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SUPPLEMENTARY INFORMATION

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Extinction debt and colonization credit delay range shifts of eastern North American trees

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Supplementary Methods

To quantify residual spatial autocorrelation from the colonization-extinction (CE) models (and thus identify species for which additional environmental factors may influence CE rates), we examined the residuals of the models for spatial autocorrelation using the Moran's I statistic. We computed Moran's I for lag distances ranging from 0 to 700 km, then produced correlograms for each species (Supplementary Figure 9). Uncertainty in Moran's I was quantified by computing residual autocorrelation across the posterior distributions of all parameters.

To explore how a spatially explicit analysis would influence parameter estimates, we implemented a spatial version of the model using the stochastic partial differential equation (SPDE) approach of [1]. The SPDE approach estimates a multivariate Gaussian random field over the spatial domain of the model, with spatial covariance among sampled points modelled using the Matern$^{3/2}$ kernel function. We implemented this version of the model using the R-INLA software package [2]. We were unable to fit the complete model in the manner, as the implementation we used did not allow us to account for prevalence and uneven time intervals (Main Text Eqn. 2). Thus, we fit only the extinction portion of the model using the subset of the data with 5-year sampling intervals. We selected this interval because it represents the large majority of sample points (53%) and provides the greatest coverage. For all comparisons, we also re-fit the original nonspatial version of the extinction model using the same subset. This allowed us to distinguish an effect of including space from an effect of subsetting the data.

References

[1] Lindgren, F., Lindström, J. & Rue, H. *An explicit link between Gaussian fields and Gaussian Markov random fields: The SPDE approach* (Mathematical Statistics, Centre for Mathematical Sciences, Faculty of Engineering, Lund University, 2010).

[2] Rue, H., Martino, S. & Chopin, N. Approximate bayesian inference for latent gaussian models by using integrated nested laplace approximations. *Journal of the royal statistical society: Series b (statistical methodology)* **71**, 319–392 (2009).

Supplemental Table 1: List of species studied and the number of observations in the database.

Scientific name	English name	Presences	Absences	Colonizations	Extinctions
Temperate					
Acer rubrum	Red maple	30403	52803	2684	1591
Acer saccharum	Sugar maple	17088	68202	953	663
Fagus grandifolia	American beech	8148	75958	732	498
Fraxinus americana	American ash	6866	77734	873	779
Fraxinus nigra	Black ash	3140	60131	399	304
Quercus macrocarpa	Bur oak	1763	58916	186	159
Quercus rubra	Northern red oak	9901	74585	915	1213
Tsuga canadensis	Eastern hemlock	5086	66947	297	213
Transitional					
Betula alleghaniensis	Yellow birch	12271	68023	899	766
Pinus resinosa	Red pine	1818	66112	112	108
Pinus strobus	White pine	6578	79137	660	345
Populus grandidentata	Large-tooth aspen	3090	69672	499	577
Boreal					
Abies balsamea	Balsam fir	22497	37265	2521	2182
Betula papyrifera	Paper birch	17466	40885	1624	1665
Larix laricina	Tamrack	2307	57266	242	151
Picea glauca	White spruce	9268	49654	1530	1200
Picea mariana	Black spruce	12334	43198	980	914
Picea rubens	Red spruce	7275	42744	777	581
Pinus banksiana	Jack pine	2530	54988	138	243
Populous tremuloides	Quaking aspen	10883	52490	1089	1396
Thuja occidentalis	Northern white cedar	6628	64925	288	266

Supplemental Table 2: Predicted mean age with standard error (SE) for selected species at 12.7 cm diameter at breast height (DBH), the minimum tree size considered in our analyses

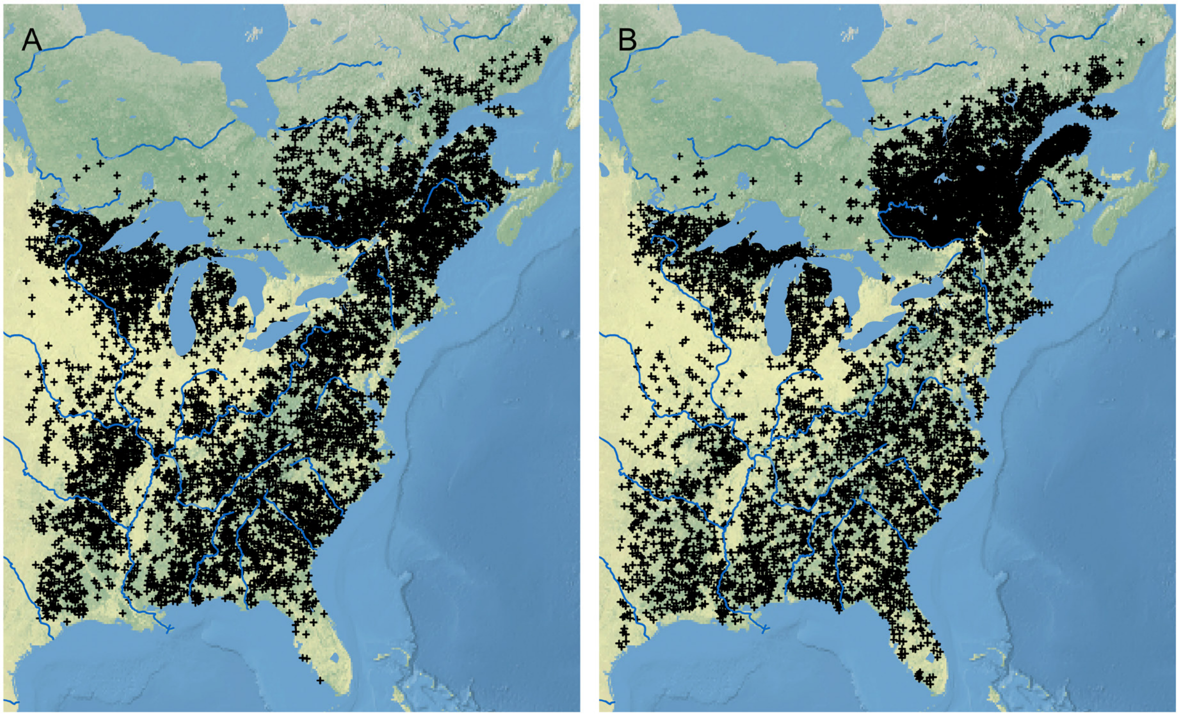
Species	Age (years)	SE
Acer rubrum	43.28	0.24
Acer saccharum	47.35	0.24
Fagus grandifolia	55.03	0.63
Fraxinus nigra	53.13	0.92
Quercus rubra	46.65	0.80
Tsuga canadensis	58.13	1.07
Pinus resinosa	30.31	2.71
Pinus strobus	43.75	0.79
Abies balsamea	53.57	0.13
Betula papyrifera	46.88	0.14
Larix laricina	53.43	1.04
Picea glauca	46.70	0.36
Picea mariana	88.80	0.19
Picea rubens	51.44	0.63
Pinus banksiana	48.12	0.21
Thuja occidentalis	60.80	0.48

Supplemental Table 3: Evaluation statistics for predictions of species ranges.

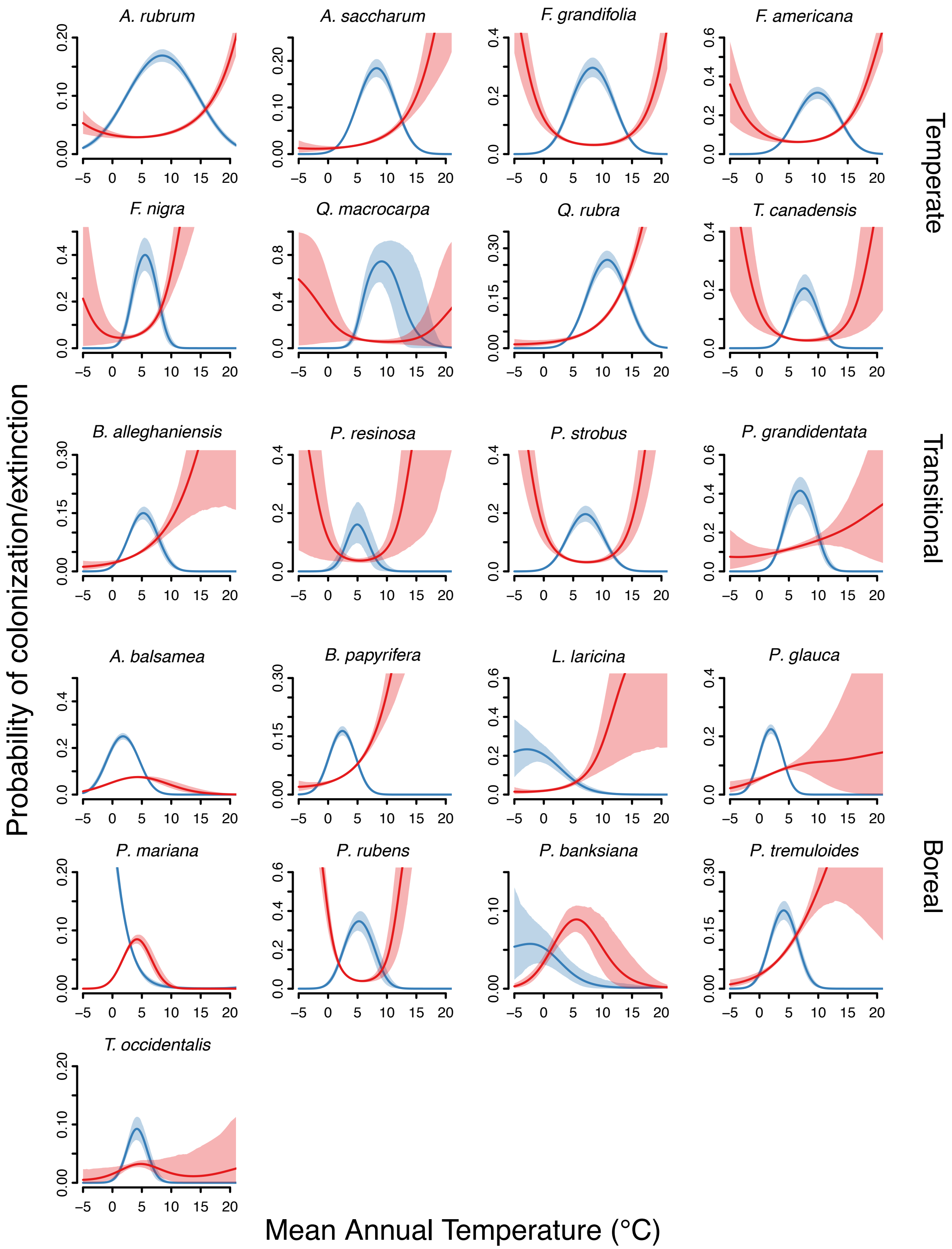
Species	ROC
Temperate	
Acer rubrum	0.60
Acer saccharum	0.80
Fagus grandifolia	0.74
Fraxinus americana	0.81
Fraxinus nigra	0.84
Quercus macrocarpa	0.91
Quercus rubra	0.78
Tsuga canadensis	0.81
Transitional	
Betula alleghaniensis	0.82
Pinus resinosa	0.86
Pinus strobus	0.80
Populus grandidentata	0.82
Boreal	
Abies balsamea	0.82
Betula papyrifera	0.80
Larix laricina	0.67
Picea glauca	0.79
Picea mariana	0.83
Picea rubens	0.85
Pinus banksiana	0.76
Populous tremuloides	0.80
Thuja occidentalis	0.84

Values given are the area under the receiver operating curve (ROC) based on the probability of presence computed at equilibrium.

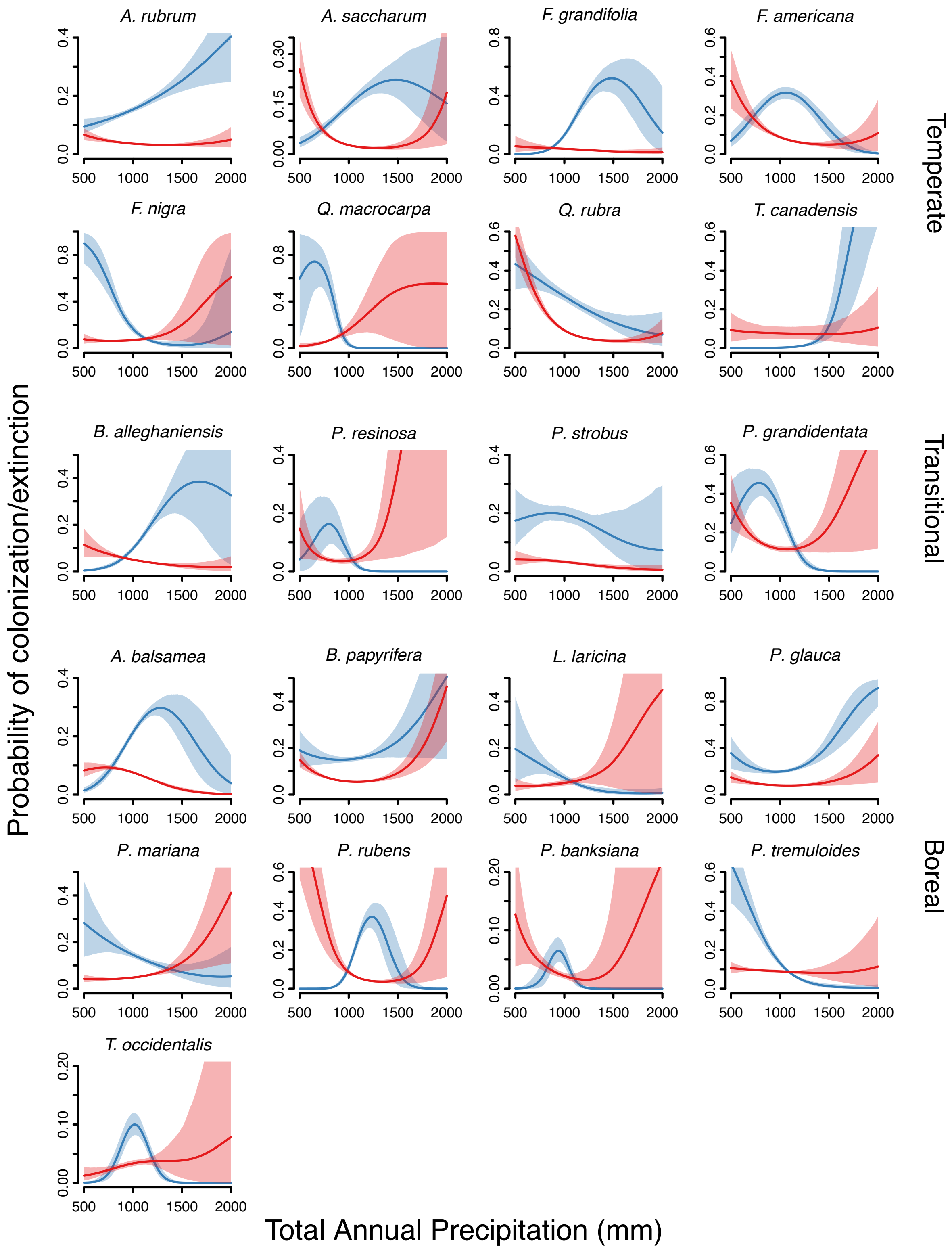
Supplemental Figure 1: Plot locations for calibration (A; n=92,724) and validation (B; n=61,579) datasets. For clarity, plots have been thinned to 10% of their original numbers.



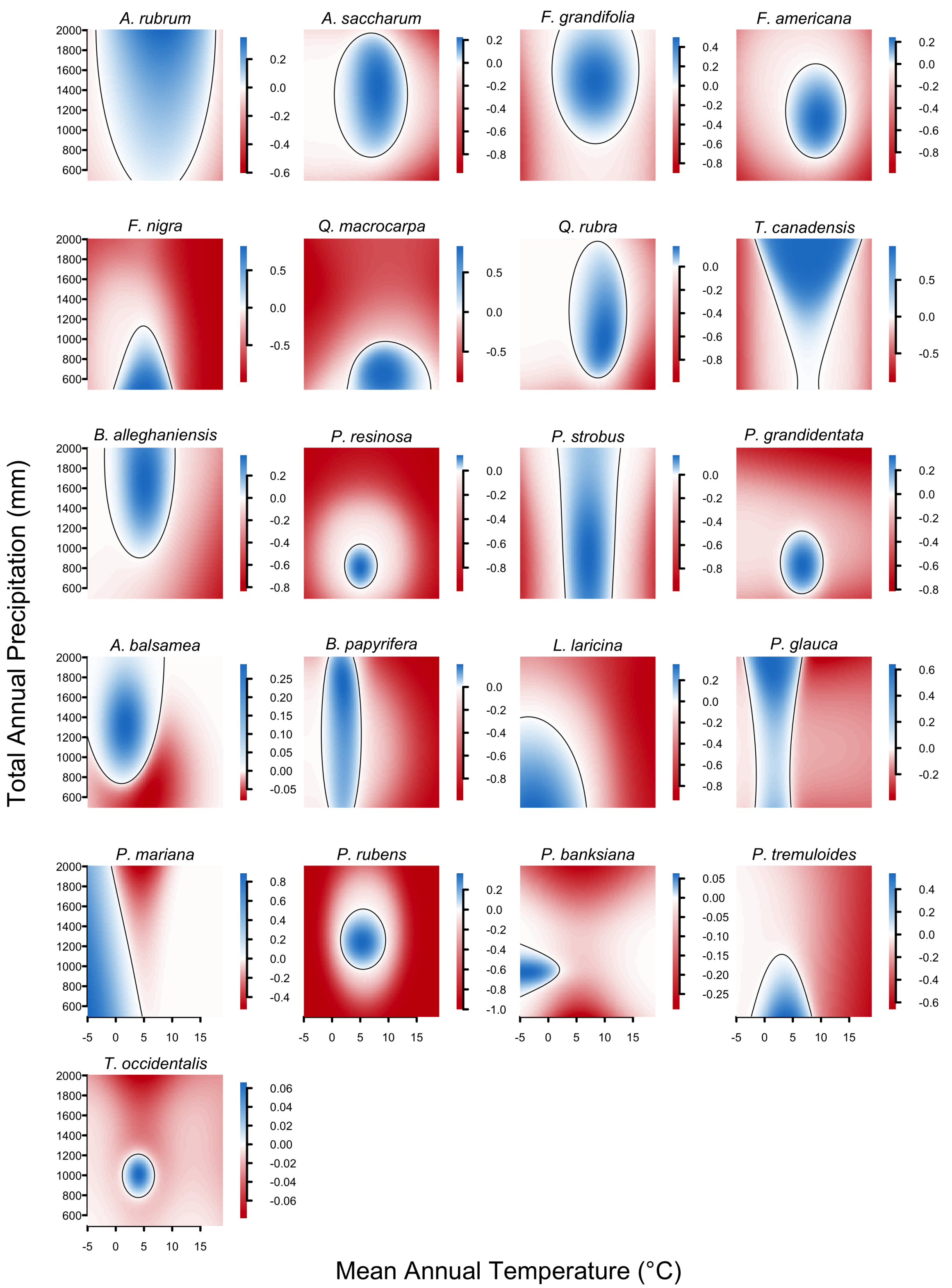
Supplemental Figure 2: Response of colonization (c; blue) and extinction (m; red) rates to temperature. Theoretical predictions indicate the species will be present where c > m and that range boundaries will occur where c = m. Shaded regions show 90% credible intervals. Precipitation was set to the median for each species.



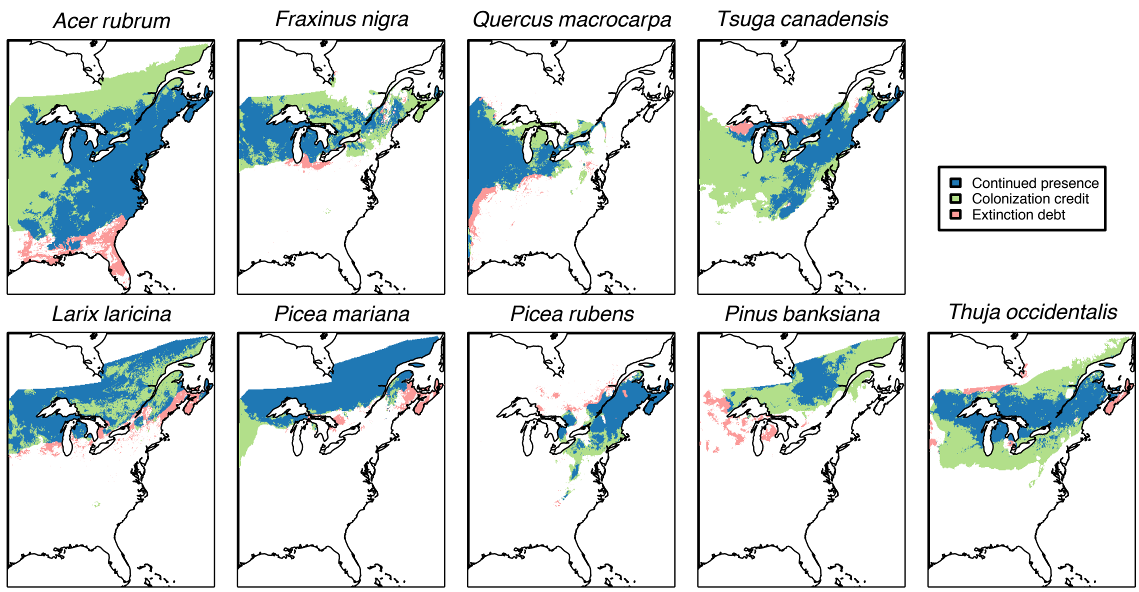
Supplemental Figure 3: Response of colonization (c; blue) and extinction (m; red) rates to precipitation. Theoretical predictions indicate the species will be present where c > m and that range boundaries will occur where c = m. Shaded regions show 90% credible intervals. Temperature was set to the median for each species.



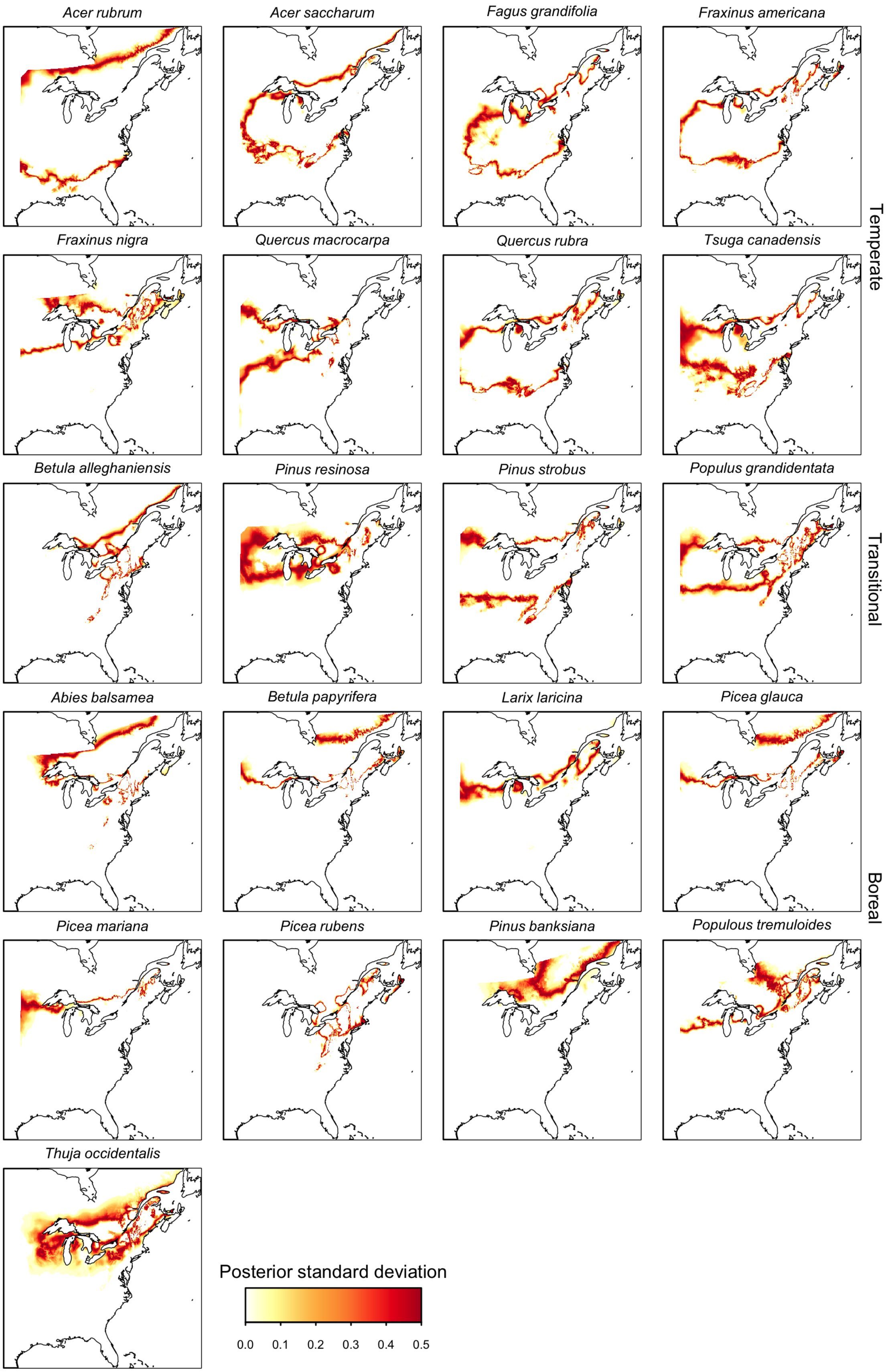
Supplemental Figure 4: Response of the rate of change $[\lambda(E) = c(E) - m(E)]$ to simultaneous variation in temperature and precipitation. Red colors indicate where extinction exceeds colonization, and thus the theoretical prediction is absence at equilibrium, and blue areas indicate where colonization exceeds extinction with presence predicted. Black contours show the predicted range limit (i.e., where $\lambda(E) = 0$).



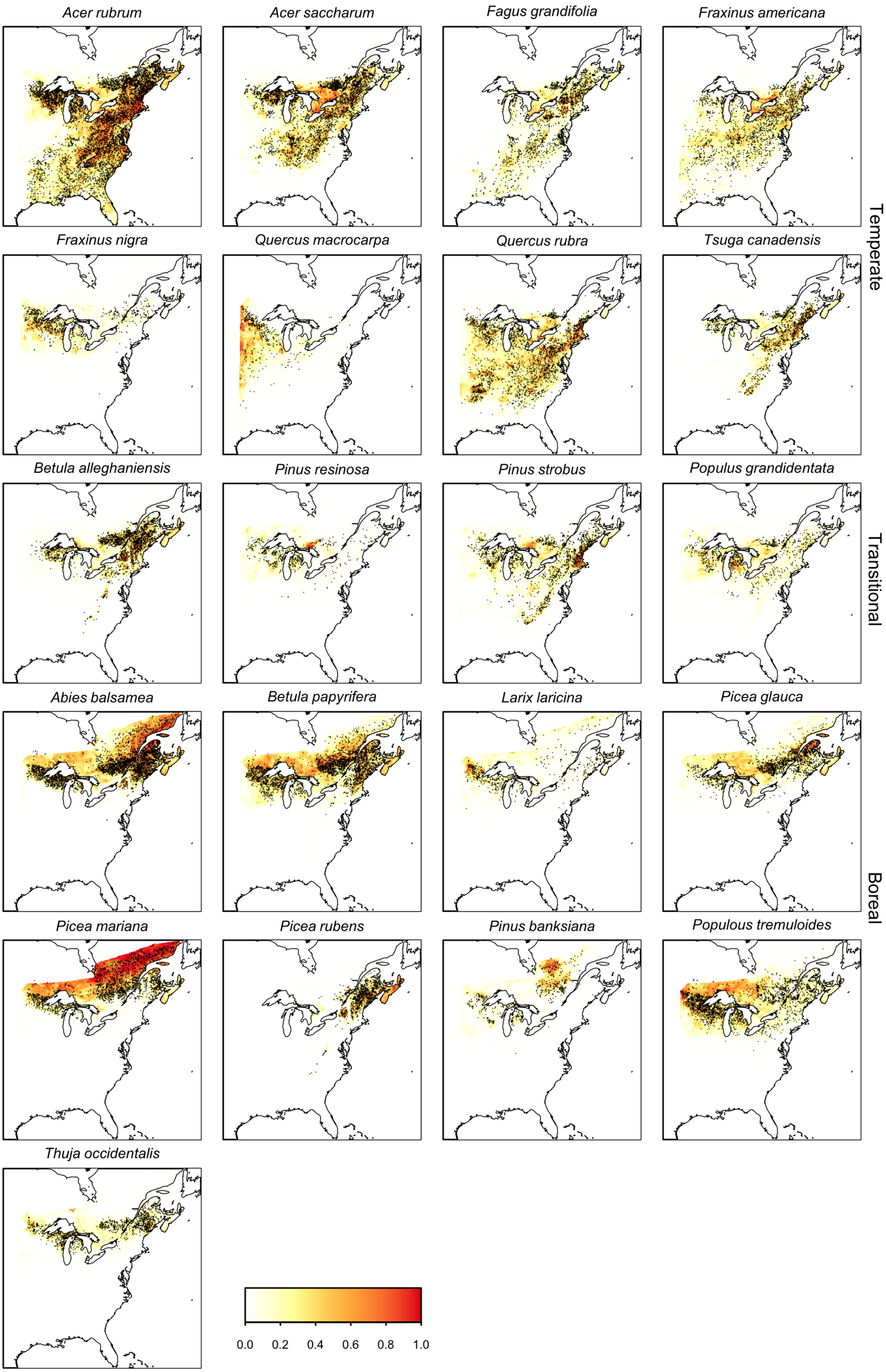
Supplemental Figure 5: Projected range with extinction debt and colonization credit for selected species not shown in main next. The map indicates, for present climatic conditions, where the species are (1) currently present and predicted to be present at equilibrium ("Continued presence;" blue), (2) currently absent but predicted to be present at equilibrium ("Colonization credit;" green), and (3) currently present but predicted to be absent at equilibrium ("Extinction debt;" pink). Equilibrium presence was assessed using the equilibrium solution of the state and transition model [i.e., $c(E) > m(E)$], and current presence was assessed using the random forest model with a threshold (computed using a semi-independent evaluation dataset) applied to the probabilities.



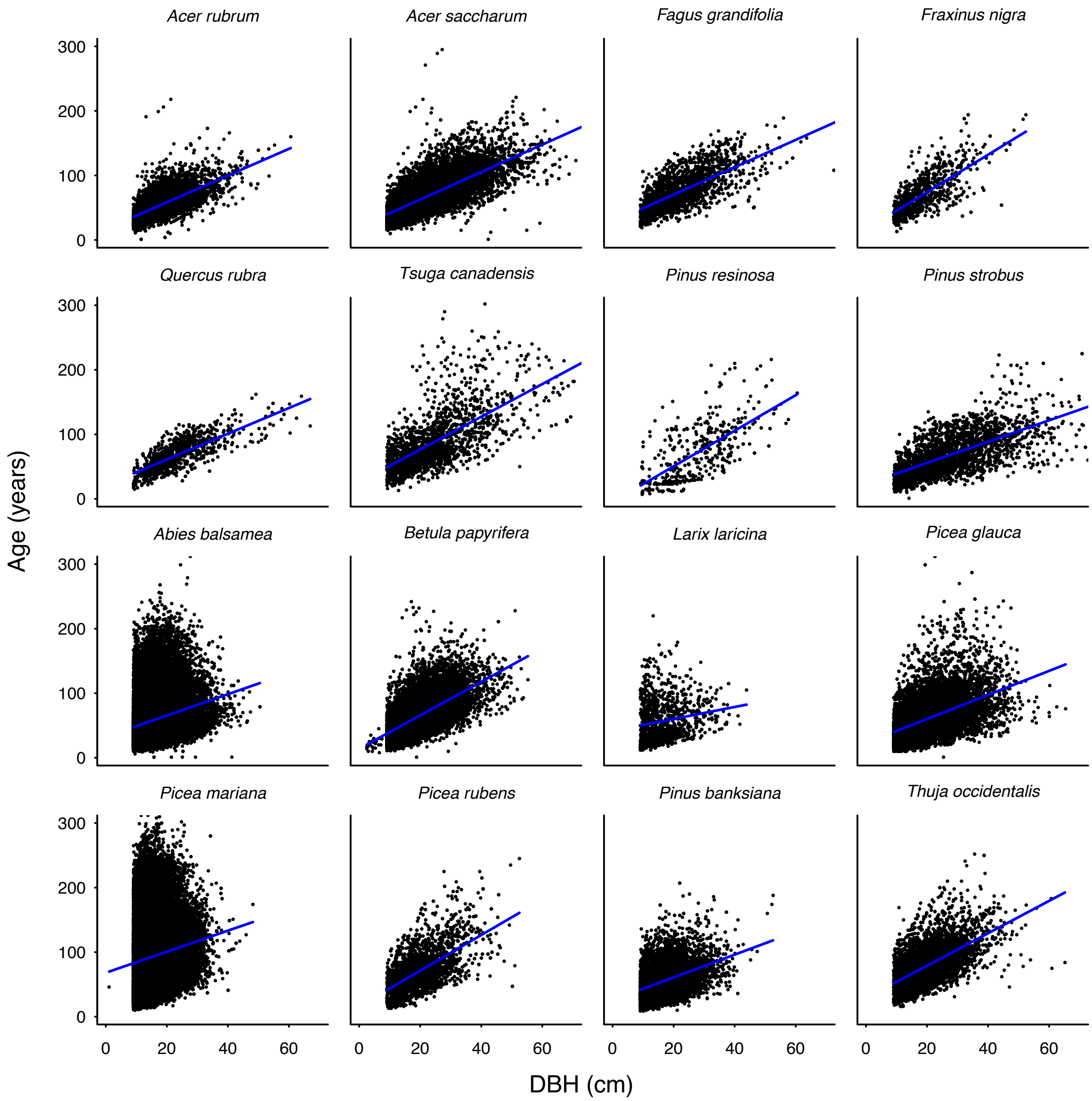
Supplemental Figure 6: Posterior uncertainty in species ranges. Uncertainty was minimal for the majority of all species ranges, whereas small regions of uncertainty surrounded range boundaries.



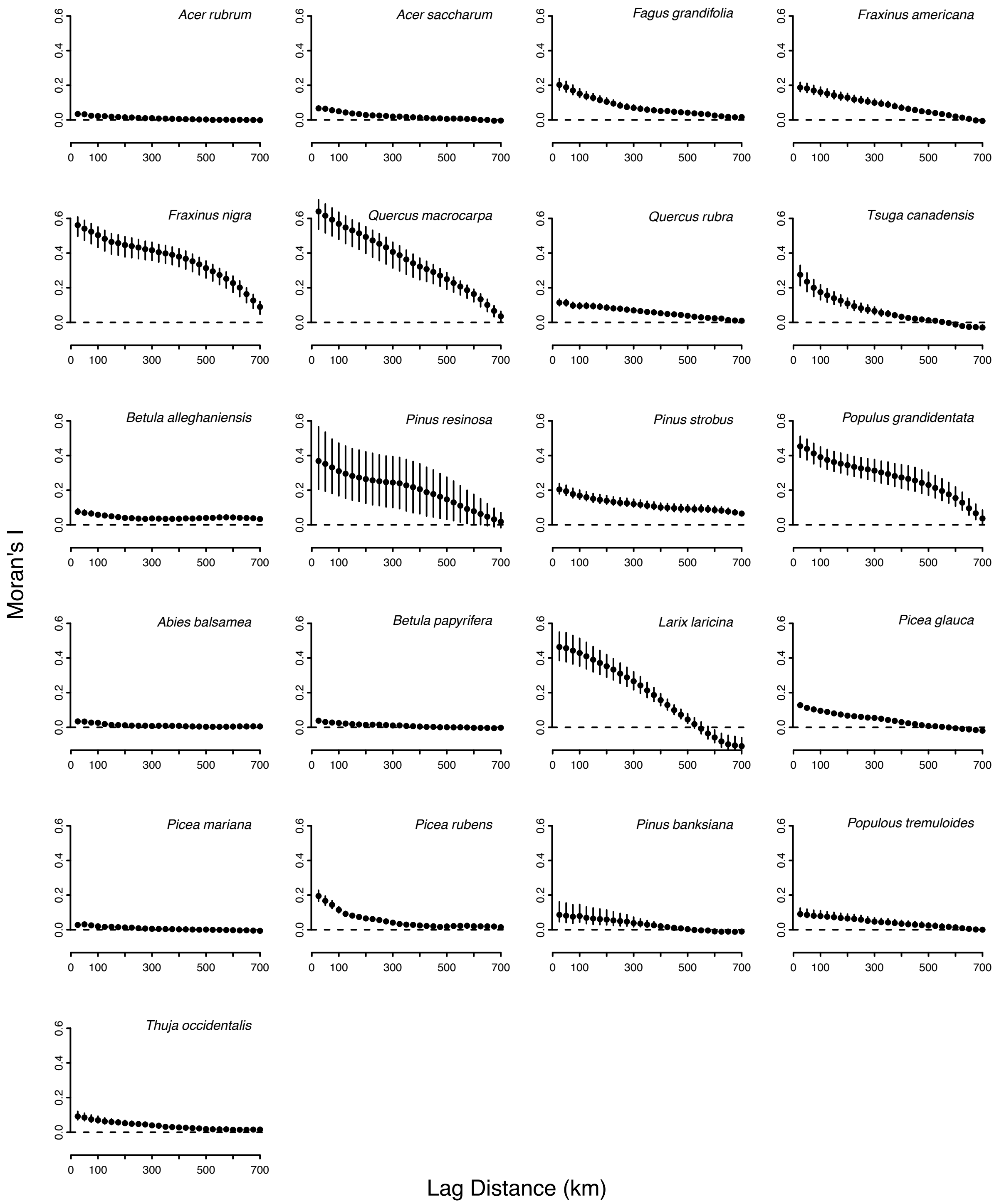
Supplemental Figure 7: Random forest predictions of species ranges. Dark points show the plots where the species was recorded.



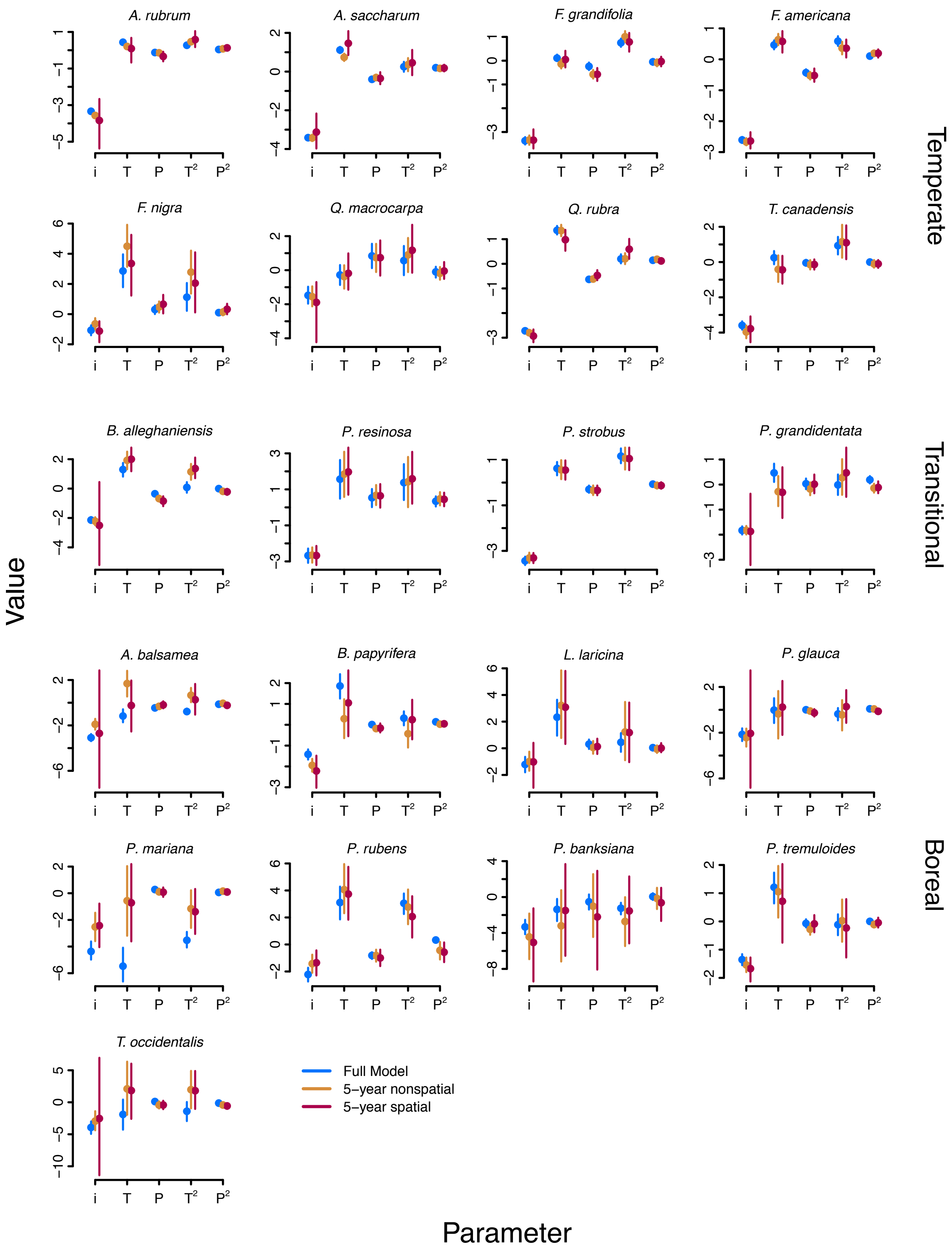
Supplemental Figure 8: Age-DBH curves for selected species.



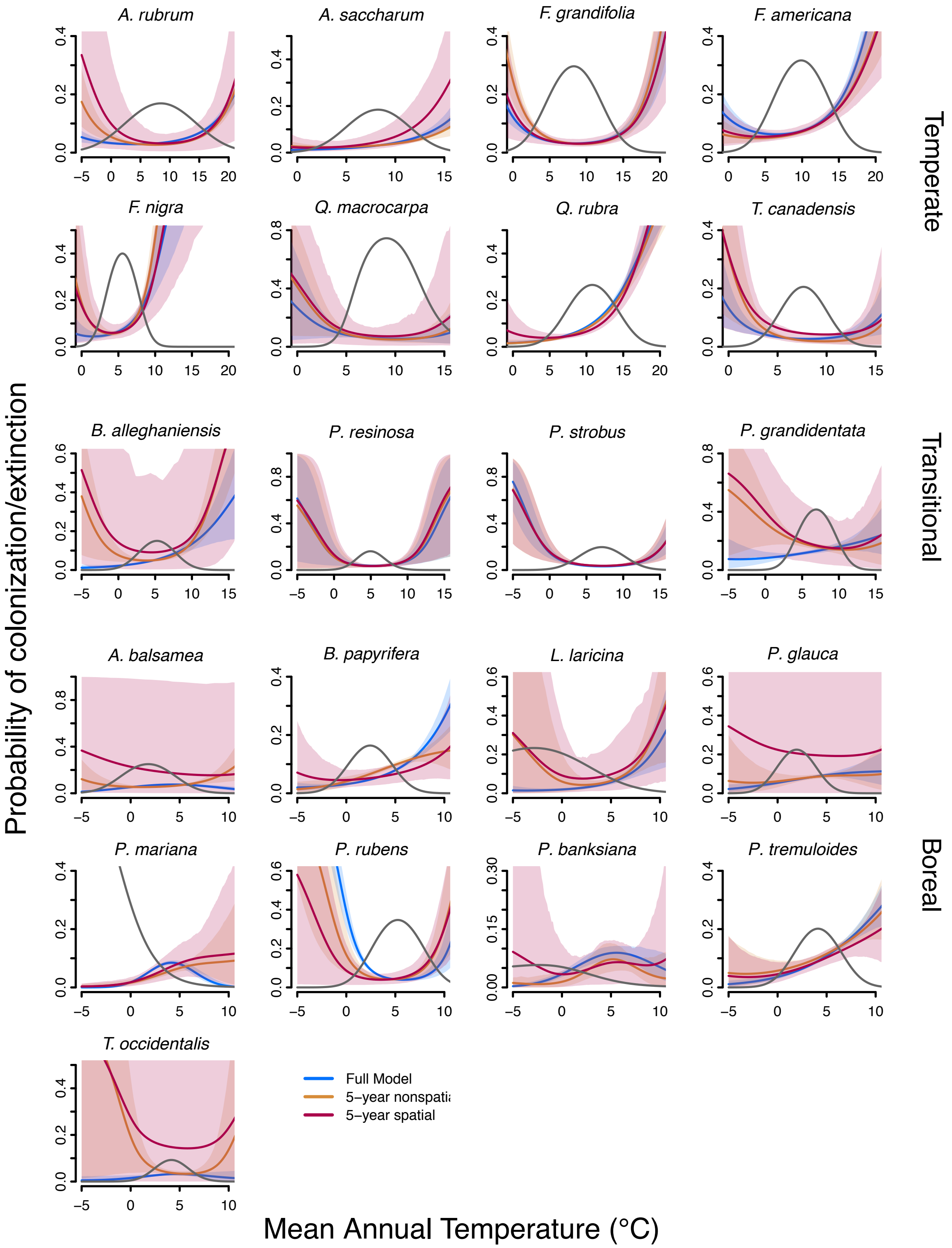
Supplemental Figure 9: Moran's I correlograms for all species. Confidence limits indicate 90% credible intervals computed across posterior replicates.



Supplemental Figure 10: Comparison of parameter estimates for spatial and nonspatial versions of the model. Colours indicate the full model including all data ("Full model," blue), an identical model but using only plots with a 5-year sampling interval ("5-year nonspatial," orange), and a model using the 5-year subset and including a spatial random effect ("5-year spatial," red). Parameters shown are coefficients for the intercept (i), temperature (T), and precipitation (P). Vertical bars show 90% credible intervals.



Supplemental Figure 11: Comparison of the response of extinction rate to temperature for spatial and nonspatial versions of the model. Colours indicate the full model including all data ("Full model," blue), an identical model but using only plots with a 5-year sampling interval ("5-year nonspatial," orange), and a model using the 5-year subset and including a spatial random effect ("5-year spatial," red). To show the projected ranges, the colonization rate from the full model is included in gray; species are predicted to be present where the colonization curve is greater than the extinction curves. Shaded regions show 90% credible intervals. Precipitation has been held constant to the median for each species.



Supplemental Figure 12: Comparison of the response of extinction rate to precipitation for spatial and nonspatial versions of the model. Colours indicate the full model including all data ("Full model," blue), an identical model but using only plots with a 5-year sampling interval ("5-year nonspatial," orange), and a model using the 5-year subset and including a spatial random effect ("5-year spatial," red). To show the projected ranges, the colonization rate from the full model is included in gray; species are predicted to be present where the colonization curve is greater than the extinction curves. Shaded regions show 90% credible intervals. Temperature has been held constant to the median for each species.