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) 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).

(e) 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.

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

(a) 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.

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) or distance from the coast (Wypych *et al.*, 2016).

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

(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 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).

   (b) (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)

   (c) 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)

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

   (d) The β coefficients and α were modeled at the species level:

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

      ...

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

   (e) 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.

   (f) 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).

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234 # Tables and Figures

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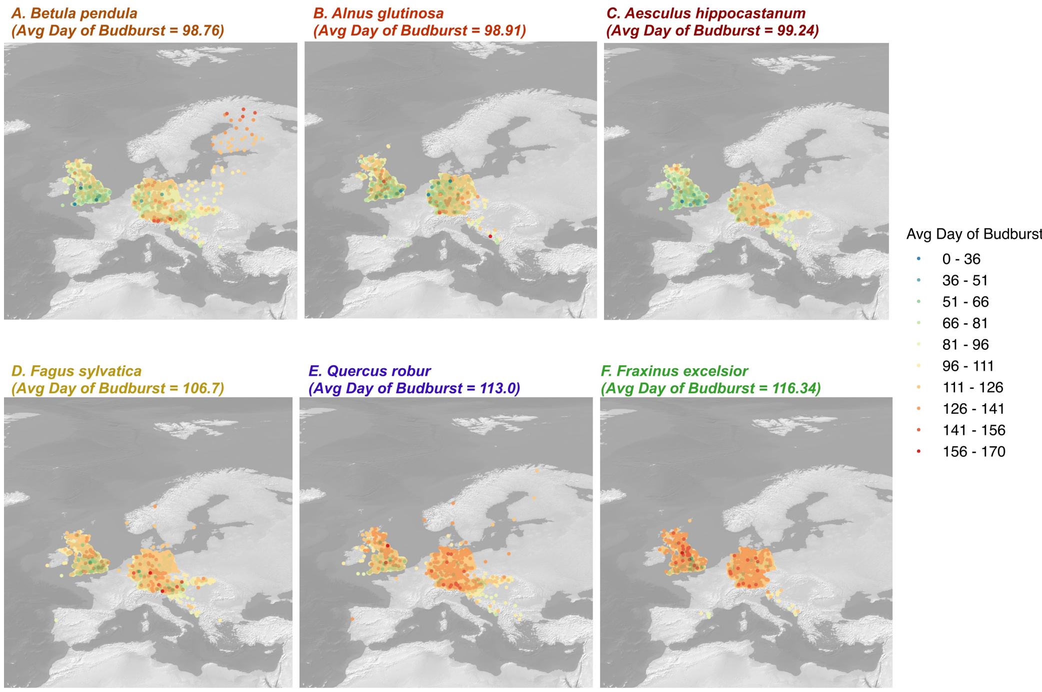

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Figure 1: The average day of budburst is mapped by site for each species. Species are ordered by day of budburst starting with *Betula pendula* as the earliest budburst date to *Fraxinus excelsior*. Earlier budburst dates are blue and later budburst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

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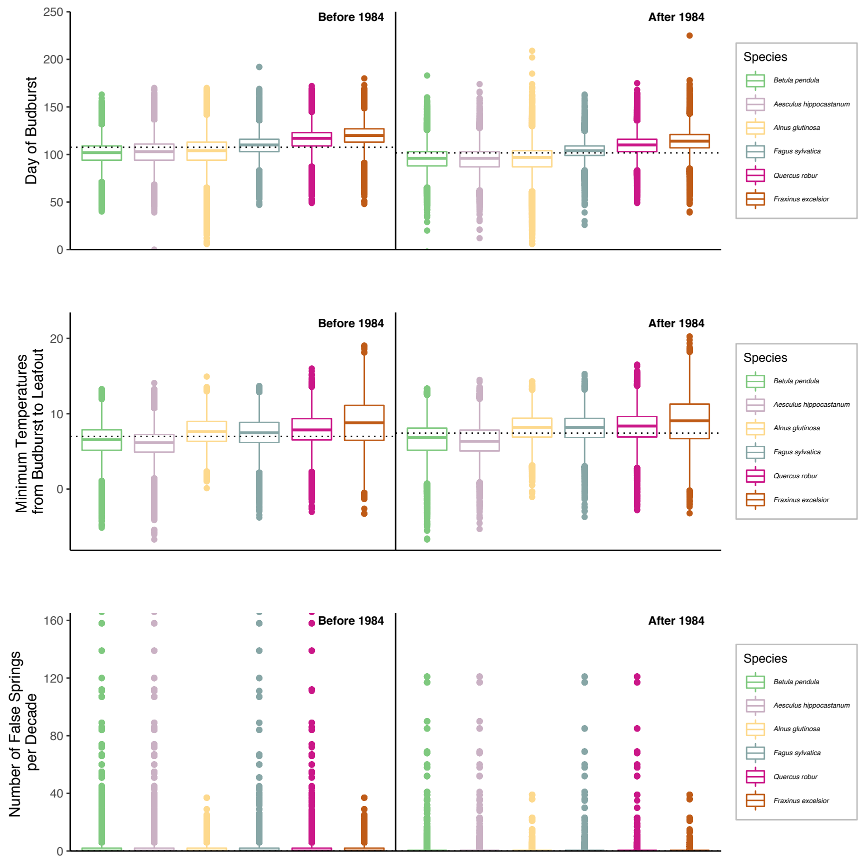
Day of Budburst
Minimum Temperatures from Budburst to Leafout
Number of False Springs per Decade
Before 1984
After 1984
Species
Betula pendula
Aesculus hippocastanum
Alnus glutinosa
Fagus sylvatica
Quercus robur
Fraxinus excelsior

Figure 2

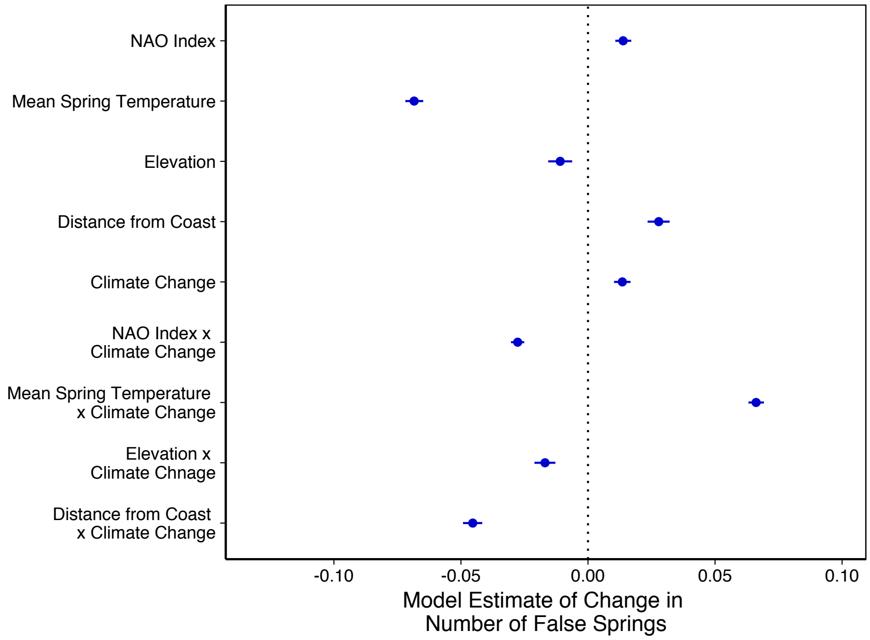
NAO Index
Mean Spring Temperature
Elevation
Distance from Coast
Climate Change
NAO Index x
Climate Change
Mean Spring Temperature
x Climate Change
Elevation x
Climate Chnage
Distance from Coast
x Climate Change
-0.10
-0.05
0.00
0.05
0.10
Model Estimate of Change in
Number of False Springs

Figure 3

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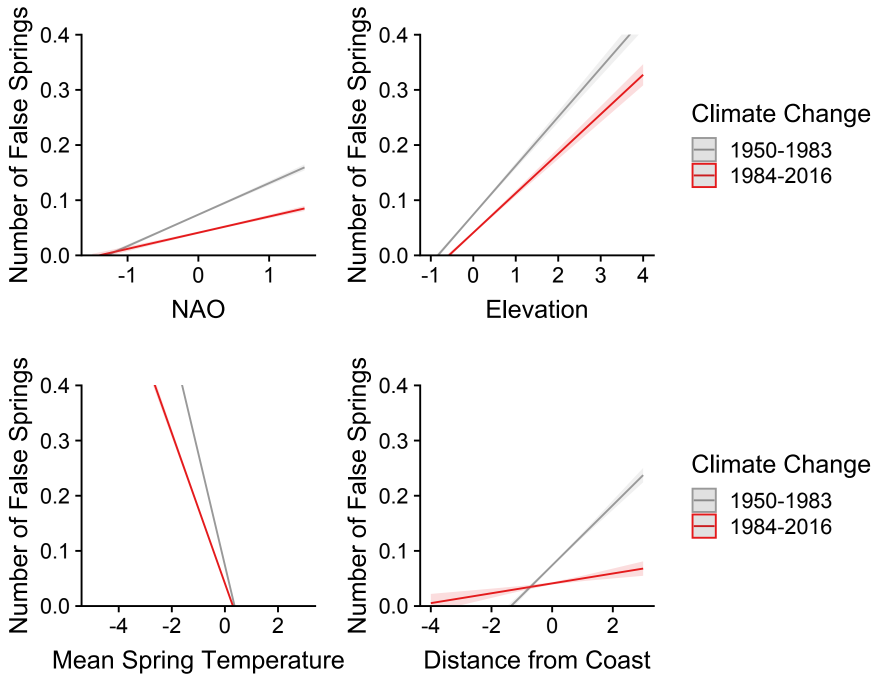

Number of False Springs
0.4
0.3
0.2
0.1
0.0
-1
0
1
NAO
Elevation
-1
0
1
2
3
4
Climate Change
1950-1983
1984-2016
Mean Spring Temperature
-4
-2
0
2
Distance from Coast

Figure 4

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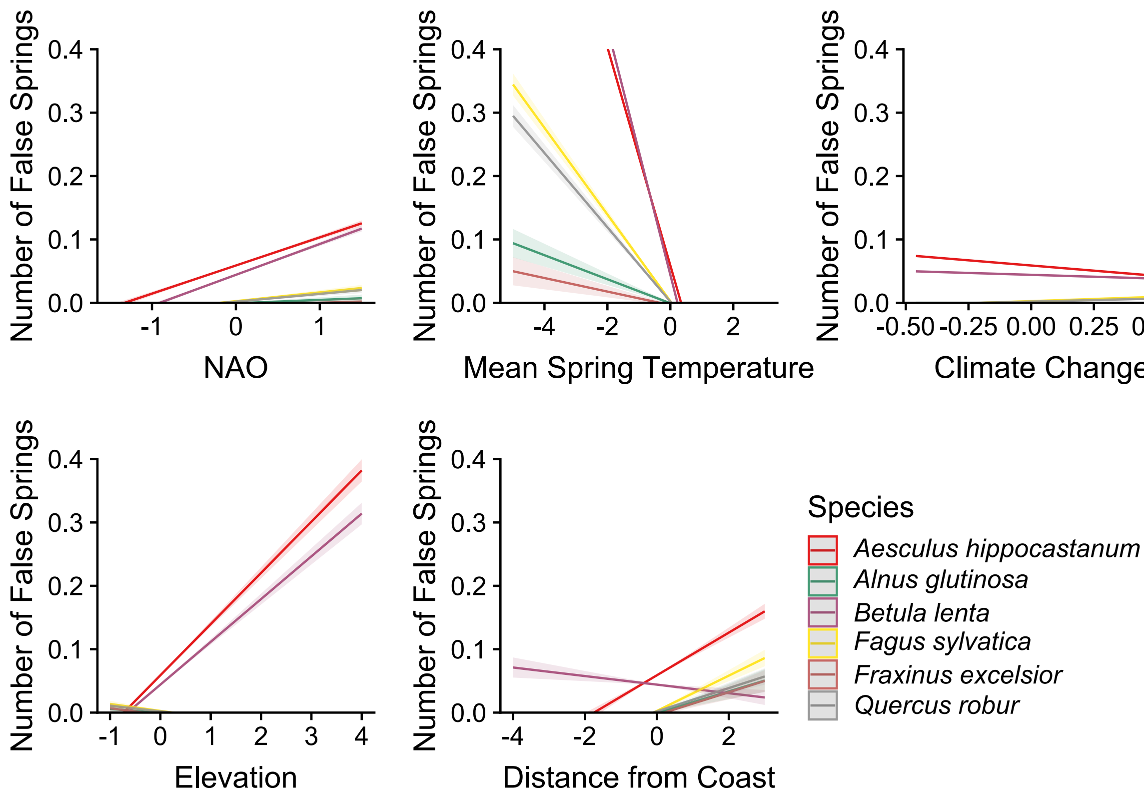

Figure 5

Supplement: Tables and Figures

Table 1: Data points collected for each species

Species	Num. of Observations	Num. of Sites	Num. of Years
Aesculus hippocastanum	216396	10158	66
Alnus glutinosa	136991	6775	66
Betula pendula	215729	10139	66
Fagus sylvatica	185949	9099	66
Fraxinus excelsior	143269	7327	65
Quercus robur	184406	8811	66

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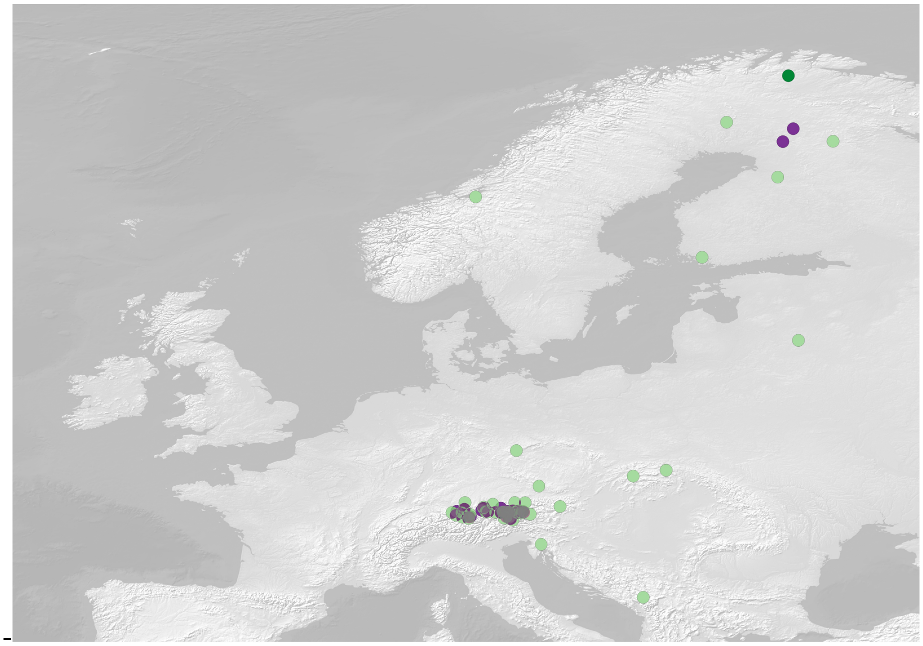

Figure 6: Space parameter values are mapped for each location to elucidate patterns in the parameter values.

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