Supplemental Materials: Climate change reshapes the drivers of false spring risk across European trees

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Methods: Space predictor

Spatial autocorrelation (SA) is a common issue in spatial ecology given that nearby spatial units tend to be more similar than units far apart, and thus, cannot be considered as independent units, which is a frequent assumption in statistical tests (Diniz-Filho *et al.*, 2003). If model residuals are spatially autocorrelated, and thus, non-independent then model coefficients and errors may be biased in a hard-to-predict way (Mauricio Bini *et al.*, 2009). On the contrary, if model residuals are not autocorrelated, then SA should not be of concern (Hawkins, 2012).

To control for spatial autocorrelation and to account for spatially structured processes independent from our environmental predictors of false springs, we generated an additional spatial predictor for the model. To avoid collinearity, we computed our spatial predictor from the residuals of a linear model of false springs as a function (Equation S1) of all other factors that are also spatially structured (e.g. spring temperature, altitude, distance to the coast), following the logic of spatial filter modelling (Diniz-Filho & Bini, 2005). The calculation of the spatial predictor followed the next steps: (a) we fit a linear model of false spring versus environmental factors, (b) we extracted the residuals of the regression Equation S1, which represent the portion of the variation in the number of false springs that is independent from the predictors in the model and (c) we utilized the residuals as our y_i values in a selection of spatial eigenvectors to retain only the minimal subset of spatial eigenvectors that are able to remove SA from model residuals. Specifically, we selected eigenvectors following the the minimization of Moran's I of the residuals (MIR) approach (Griffith & Peres-Neto, 2006; Diniz-Filho *et al.*, 2012; Bauman *et al.*, 2017). (d) Next, we fit a linear model between the residuals of Equation S1 and the subset of selected eigenvectors. And, finally, (e) we took the fitted values from this regression as our spatial predictor in our final model (see equation from main text, Equation 1), which can be interpreted as a latent variable summarizing the spatial structure in false springs that is unaccounted for by the rest of the environmental factors in our model (Morales-Castilla *et al.*, 2012).

$$
\begin{aligned}
y_i = \alpha_{[i]} &+ \beta_{NAO_{[i]}} + \beta_{MST_{[i]}} + \beta_{Elevation_{[i]}} + \beta_{DistanceCoast_{[i]}} \\
&+ \beta_{ClimateChange_{[i]}} + \beta_{NAO \times Species_{[i]}} + \beta_{MST \times Species_{[i]}} + \beta_{Elevation \times Species_{[i]}} \\
&+ \beta_{DistanceCoast \times Species_{[i]}} + \beta_{ClimateChange \times Species_{[i]}} \\
&+ \beta_{NAO \times ClimateChange_{[i]}} + \beta_{MST \times ClimateChange_{[i]}} + \beta_{Elevation \times ClimateChange_{[i]}} \\
&+ \beta_{DistanceCoast \times ClimateChange_{[i]}} + \sigma_{[i]}
\end{aligned} \tag{S1}
$$

Species rate of budburst calculations

Due to the paucity of data for BBCH 7 in the PEP725 dataset, we were unable to use observations for both budburst and leafout to determine the durations of vegetative risk. Instead, we used data from a growth chamber experiment (Flynn & Wolkovich, 2018) to determine the average number of days between budburst and leafout for our study species. We took the mean number of days between budburst and leafout for the entire experiment, which was 12 days. We compared this number to a field observation study (Donnelly *et al.*, 2017) that looked at the time between budburst and leafout across 10 species over 5 years. Finally, we assessed data that were provided by the USA National Phenology Network and the many participants who contribute to its Nature's Notebook program (USA-NPN,2019; www.usanpn.org/data/observational) for *Aesculus flava* (Sol.), *Aesculus glabra* (Willd.), *Alnus incana* (Moench.), *Betula nigra* (L.), *Betula papyrifera* (Marshall), *Fagus grandifolia* (Ehrh.), *Fraxinus americana* (L.), *Fraxinus nigra* (Marshall) and *Quercus velutina* (Lam.) and took the mean number of days between budburst and leafout. Across all three approaches, the average number of days between budburst and leafout was approximately 12 days. Thus, we expanded our rate of budburst through full leaf expansion by subtracting 12 days from the first leaf to find budburst and adding 12 days to the first leaf to find full leafout.

Again, due to a lack of BBCH 7 data, we were unable to determine species-specific averages of number of days between budburst and leafout. We used a similar approach as above by using data from the growth chamber experiment (Flynn & Wolkovich, 2018) but instead of finding whole experiment means we determined species-specific averages. We used the rate of budburst of *Acer saccharum* (Marshall) for *Aesculus hippocastanum* (Buerki *et al.*, 2010), *Alnus incana* for *Alnus glutinosa*, *Betula papyrifera* for *Betula pendula* (Wang *et al.*, 2016), *Fagus grandifolia* for *Fagus sylvatica*, *Fraxinus nigra* for *Fraxinus excelsior* and *Quercus alba* (L.) for *Quercus robur* (Hipp *et al.*, 2017).

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Supplement: Tables and Figures

Table S1: Data collected from PEP725 for each species and the calculated number of false spring years

Species	Num. of Observations	Num. of False Springs	Num. of Sites	Num. of Years
Aesculus hippocastanum	156468	44746	10157	66
Alnus glutinosa	91094	27296	6775	65
Betula pendula	154897	46685	10139	66
Fagus sylvatica	129133	29237	9099	66
Fraxinus excelsior	92665	8256	7327	65
Quercus robur	131635	16657	8811	66

Table S2: Mean day of budburst and standard deviation for each species for before (1951-1983) and after recent climate change (1984-2016).

	1951-1983		1984-2016	
	mean	sd	mean	sd
Aesculus hippocastanum	102.2	12.44	95.35	12.09
Alnus glutinosa	102.8	14.81	94.90	14.71
Betula pendula	101.3	11.76	95.44	11.25
Fagus sylvatica	109.1	9.978	103.7	9.623
Fraxinus excelsior	119.4	11.79	113.5	11.53
Quercus robur	115.9	11.31	109.6	10.95

Table S3: Summary of simple linear regression model of day of budburst before and after climate change across species.

	mean	2%	98%
Intercept	102.27	102.18	102.36
Climate Change	-6.98	-7.13	-6.84
Alnus glutinosa	0.61	0.45	0.77
Betula pendula	-0.89	-1.02	-0.76
Fagus sylvatica	6.85	6.71	6.98
Fraxinus excelsior	17.16	17.01	17.33
Quercus robur	13.67	13.53	13.81
Climate Change x *Alnus glutinosa*	-0.97	-1.20	-0.74
Climate Change x *Betula pendula*	1.06	0.86	1.26
Climate Change x *Fagus sylvatica*	1.61	1.41	1.82
Climate Change x *Fraxinus excelsior*	1.07	0.84	1.30
Climate Change x *Quercus robur*	0.67	0.46	0.88

Table S4: Summary of simple linear regression model of average minimum temperature between budburst and leafout before and after climate change across species.

	mean	2%	98%
Intercept	5.99	5.97	6.00
Climate Change	0.83	0.80	0.85
Alnus glutinosa	1.65	1.62	1.68
Betula pendula	0.50	0.48	0.53
Fagus sylvatica	1.50	1.47	1.52
Fraxinus excelsior	2.76	2.73	2.79
Quercus robur	1.88	1.86	1.91
Climate Change x *Alnus glutinosa*	-0.04	-0.08	0.01
Climate Change x *Betula pendula*	-0.31	-0.35	-0.27
Climate Change x *Fagus sylvatica*	0.08	0.04	0.11
Climate Change x *Fraxinus excelsior*	-0.26	-0.30	-0.22
Climate Change x *Quercus robur*	-0.10	-0.14	-0.06

Table S5: Summary of simple linear regression model of the number of false springs before and after climate change across species.

	mean	2%	98%
Intercept	5.56	5.52	5.59
Climate Change	1.26	1.21	1.30
Alnus glutinosa	-1.22	-1.27	-1.17
Betula pendula	0.13	0.09	0.17
Fagus sylvatica	-0.94	-0.98	-0.89
Fraxinus excelsior	-3.73	-3.78	-3.68
Quercus robur	-2.98	-3.03	-2.94
Climate Change x *Alnus glutinosa*	1.21	1.14	1.28
Climate Change x *Betula pendula*	0.08	0.01	0.15
Climate Change x *Fagus sylvatica*	-1.41	-1.48	-1.34
Climate Change x *Fraxinus excelsior*	-1.56	-1.64	-1.49
Climate Change x *Quercus robur*	-1.43	-1.50	-1.36

Table S6: Summary of Bernoulli model with the effects of species, climatic and geographical predictors on false spring risk.

	mean	2%	10%	25%	75%	90%	98%
Intercept	-0.42	-0.43	-0.43	-0.42	-0.41	-0.41	-0.41
NAO Index	0.26	0.23	0.24	0.25	0.26	0.28	0.28
Mean Spring Temperature	-0.20	-0.24	-0.23	-0.21	-0.19	-0.18	-0.17
Distance from Coast	0.28	0.25	0.26	0.27	0.29	0.31	0.32
Elevation	0.29	0.25	0.26	0.28	0.30	0.32	0.33
Space Parameter	-0.01	-0.04	-0.03	-0.02	-0.01	0.00	0.01
Climate Change	0.12	0.09	0.10	0.11	0.13	0.14	0.15
Alnus glutinosa	0.02	-0.00	0.01	0.01	0.03	0.03	0.04
Betula pendula	0.08	0.06	0.07	0.07	0.08	0.09	0.10
Fagus sylvatica	-0.54	-0.56	-0.56	-0.55	-0.54	-0.53	-0.52
Fraxinus excelsior	-1.68	-1.71	-1.70	-1.69	-1.67	-1.66	-1.65
Quercus robur	-1.26	-1.28	-1.27	-1.26	-1.25	-1.24	-1.23
NAO Index x *Alnus glutinosa*	-0.10	-0.15	-0.13	-0.11	-0.09	-0.07	-0.05
NAO Index x *Betula pendula*	-0.07	-0.11	-0.09	-0.08	-0.06	-0.04	-0.03
NAO Index x *Fagus sylvatica*	0.08	0.03	0.05	0.07	0.09	0.11	0.12
NAO Index x *Fraxinus excelsior*	-0.08	-0.15	-0.13	-0.10	-0.06	-0.04	-0.02
NAO Index x *Quercus robur*	-0.01	-0.06	-0.04	-0.02	0.01	0.03	0.05
Mean Spring Temperature x *Alnus glutinosa*	0.18	0.13	0.14	0.16	0.20	0.22	0.23
Mean Spring Temperature x *Betula pendula*	-0.02	-0.06	-0.05	-0.03	-0.00	0.01	0.03
Mean Spring Temperature x *Fagus sylvatica*	-0.16	-0.21	-0.20	-0.18	-0.15	-0.13	-0.12
Mean Spring Temperature x *Fraxinus excelsior*	0.26	0.18	0.21	0.24	0.28	0.31	0.34
Mean Spring Temperature x *Quercus robur*	0.04	-0.01	0.00	0.03	0.06	0.08	0.10
Distance from Coast x *Alnus glutinosa*	-0.04	-0.10	-0.08	-0.06	-0.03	-0.00	0.01
Distance from Coast x *Betula pendula*	0.01	-0.03	-0.02	0.00	0.03	0.05	0.06
Distance from Coast x *Fagus sylvatica*	0.11	0.06	0.07	0.09	0.12	0.15	0.16
Distance from Coast x *Fraxinus excelsior*	0.34	0.27	0.29	0.32	0.37	0.40	0.42
Distance from Coast x *Quercus robur*	0.00	-0.06	-0.04	-0.01	0.02	0.05	0.06
Elevation x *Alnus glutinosa*	0.06	-0.00	0.02	0.04	0.08	0.11	0.13
Elevation x *Betula pendula*	0.05	-0.00	0.01	0.03	0.06	0.08	0.10
Elevation x *Fagus sylvatica*	-0.03	-0.09	-0.07	-0.05	-0.01	0.01	0.02
Elevation x *Fraxinus excelsior*	-0.34	-0.43	-0.40	-0.37	-0.32	-0.28	-0.26
Elevation x *Quercus robur*	-0.10	-0.16	-0.15	-0.12	-0.08	-0.06	-0.04
Space Parameter x *Alnus glutinosa*	0.01	-0.03	-0.02	0.00	0.02	0.04	0.05
Space Parameter x *Betula pendula*	-0.01	-0.05	-0.04	-0.02	-0.00	0.01	0.02
Space Parameter x *Fagus sylvatica*	-0.05	-0.09	-0.08	-0.07	-0.04	-0.03	-0.02
Space Parameter x *Fraxinus excelsior*	0.03	-0.03	-0.01	0.01	0.05	0.07	0.09
Space Parameter x *Quercus robur*	0.00	-0.04	-0.03	-0.01	0.01	0.03	0.05
Climate Change x *Alnus glutinosa*	0.06	0.01	0.02	0.04	0.07	0.09	0.10
Climate Change x *Betula pendula*	0.04	0.00	0.02	0.03	0.05	0.07	0.08
Climate Change x *Fagus sylvatica*	-0.30	-0.34	-0.33	-0.31	-0.28	-0.27	-0.25
Climate Change x *Fraxinus excelsior*	-0.40	-0.46	-0.44	-0.41	-0.38	-0.35	-0.34
Climate Change x *Quercus robur*	-0.30	-0.35	-0.34	-0.32	-0.29	-0.27	-0.26
NAO Index x Climate Change	-1.10	-1.13	-1.12	-1.11	-1.09	-1.08	-1.07
Mean Spring Temperature x Climate Change	0.07	0.04	0.05	0.06	0.08	0.09	0.10
Distance from Coast x Climate Change	0.00	-0.03	-0.02	-0.01	0.01	0.03	0.03
Elevation x Climate Change	-0.27	-0.31	-0.30	-0.28	-0.26	-0.25	-0.24
Space Parameter x Climate Change	-0.04	-0.06	-0.06	-0.04	-0.03	-0.02	-0.01

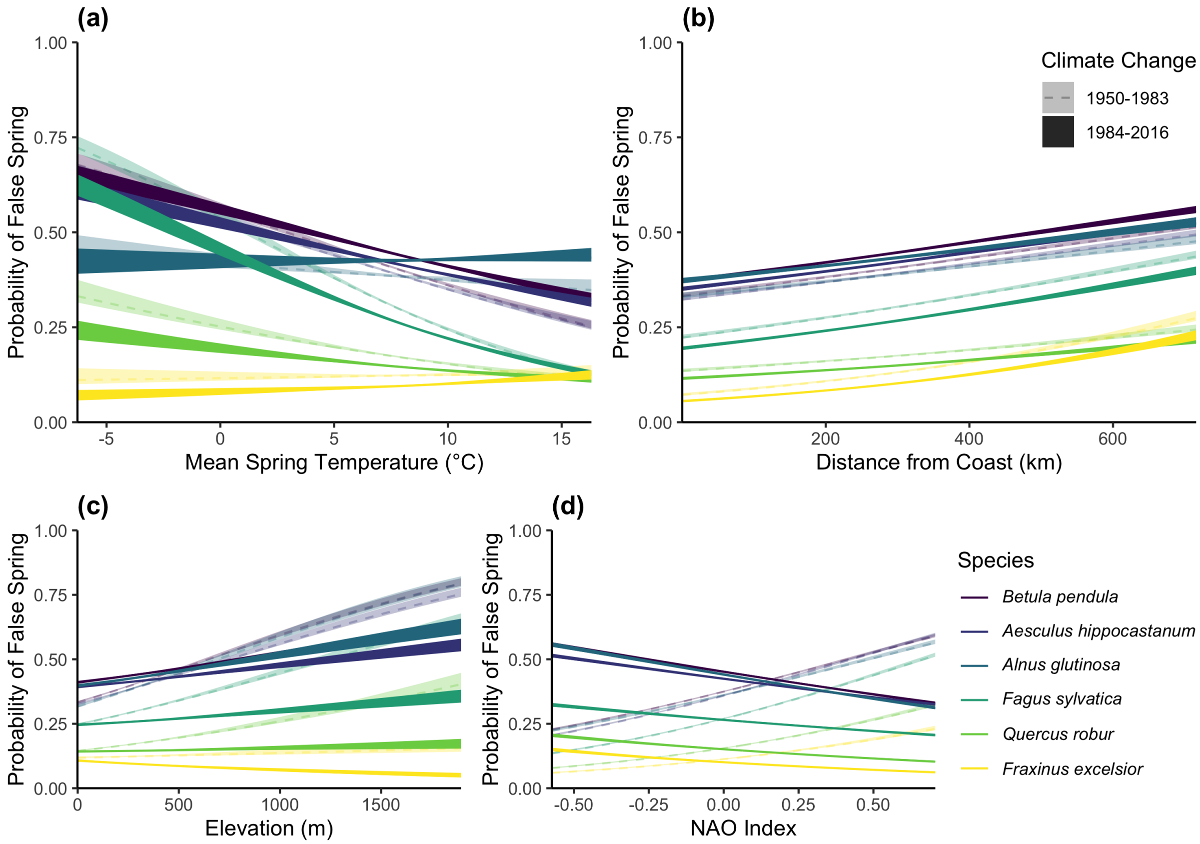

Figure S1: Average predictive comparisons for all climate change interactions with each of the main effects (i.e., mean spring temperature, distance from the coast, elevation, and NAO index) for all species. Shading around the lines represent the 98% uncertainty intervals.

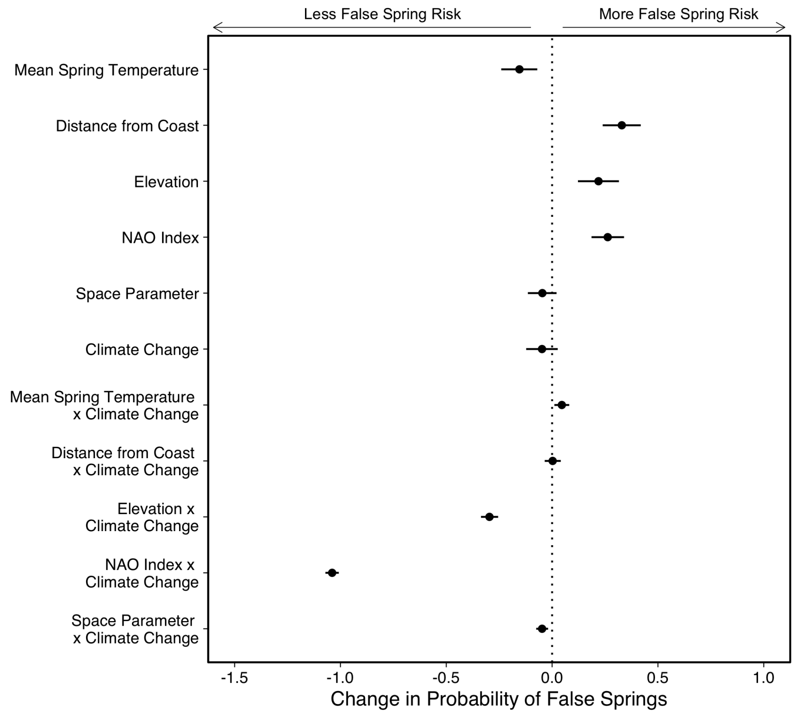

Figure S2: Effects of species, climatic and geographical predictors on false spring risk with different rates of leafout for each species. More positive values indicate an increased probability of a false spring whereas more negative values suggest a lower probability of a false spring. Dots and lines show means and 98% uncertainty intervals. See Table S7 for full model output.

Table S7: Summary of Bernoulli model of false spring risk with different rates of leafout for each species.

	mean	2%	10%	25%	75%	90%	98%
Intercept	-0.53	-0.55	-0.54	-0.54	-0.53	-0.52	-0.52
NAO Index	0.27	0.25	0.25	0.27	0.28	0.30	0.30
Mean Spring Temperature	-0.24	-0.27	-0.26	-0.25	-0.23	-0.21	-0.21
Distance from Coast	0.29	0.25	0.26	0.28	0.30	0.31	0.32
Elevation	0.25	0.22	0.23	0.24	0.26	0.28	0.29
Space Parameter	-0.02	-0.05	-0.04	-0.03	-0.01	-0.00	0.00
Climate Change	0.13	0.10	0.11	0.12	0.13	0.15	0.15
Alnus glutinosa	0.13	0.11	0.12	0.12	0.14	0.15	0.15
Betula pendula	0.08	0.06	0.06	0.07	0.08	0.09	0.09
Fagus sylvatica	-1.55	-1.58	-1.57	-1.56	-1.54	-1.53	-1.53
Fraxinus excelsior	-2.32	-2.36	-2.35	-2.33	-2.31	-2.29	-2.28
Quercus robur	-1.93	-1.96	-1.95	-1.94	-1.92	-1.91	-1.91
NAO Index x *Alnus glutinosa*	-0.13	-0.17	-0.16	-0.14	-0.11	-0.10	-0.08
NAO Index x *Betula pendula*	-0.07	-0.11	-0.10	-0.08	-0.06	-0.04	-0.03
NAO Index x *Fagus sylvatica*	0.19	0.13	0.15	0.17	0.20	0.23	0.25
NAO Index x *Fraxinus excelsior*	-0.11	-0.19	-0.17	-0.13	-0.09	-0.05	-0.03
NAO Index x *Quercus robur*	0.05	-0.01	0.01	0.03	0.07	0.10	0.11
Mean Spring Temperature x *Alnus glutinosa*	0.21	0.16	0.18	0.20	0.23	0.25	0.27
Mean Spring Temperature x *Betula pendula*	-0.01	-0.05	-0.04	-0.02	0.01	0.02	0.04
Mean Spring Temperature x *Fagus sylvatica*	-0.17	-0.23	-0.21	-0.19	-0.15	-0.13	-0.11
Mean Spring Temperature x *Fraxinus excelsior*	0.40	0.30	0.33	0.37	0.43	0.47	0.49
Mean Spring Temperature x *Quercus robur*	0.06	-0.01	0.01	0.04	0.08	0.11	0.13
Distance from Coast x *Alnus glutinosa*	-0.05	-0.10	-0.09	-0.06	-0.03	-0.01	0.01
Distance from Coast x *Betula pendula*	0.01	-0.03	-0.02	-0.00	0.03	0.05	0.06
Distance from Coast x *Fagus sylvatica*	0.07	0.00	0.02	0.05	0.09	0.12	0.13
Distance from Coast x *Fraxinus excelsior*	0.29	0.19	0.22	0.26	0.32	0.36	0.39
Distance from Coast x *Quercus robur*	-0.08	-0.15	-0.13	-0.10	-0.06	-0.03	-0.00
Elevation x *Alnus glutinosa*	0.10	0.03	0.05	0.08	0.12	0.14	0.16
Elevation x *Betula pendula*	0.05	0.00	0.01	0.04	0.06	0.09	0.10
Elevation x *Fagus sylvatica*	-0.11	-0.18	-0.16	-0.13	-0.09	-0.07	-0.05
Elevation x *Fraxinus excelsior*	-0.25	-0.36	-0.33	-0.28	-0.22	-0.17	-0.14
Elevation x *Quercus robur*	0.02	-0.06	-0.04	-0.00	0.04	0.07	0.09
Space Parameter x *Alnus glutinosa*	0.00	-0.04	-0.03	-0.01	0.01	0.03	0.04
Space Parameter x *Betula pendula*	-0.01	-0.04	-0.03	-0.02	0.00	0.02	0.03
Space Parameter x *Fagus sylvatica*	-0.08	-0.13	-0.12	-0.10	-0.07	-0.05	-0.03
Space Parameter x *Fraxinus excelsior*	-0.03	-0.11	-0.09	-0.06	-0.01	0.02	0.04
Space Parameter x *Quercus robur*	-0.03	-0.09	-0.07	-0.05	-0.02	0.01	0.02
Climate Change x *Alnus glutinosa*	0.05	0.01	0.02	0.04	0.06	0.08	0.10
Climate Change x *Betula pendula*	0.05	0.01	0.02	0.04	0.06	0.07	0.09
Climate Change x *Fagus sylvatica*	-0.34	-0.39	-0.38	-0.36	-0.32	-0.30	-0.29
Climate Change x *Fraxinus excelsior*	-0.45	-0.53	-0.50	-0.47	-0.42	-0.39	-0.37
Climate Change x *Quercus robur*	-0.35	-0.41	-0.39	-0.37	-0.33	-0.31	-0.29
NAO Index x Climate Change	-1.04	-1.07	-1.06	-1.05	-1.03	-1.02	-1.01
Mean Spring Temperature x Climate Change	0.05	0.01	0.02	0.04	0.06	0.07	0.08
Distance from Coast x Climate Change	0.00	-0.03	-0.02	-0.01	0.01	0.03	0.04
Elevation x Climate Change	-0.30	-0.34	-0.32	-0.31	-0.28	-0.27	-0.25
Space Parameter x Climate Change	-0.05	-0.08	-0.07	-0.06	-0.04	-0.03	-0.02

..//analyses/figures/model_output_98_fivelong.png

Figure S3: Effects of species, climatic and geographical predictors on false spring risk with a lower temperature threshold (-5°C) for defining a false spring. More positive values indicate an increased probability of a false spring whereas more negative values suggest a lower probability of a false spring. Dots and lines show means and 98% uncertainty intervals. See Table ?? for full model output.

```
## Error:  '\c' is an unrecognized escape in character string starting ""Summary of Bernoulli model of false spring risk with a lower temperature threshold (-5$^{\c"
```

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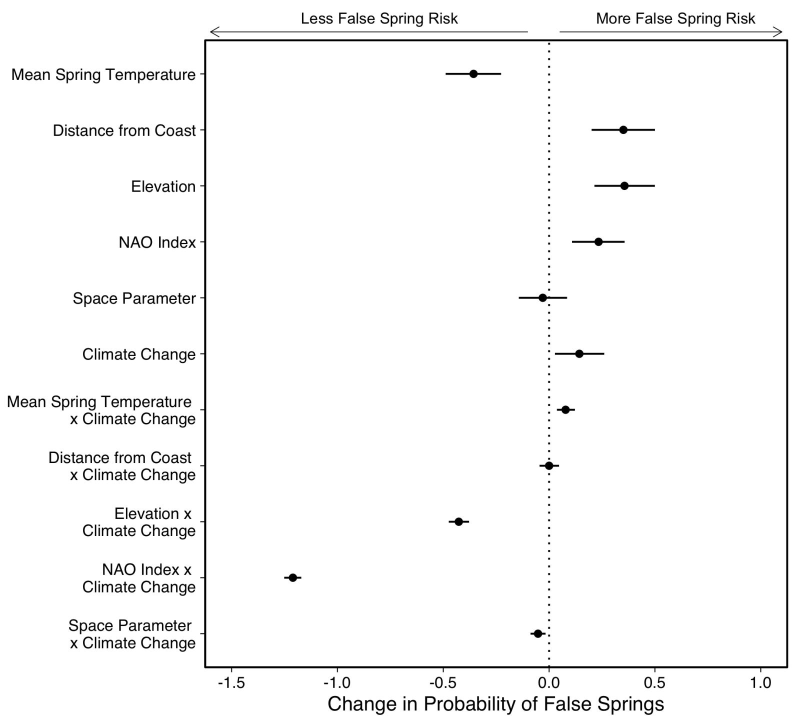

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Figure S4: Effects of species, climatic and geographical predictors on false spring risk with a lower temperature threshold (-5°C) for early-leafout species (i.e., *Aesculus hippocastanum*, *Alnus glutinosa* and *Betula pendula*) and a higher temperature threshold (-2.2°C) for late-leafout species (i.e., *Fagus sylvatica*, *Fraxinus excelsior* and *Quercus robur*). More positive values indicate an increased probability of a false spring whereas more negative values suggest a lower probability of a false spring. Dots and lines show means and 98% uncertainty intervals. See Table **??** for full model output.

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```
## Error:  '\c' is an unrecognized escape in character string starting ""Summary of Bernoulli
model of false spring risk with with a lower temperature threshold (-5$^{\c"
```