Supplemental Materials: Photoperiod and temperature interactively drive spring phenology in multiple species

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Literature Review

We conducted a literature review, finding 109 studies which investigated effects of photoperiod, temperature, or their interaction on the timing of bud burst or flowering for woody or semi-woody plants. No study varied chilling period, photoperiod, and temperature simultaneously across multiple species at multiple sites. Of those studies, eight simultaneously manipulated photoperiod and temperature. Basler & Koerner [1] found a negative tradeoff between sensitivity to photoperiod and sensitivity to warming for four species, for example with *Fagus sylvatica* advanced on average in leafout by 12 days in response to experimentally lengthened photoperiod, but only ca. 8 days in response to warmer temperatures, while *Acer pseudoplatanus* advanced in leafout by 17 days in response to warming but essentially had no change in response to photoperiod. The current study expands on this work by including 28 species, across two sites, with addition manipulations of chilling temperature.

Chilling calculations

The cuttings were harvested in late January 2015, and thus experienced substantial natural chilling by the time they were harvested. Using weather station data from the Harvard Forest and St. Hippolyte site, chilling hours (below 7.2°C), Utah Model chill portions (hours below 7.2°C and between 0°C and 7.2°C) and Dynamic Model [2] chill portions were calculated both for the natural chilling experienced by harvest and the chilling experienced in the 4°C and 1.5°C treatments. The Utah Model and Dynamic Model of chill portions account for variation in the amount of chilling accumulated at different temperatures, with the greatest chilling occurring approximately between 5-10°C, and fewer chill portions accumulating at low temperatures and that higher temperatures can reduce accumulated chilling effects. The two differ in the parameters used to determine the shape of the chilling accumulation curve, with the Dynamic Model being shown to be the most successful in predicting phenology for some woody species [3]. With both the Utah and Dynamic model, the more severe chilling treatment resulted in fewer calculated chilling portions.

References Cited

References

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

[2] Erez, A., Fishman, S., Gat, Z. & Couvillon, G. A. Evaluation of winter climate for breaking bud rest using the dynamic model 76–89 (1988).

[3] Luedeling, E., Zhang, M., McGranahan, G. & Leslie, C. Validation of winter chill models using historic records of walnut phenology. *Agricultural and Forest Meteorology* **149**, 1854–1864 (2009).

Supplemental Figures and Tables

Table S1: Mean leafout and budburst days for the 28 species at both Harvard Forest, USA and St. Hippoltye, Canada

Species	Budburst.HF	Budburst.SH	Leafout.HF	Leafout.SH
Acer pensylvanicum	16.40	18.33	40.88	46.94
Acer rubrum	22.40	25.15	40.59	44.40
Acer saccharum	44.96	36.48	57.07	46.88
Alnus incana subsp. rugosa	32.91	25.36	45.15	44.36
Aronia melanocarpa	13.62		29.83	
Betula alleghaniensis	19.67	20.77	33.51	34.64
Betula lenta	29.83		50.57	
Betula papyrifera	16.89	18.04	28.71	35.63
Corylus cornuta	24.86	19.04	33.95	30.38
Fagus grandifolia	41.82	43.13	48.54	46.90
Fraxinus nigra	38.00	38.00	52.28	46.91
Hamamelis virginiana	43.67		47.38	
Ilex mucronatus	15.80	15.49	26.97	25.15
Kalmia angustifolia	30.25	32.48	37.80	42.20
Lonicera canadensis	16.91	15.75	28.26	25.08
Lyonia ligustrina	30.87		49.50	
Nyssa sylvatica	31.65		52.87	
Populus grandidentata	33.43	31.23	46.21	45.17
Prunus pensylvanica	17.81	16.21	32.13	29.65
Quercus alba	45.23		52.91	
Quercus rubra	36.43	33.57	45.02	42.80
Quercus velutina	52.09		59.16	
Rhamnus frangula	32.38		37.29	
Rhododendron prinophyllum	29.25		52.14	
Spiraea alba	18.00	20.21	25.94	24.62
Vaccinium myrtilloides	13.12	17.27	27.00	28.95
Viburnum cassinoides	15.41	18.46	16.80	18.71
Viburnum lantanoides	31.25	27.54	32.02	26.41

Table S2: Summary of mixed effect model of budburst day by species.

	mean	sd	25%	50%	75%	Rhat
Temperature	-6.80	1.71	-7.95	-7.02	-5.63	1.05
Photoperiod	-3.96	1.67	-5.13	-4.13	-2.80	1.05
Chilling 4 °C	-22.09	2.84	-24.05	-21.75	-20.26	1.03
Chilling 1.5 °C	-19.79	2.96	-22.32	-19.90	-17.78	1.13
Site	2.59	1.88	0.93	2.54	3.93	1.13
Temperature × Photoperiod	-0.60	0.72	-1.07	-0.46	-0.24	1.02
Temperature × Site	9.17	1.00	8.50	9.32	9.77	1.03
Photoperiod × Site	9.68	1.06	9.11	9.57	10.33	1.00
Temperature × Chilling 4 °C	-0.18	0.96	-0.82	-0.06	0.47	1.04
Temperature × Chilling 1.5 °C	-0.02	1.03	-0.67	0.14	0.48	1.02
Photoperiod × Chilling 4 °C	-1.48	0.76	-1.99	-1.35	-1.00	1.04
Photoperiod × Chilling 1.5 °C	0.05	0.79	-0.52	0.09	0.76	1.10
Site × Chilling 4 °C	-1.96	1.33	-2.84	-1.86	-0.85	1.09
Site × Chilling 1.5 °C	-3.49	1.23	-4.14	-3.55	-2.78	1.01

Table S3: Summary of mixed effect model of leafout day by species.

	mean	sd	25%	50%	75%	Rhat
Temperature	-21.91	1.72	-23.05	-21.90	-20.75	1.01
Photoperiod	-13.68	1.69	-14.79	-13.71	-12.56	1.02
Chilling 4 °C	-26.37	3.09	-28.41	-26.41	-24.41	1.01
Chilling 1.5 °C	-26.14	3.09	-28.29	-26.23	-24.03	1.01
Site	3.00	2.05	1.67	3.00	4.43	1.02
Temperature × Photoperiod	3.54	0.77	2.99	3.54	4.07	1.02
Temperature × Site	10.19	1.16	9.47	10.12	10.93	1.00
Photoperiod × Site	11.29	1.25	10.44	11.26	12.09	1.01
Temperature × Chilling 4 °C	0.77	1.05	0.08	0.79	1.48	1.00
Temperature × Chilling 1.5 °C	2.41	1.27	1.60	2.41	3.24	1.01
Photoperiod × Chilling 4 °C	-0.59	0.82	-1.11	-0.58	-0.04	1.03
Photoperiod × Chilling 1.5 °C	-1.00	0.83	-1.55	-1.01	-0.42	1.02
Site × Chilling 4 °C	-1.87	1.26	-2.67	-1.92	-1.05	1.01
Site × Chilling 1.5 °C	-3.46	1.38	-4.39	-3.44	-2.52	1.01

Table S4: Chill units in field and field and growth chamber conditions.

Site	Treatment	Chilling Hours	Utah Model	Chill portions
Harvard Forest	Field chilling	892	814.50	56.62
	4.0 °C x 30 d	2140	2062.50	94.06
	1.5 °C x 30 d	2140	1702.50	91.17
St. Hippolyte	Field chilling	682	599.50	44.63
	4.0 °C x 30 d	1930	1847.50	82.06
	1.5 °C x 30 d	1930	1487.50	79.18

Table S5: Phylogenetic signal in timing of bud burst and leaf out and species specific traits, as estimated in the caper package with simultaneous fitting of lambda. Pore anatomy (ring- versus diffuse-porous species) was highly clustered phylogenetically, but no other trait examined demonstrated significant phylogenetic signal

Relationship	Lambda
SLA - Temperature	0.000
SLA - Photoperiod	0.000
SLA - Chilling 4 °C	0.000
SLA - Chilling 1.5 °C	0.000
Wood Density - Temperature	0.000
Wood Density - Photoperiod	0.000
Wood Density - Chilling 4 °C	0.000
Wood Density - Chilling 1.5 °C	0.000
% N - Temperature	0.285
% N - Photoperiod	0.203
% N - Chilling 4 °C	0.127
% N - Chilling 1.5 °C	0.130
Pore anatomy - Temperature	1.000
Pore anatomy - Photoperiod	1.000
Pore anatomy - Chilling 4 °C	1.000
Pore anatomy - Chilling 1.5 °C	1.000

Figure S1: Coordinated responses of 28 woody plant species to photoperiod and temperature cues for leaf out. Color of circle reflect unmodeled data on average leaf out day across treatments, across sites of origin, while size of circle represents the total number of clippings in the experiment—this varies mainly based on whether the species was found at both sites and whether it was exposed to all three chilling treatments.

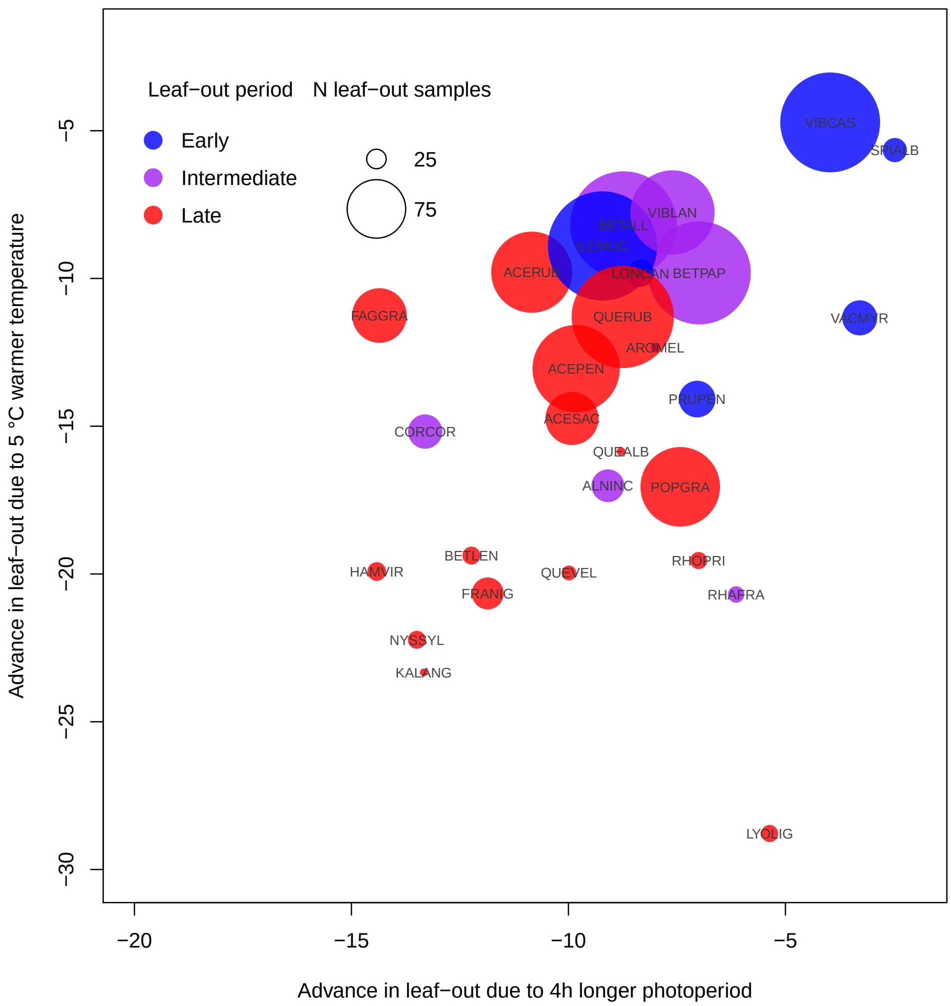

Figure S2: Model estimates of effects of each predictors on bud burst, including species-level effects.

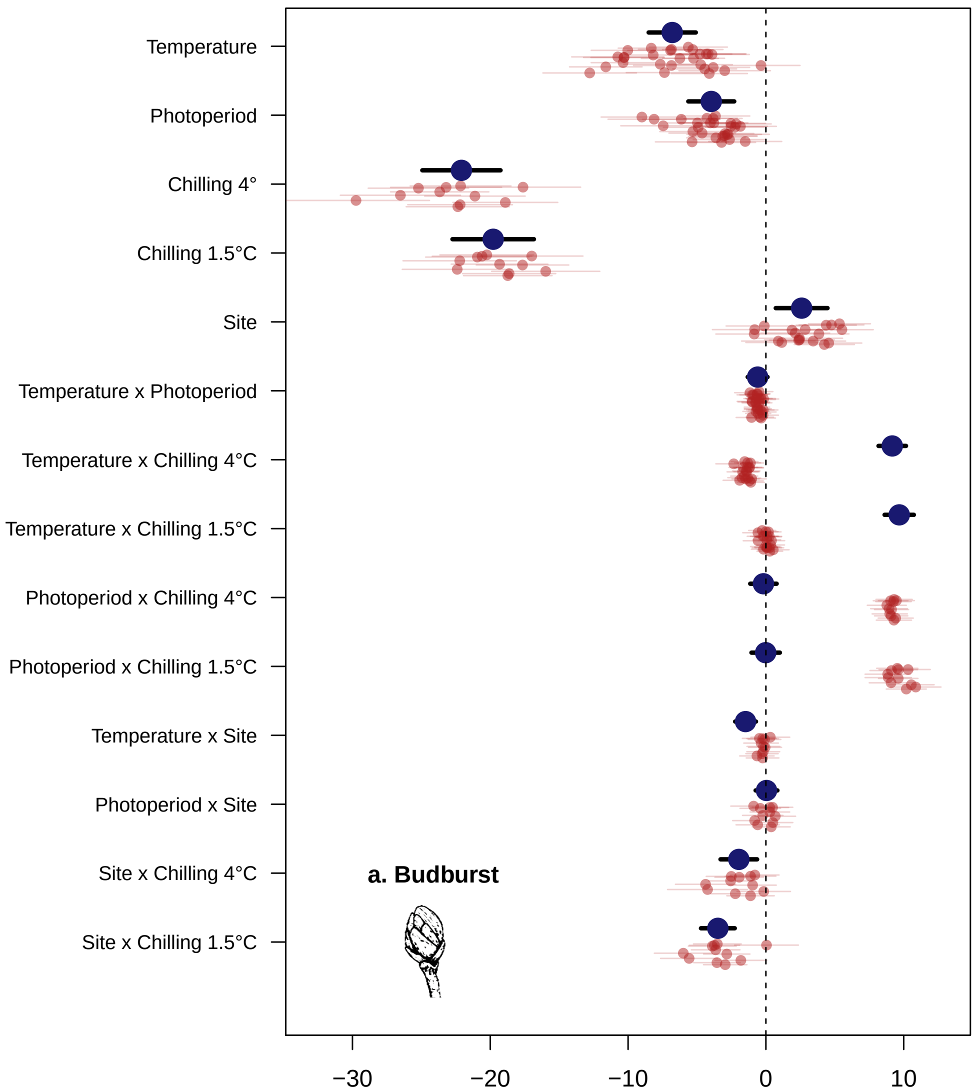

Figure S3: Model estimates of leafout, including species-level effects.

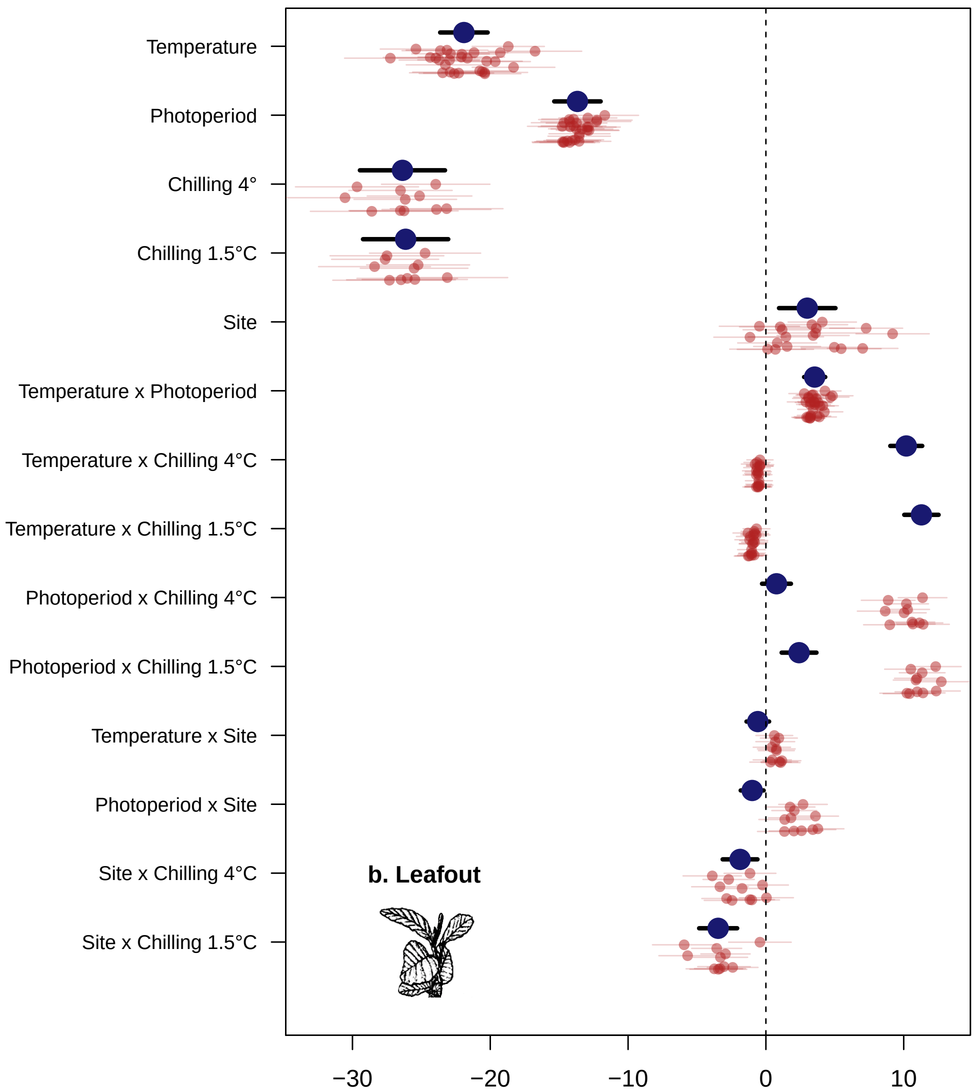

Figure S4: Model estimates of sensitivity to warming, photoperiod, and chilling, compared to day of budburst (upper panels) or leafout (lower panels) across all experimental conditions.

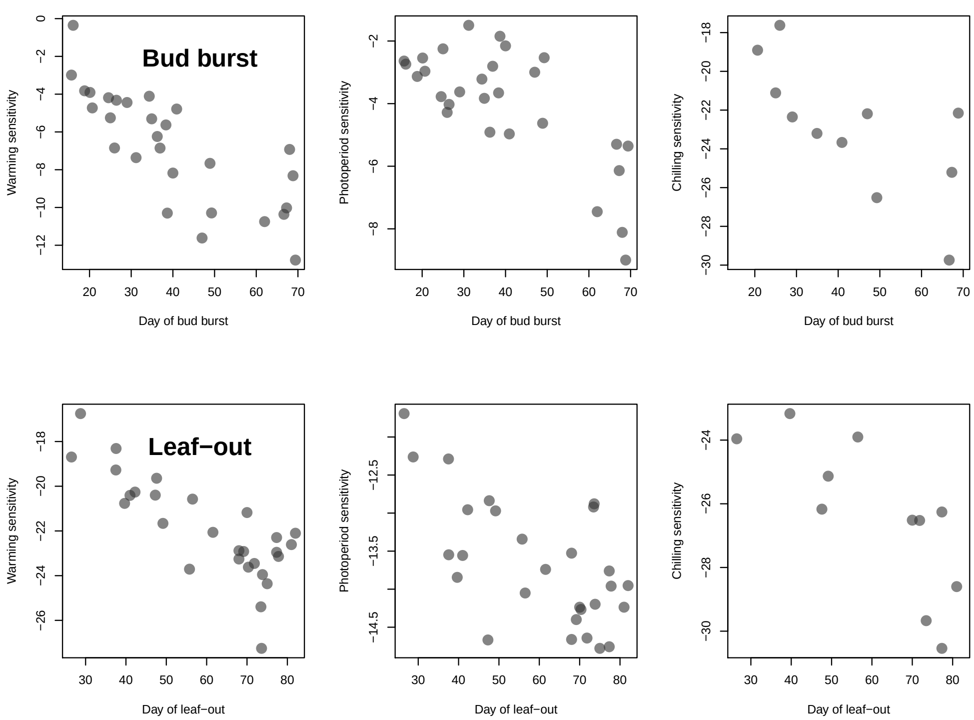

Figure S5: Trait sensitivity based on specific leaf area

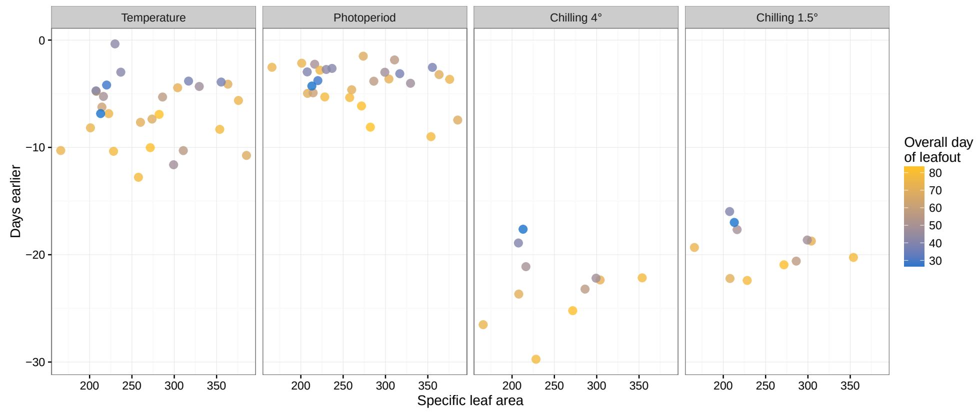

Figure S6: Trait sensitivity based on stem density

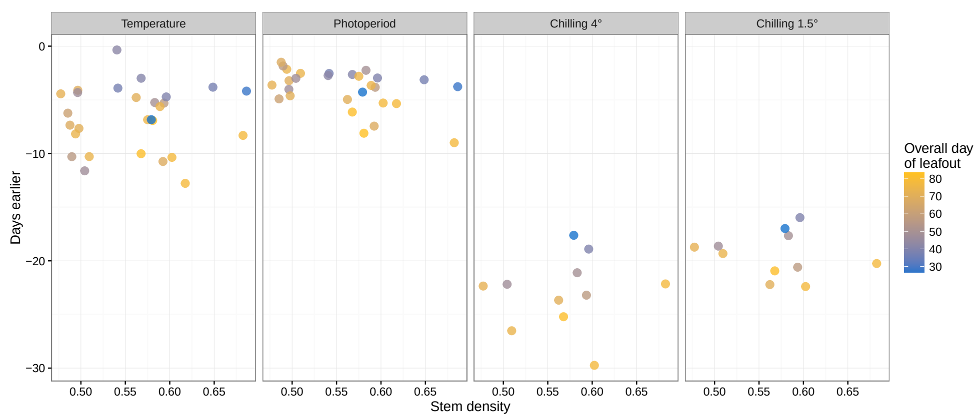

Figure S7: Trait sensitivity based on % nitrogen

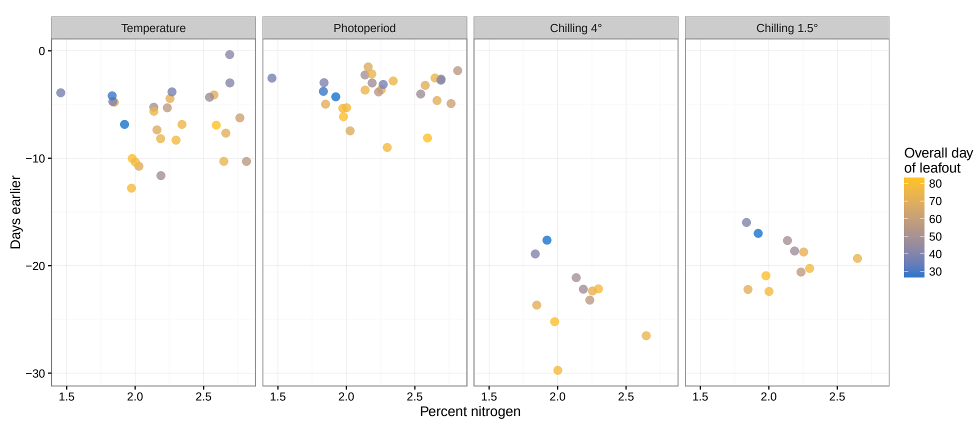

Figure S8: Specific leaf area and stem density by trees vs shrubs

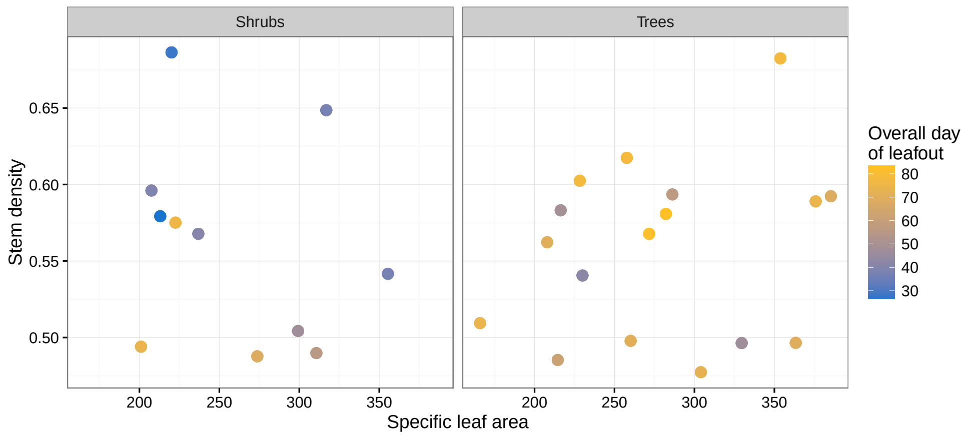

Figure S9: Specific leaf area and percent nitrogen by trees vs shrubs

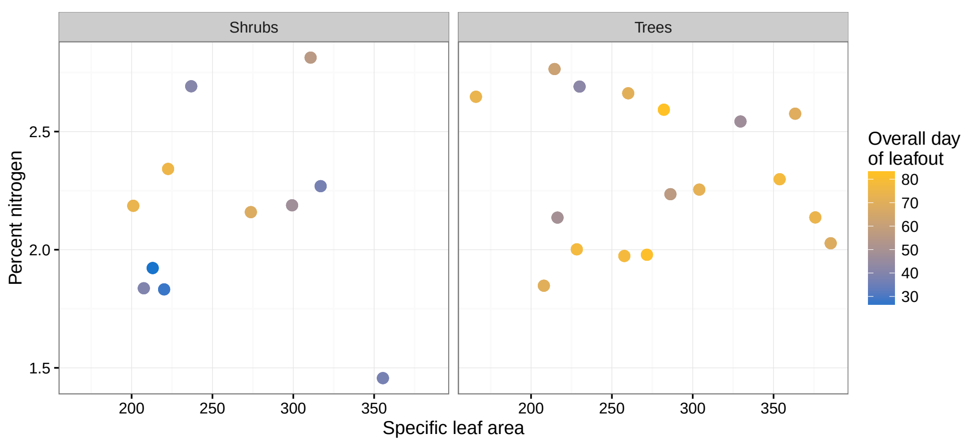

Figure S10: Stem density and percent nitrogen by trees vs shrubs

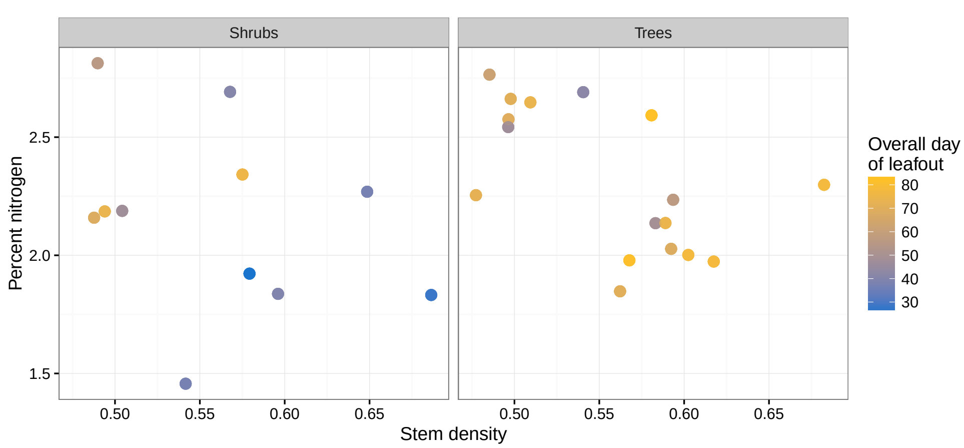

Figure S11: Leafout rank order in experimental treatments vs. O'Keefe observations

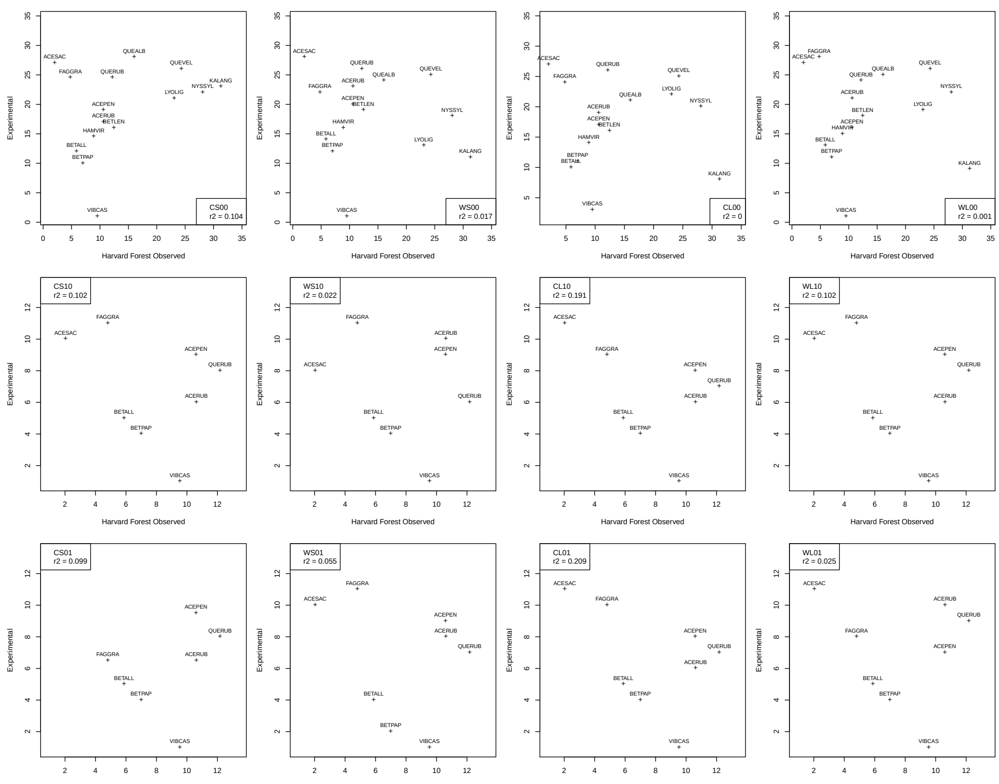

Figure S12: Leafout day of year in experimental treatments vs. O'Keefe observations