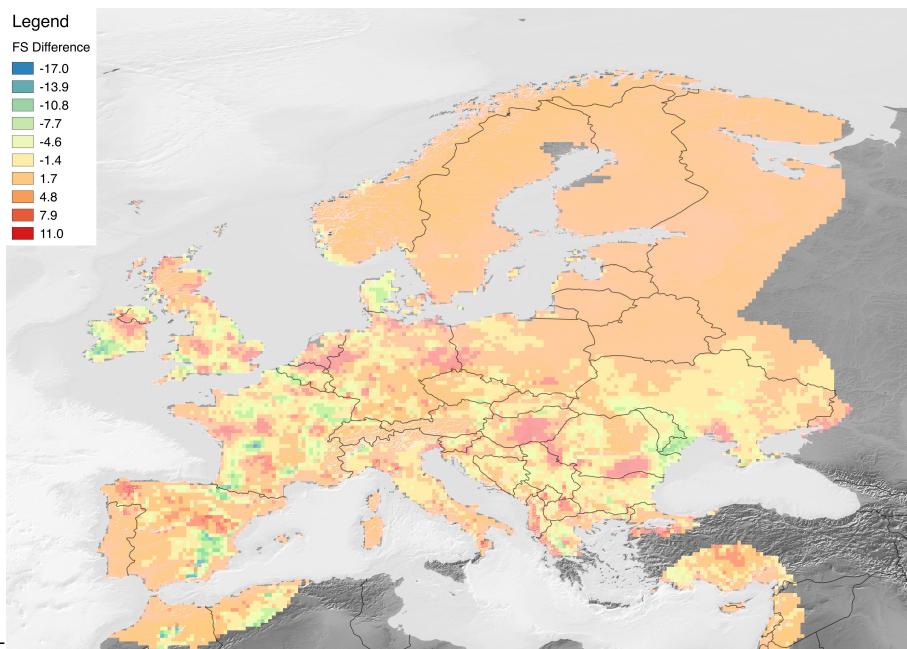


Figure 4: Number of years with freezing events that occurred before temperature shifts related to climate change began (1951-1983) as compared to after reported climate shifts (1984-2016). If temperatures fell below  $-2^{\circ}\text{C}$  between March 1 and June 30, a year with a spring freeze was tallied. 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.

<sup>292</sup>

Table 1: Data points collected for each species

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

<sup>293</sup>

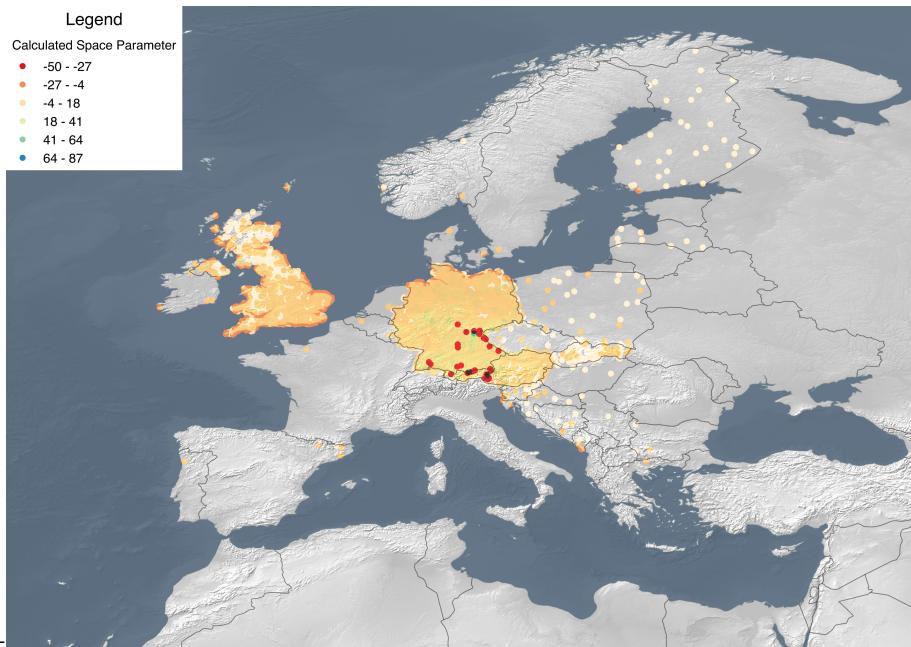


Figure 5: Space parameter values are mapped for each location to elucidate patterns in the parameter values.