Supporting Information
Temperature and photoperiod drive spring phenology across all species in a temperate forest community

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Supplemental Methods

Temperature and photoperiod variation at study sites

Spring climate regimes between our two sites (Harvard Forest and St. Hippolyte) vary, with temperatures generally being colder in the spring at the further north site (St. Hippolyte). Considering daily temperature data between 2000-2015 at both sites, daily minima, averaged over January-March each year, span -11.96 to -4.07°C and -19.74 to -8.88°C; daily maxima over the same period span -1.53 to 6.13°C and -9.99 to -0.26°C, at Harvard Forest and St. Hippolyte, respectively. Considering the period of April-May, daily minima span 2.90 to 6.19°C and 0.62 to 4.14°C; daily maxima over the same period span 14.23 to 19.00°C and 11.28 to 15.83°C at Harvard Forest and St. Hippolyte, respectively.

As Saint Hippolyte is further north, its daylength (photoperiod) change in the spring is more extreme than at Harvard Forest: change from 1 March to 15 May is approximately 4 hours, while a similar change in Harvard Forest occurs over 1 March to 31 May.

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 (Richardson *et al.*, 1974), and Dynamic Model (Erez *et al.*, 1988) 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 (Luedeling *et al.*, 2009). With both the Utah and Dynamic model, the more severe chilling treatment resulted in fewer calculated chilling portions (Table S7).

To provide a comparison with estimated chilling under natural conditions we also show chilling for the study winter (2014-2015) until 1 April and 1 May (Table S7). Under the chilling hours and Utah model the greatest chilling occurred in our 4°C treatment, and both the 4°C and 1.5°C treatments provided more chilling than under natural conditions (until either 1 April or 1 May). In the Dynamic Model (chill portions) chilling was slightly higher by 1 May compared to our experimental chilling, but not when compared to 1 April. Taken together, our calculated chilling effects (Table S7) suggest that our experimental chilling effects would most likely have resulted in more chilling than experienced at either field site under natural conditions.

Budburst and leafout success

We assessed how species and treatments affected budburst and leafout success (Table S2) using a similar Bayesian hierarchical model as presented for days to budburst or leafout in the main text, but modeling species as a group only on the intercept (Fig. S2-S3) due to a limited amount of data (i.e., of all cuttings only 9.8-20.2% did not burst bud or leaf out, yielding limited data when compared to days to budburst or leafout where we—conversely—had data for 79.8-90.2% of all cuttings). Analysis of non-leafouts considered only the cuttings that burst bud (n=1 926, rather than the total cutting number of n=2 136). Models were fit in `rstan` implemented via `rstanarm` version 2.17.2 using a binomial family and logit-link function. Full results are presented in Tables S3-S4 and Figures S2-S3.

Variation in budburst and leafout success was highest due to species identity and ranged from complete budburst and leafout (e.g., *Hamamaelis*) to only 65% budburst (*Quercus alba*), 50% or lower leafout (*Fagus grandifolia*, *Acer saccharum*, *Kalmia angustifolia*) across all treatments (Table S2). The percent of non-leafouts by site was similar, with 20.6% of Harvard Forest and 19.7% of St. Hippolyte samples failing to leafout. Additional chilling decreased budburst and leafout success (Tables S3-S4; Fig. S2-S3), with 30 d at 1.5°C having the largest effects (cuttings with 1.5°C were 14.2% less likely to reach budburst). Other effects were weaker and varied by budburst versus leafout (Tables S3-S4; Fig. S2-S3): for example, forcing temperatures and photoperiod affected leafout only (increased forcing increased leafout by 3.9% while longer days increased leafout by 4.2% though the combined effect of increased forcing and longer days together was only 3.0% due to a negative interaction of the two effects, see Figure S3).

Days to budburst and days to leafout models performed on a subset of the data with higher rates of budburst (93% overall) and leafout (88%) produced qualitatively similar estimates, with most parameter estimates differing by less than 10% compared to the full model. These models excluded the five species (*Acer saccharum*, *Fagus grandifolia*, *Kalmia angustifolia*, *Quercus alba* and *Viburnum lantanoides*) that had budburst success below 80% and/or leafout success below 75%.

Effects of chilling at 16 and 32 day lengths

In the winter of 2015-2016 we conducted a follow-up study to test (1) whether our findings regarding different chilling temperatures in the winter of 2014-2015 were consistent across years and, (2) to test effects of chilling under a shorter duration of experimental chilling. For this experiment we tested the effects of field chilling plus chilling at two different temperatures, 1°C and 4 °C, and three different period of chilling: no additional, 16 days or 32 days. Treatments were fully crossed resulting in six different combinations of treatment conditions. We collected cuttings as previously described from Harvard Forest on 18 December 2015 for seven species (*Acer saccharum, Betula alleghaniensis, Fagus grandifolia, Hamamelis virginiana, Ilex mucronatus, Quercus rubra, Viburnum cassinoides*). All cuttings were kept at 4°C until 1 January when they were put into treatment conditions. Forcing conditions were set as 20°C days with 10°C nights and 12 hour photoperiods. We assessed how species and treatments affected days to budburst using a similar Bayesian hierarchical model as presented for days to budburst or leafout in the main text but for this set of treatments (models were fit in `rstan` implemented via `rstanarm` version 2.17.2).

Our findings were generally consistent with those from our previous year's experiment: effects of chilling were similar across the two temperatures (1°C and 4°C), Figure S9). Additional chilling time advanced budburst by 7.8 or 10.4 days, for 16 or 32 additional days of chilling, respectively (Fig. S9). The additional advance of only 2.6 days between the treatments of 16 and 32 days experimental chilling suggests that effects of chilling over time are non-linear and that additional chilling time beyond 32 days may have had only small effects, this is consistent with metrics of chilling hours (see Table S7), which suggests our previous year's experimental chilling would have been as high (or higher) than a full season of field chilling.

References

Erez A, Fishman S, Gat Z , Couvillon GA. 1988. Evaluation of winter climate for breaking bud rest using the dynamic model. *Acta Horticulturae*, pp. 76–89.

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

Richardson EA, Seeley SD , Walker DR. 1974. A model for estimating the completion of rest for 'redhaven and 'elberta' peach trees. *HortScience*, **9**: 331–332.

Supplemental Figures and Tables

Table S1: Mean leafout and budburst days after exposure to controlled environment forcing conditions (across all treatments, based on raw data) for the 28 species at both Harvard Forest (HF), USA and St. Hippoltye (SH), 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: Mean leafout and budburst success after exposure to controlled environment forcing conditions (across all treatments, based on raw data) for the 28 species.

Species	Budburst.success	Leafout.success
Acer pensylvanicum	0.99	0.78
Acer rubrum	0.92	0.79
Acer saccharum	0.78	0.47
Alnus incana subsp. rugosa	0.94	0.88
Aronia melanocarpa	0.81	0.75
Betula alleghaniensis	0.97	0.95
Betula lenta	1.00	0.96
Betula papyrifera	0.93	0.92
Corylus cornuta	0.94	0.92
Fagus grandifolia	0.80	0.49
Fraxinus nigra	0.88	0.85
Hamamelis virginiana	1.00	1.00
Ilex mucronatus	0.97	0.97
Kalmia angustifolia	0.98	0.21
Lonicera canadensis	0.97	0.97
Lyonia ligustrina	0.96	0.92
Nyssa sylvatica	0.96	0.96
Populus grandidentata	0.83	0.77
Prunus pensylvanica	0.89	0.84
Quercus alba	0.65	0.55
Quercus rubra	0.95	0.91
Quercus velutina	0.92	0.79
Rhamnus frangula	1.00	0.88
Rhododendron prinophyllum	1.00	0.92
Spiraea alba	0.80	0.78
Vaccinium myrtilloides	0.96	0.94
Viburnum cassinoides	0.89	0.89
Viburnum lantanoides	0.79	0.75

Table S3: Summary of mixed-effects model of budburst success (estimates presented on logit scale). See also Figure S2.

	mean	sd	2.5%	50%	97.5%	Rhat
Forcing Temperature	-0.09	0.31	-0.71	-0.09	0.51	1.00
Photoperiod	-0.01	0.31	-0.61	-0.01	0.62	1.00
Chilling 4 °C	-0.70	0.40	-1.47	-0.71	0.10	1.00
Chilling 1.5 °C	-1.48	0.35	-2.17	-1.48	-0.80	1.00
Site	0.42	0.35	-0.24	0.41	1.12	1.00
Forcing Temperature × Photoperiod	-0.31	0.31	-0.94	-0.31	0.30	1.00
Forcing Temperature × Chilling 4 °C	0.59	0.41	-0.21	0.59	1.38	1.00
Forcing Temperature × Chilling 1.5 °C	0.02	0.35	-0.65	0.03	0.70	1.00
Photoperiod × Chilling 4 °C	0.58	0.42	-0.24	0.58	1.37	1.00
Photoperiod × Chilling 1.5 °C	0.48	0.34	-0.19	0.48	1.15	1.00
Forcing Temperature × Site	-0.22	0.31	-0.82	-0.22	0.39	1.00
Photoperiod × Site	-0.07	0.31	-0.68	-0.07	0.52	1.00
Site × Chilling 4 °C	0.15	0.42	-0.66	0.14	0.97	1.00
Site × Chilling 1.5 °C	0.50	0.36	-0.21	0.50	1.18	1.00

Table S4: Summary of mixed-effects model of leafout success (estimates presented on logit scale). See also Figure S3.

	mean	sd	2.5%	50%	97.5%	Rhat
Forcing Temperature	1.09	0.35	0.39	1.08	1.80	1.00
Photoperiod	1.27	0.35	0.59	1.27	1.96	1.00
Chilling 4 °C	-0.84	0.41	-1.63	-0.85	-0.04	1.00
Chilling 1.5 °C	-1.88	0.40	-2.63	-1.88	-1.10	1.00
Site	-0.29	0.35	-0.98	-0.29	0.37	1.00
Forcing Temperature × Photoperiod	-1.64	0.35	-2.30	-1.63	-0.95	1.00
Forcing Temperature × Chilling 4 °C	0.67	0.44	-0.19	0.66	1.56	1.00
Forcing Temperature × Chilling 1.5 °C	0.38	0.43	-0.46	0.38	1.19	1.00
Photoperiod × Chilling 4 °C	0.21	0.42	-0.65	0.21	1.04	1.00
Photoperiod × Chilling 1.5 °C	0.54	0.41	-0.25	0.54	1.33	1.00
Forcing Temperature × Site	0.24	0.36	-0.49	0.24	0.94	1.00
Photoperiod × Site	-0.40	0.35	-1.09	-0.41	0.30	1.00
Site × Chilling 4 °C	0.13	0.44	-0.74	0.13	1.01	1.00
Site × Chilling 1.5 °C	0.80	0.41	-0.00	0.81	1.59	1.00

Table S5: Summary of mixed-effects model of budburst day. See also Figure S4

	mean	sd	2.5%	50%	97.5%	Rhat
Forcing Temperature	-8.82	1.05	-10.87	-8.82	-6.73	1.00
Photoperiod	-4.53	0.90	-6.28	-4.53	-2.73	1.00
Chilling 4 °C	-15.82	2.13	-20.06	-15.82	-11.59	1.00
Chilling 1.5 °C	-13.13	2.00	-17.04	-13.14	-9.08	1.00
Site	1.31	1.08	-0.84	1.31	3.45	1.00
Forcing Temperature × Photoperiod	-0.62	0.79	-2.14	-0.63	0.95	1.00
Forcing Temperature × Chilling 4 °C	9.09	1.09	6.94	9.09	11.23	1.00
Forcing Temperature × Chilling 1.5 °C	9.78	1.17	7.50	9.79	12.07	1.00
Photoperiod × Chilling 4 °C	-0.26	1.11	-2.48	-0.26	1.98	1.00
Photoperiod × Chilling 1.5 °C	-0.14	1.25	-2.63	-0.13	2.27	1.00
Forcing Temperature × Site	-1.51	0.85	-3.13	-1.51	0.16	1.00
Photoperiod × Site	-0.08	0.81	-1.70	-0.08	1.49	1.00
Site × Chilling 4 °C	-2.26	1.21	-4.64	-2.25	0.13	1.00
Site × Chilling 1.5 °C	-3.47	1.34	-6.10	-3.48	-0.85	1.00

Table S6: Summary of mixed-effects model of leafout day. See also Figure S5.

	mean	sd	2.5%	50%	97.5%	Rhat
Forcing Temperature	-19.06	1.04	-21.10	-19.05	-17.05	1.00
Photoperiod	-11.19	0.86	-12.91	-11.18	-9.53	1.00
Chilling 4 °C	-17.44	2.07	-21.55	-17.42	-13.34	1.00
Chilling 1.5 °C	-15.84	2.05	-20.02	-15.80	-11.88	1.00
Site	1.34	1.24	-1.12	1.35	3.76	1.00
Forcing Temperature × Photoperiod	3.68	0.85	2.06	3.66	5.39	1.00
Forcing Temperature × Chilling 4 °C	10.30	1.17	8.01	10.30	12.62	1.00
Forcing Temperature × Chilling 1.5 °C	11.22	1.32	8.61	11.24	13.81	1.00
Photoperiod × Chilling 4 °C	0.79	1.18	-1.47	0.79	3.16	1.00
Photoperiod × Chilling 1.5 °C	2.35	1.32	-0.32	2.37	4.87	1.00
Forcing Temperature × Site	-0.50	0.83	-2.11	-0.50	1.15	1.00
Photoperiod × Site	-0.87	0.83	-2.51	-0.87	0.75	1.00
Site × Chilling 4 °C	-1.75	1.28	-4.26	-1.76	0.77	1.00
Site × Chilling 1.5 °C	-3.35	1.51	-6.35	-3.34	-0.41	1.00

Table S7: Chill units in the field before harvest (January 2015), until 1 April and 1 May 2015 at each site, and in growth chamber conditions (including field chilling experienced before cuttings entered the chambers).

Site	Treatment	Chilling Hours	Utah Model	Chill portions
Harvard Forest	Field chilling until collection	892	814.50	56.62
	Field chilling to 1 Apr	1153	980.00	79.37
	Field chilling to 1 May	1449	1360.50	99.94
	Field chilling + 4.0 °C x 30 d	2140	2062.50	94.06
	Field chilling + 1.5 °C x 30 d	2140	1702.50	91.17
St. Hippolyte	Field chilling until collection	682	599.50	44.63
	Field chilling to 1 Apr	796	653.50	63.55
	Field chilling to 1 May	1166	937.00	83.83
	Field chilling + 4.0 °C x 30 d	1930	1847.50	82.06
	Field chilling + 1.5 °C x 30 d	1930	1487.50	79.18

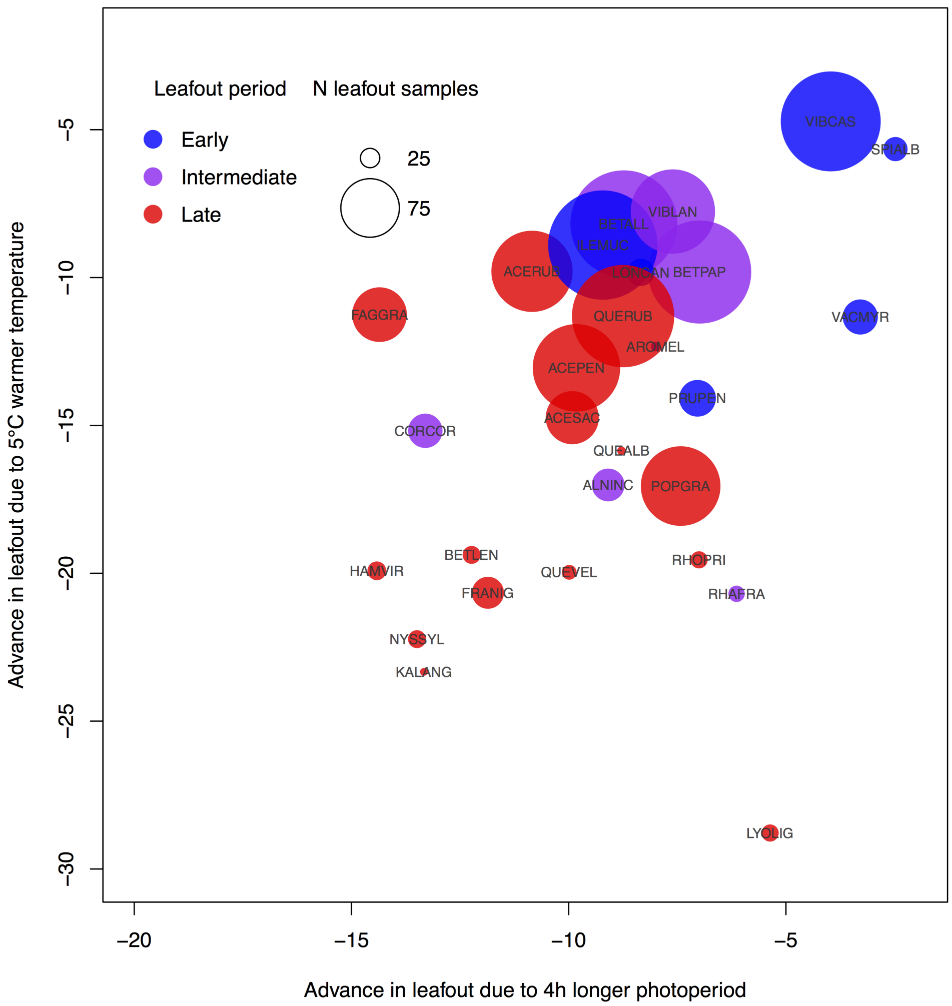

Figure S1: Responses of 28 woody plant species to photoperiod and temperature cues for leafout. Color of circle reflect unmodeled data on average leafout day across treatments, across sites of origin, while size of circle represents the total number of clippings in the experiment—this varies mainly based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

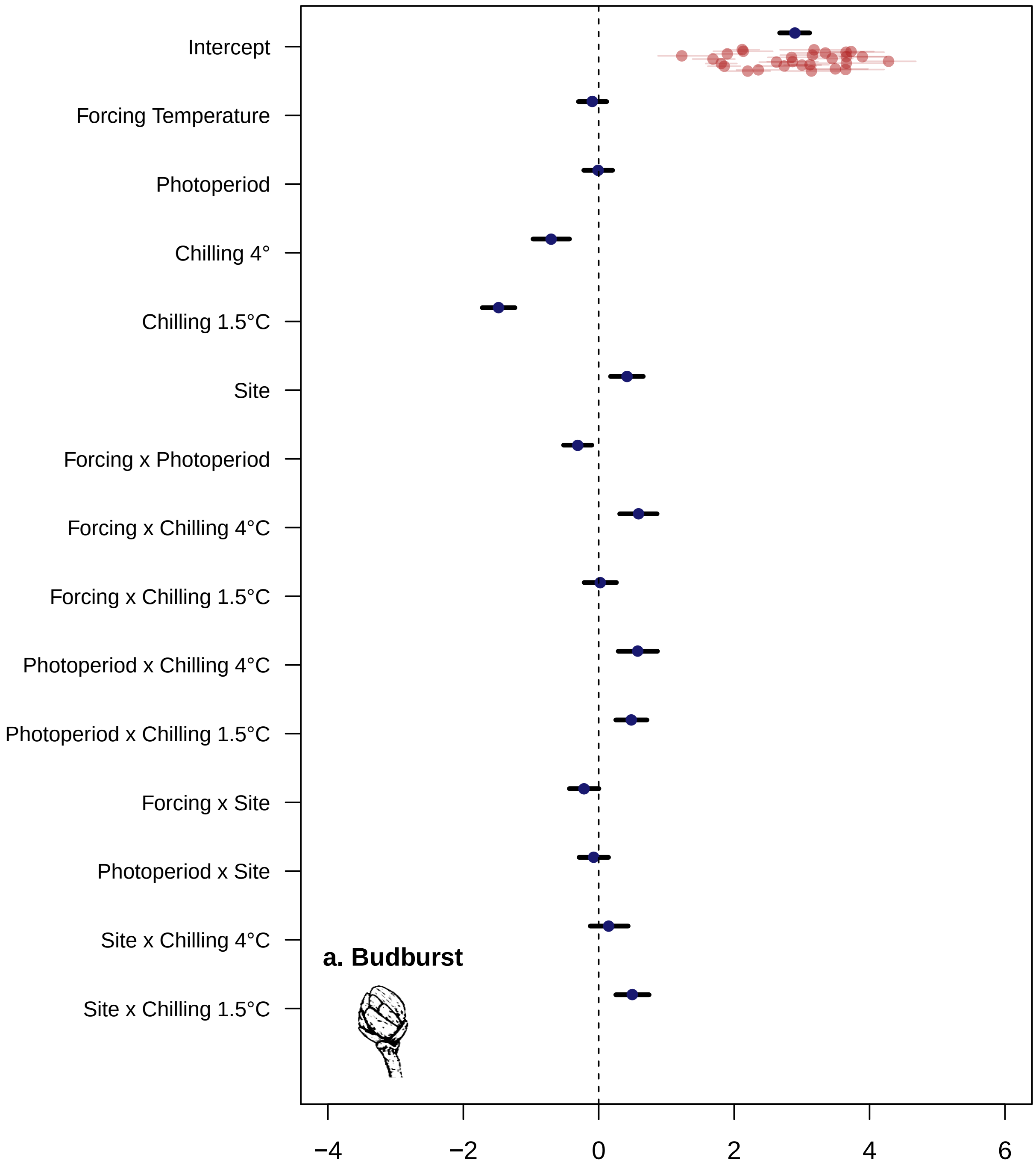

Figure S2: Model estimates of budburst success, including species-level effects, presented on logit scale. Dots and bars show mean and 50% credible intervals. See also Table S2.

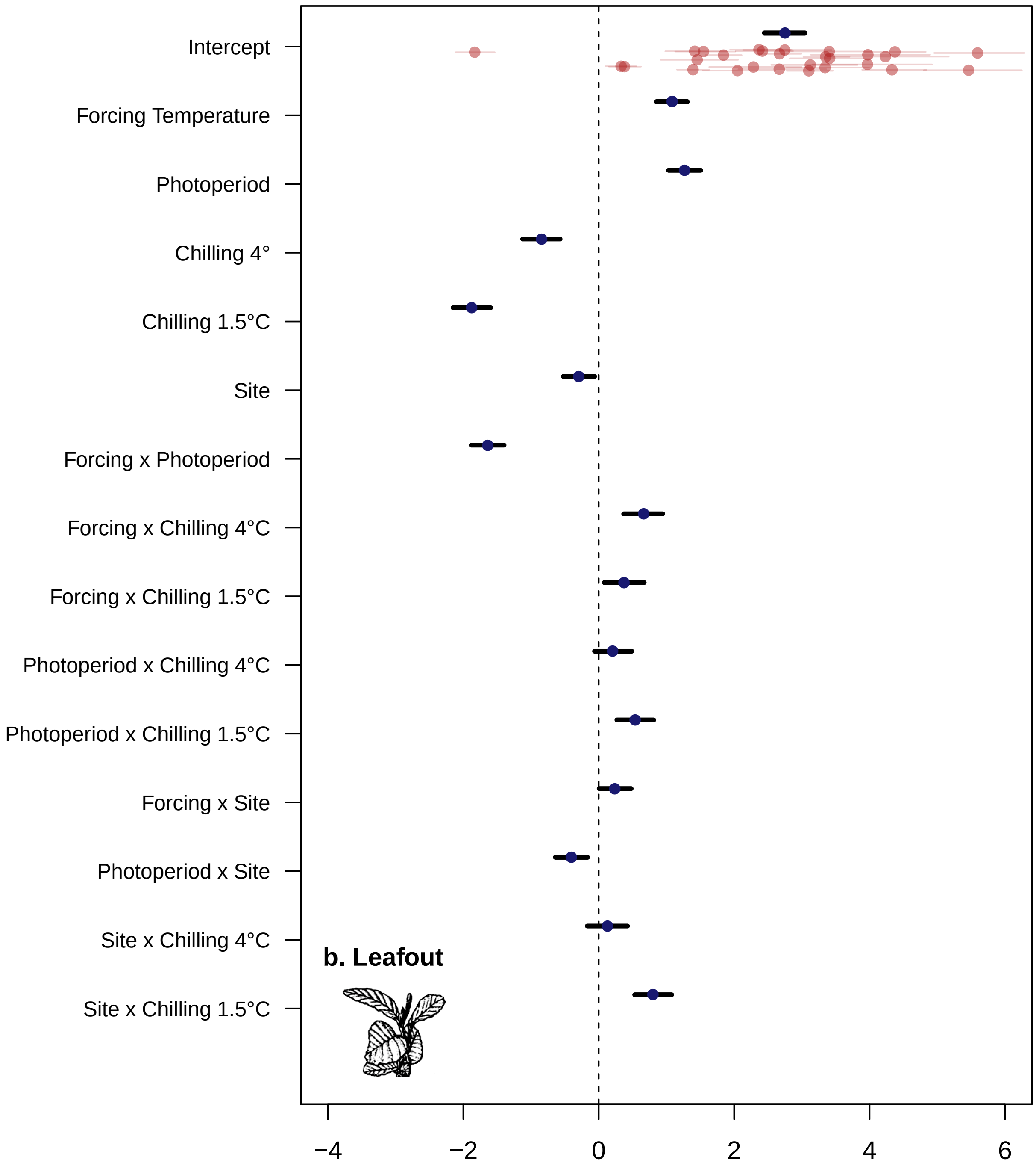

Figure S3: Model estimates of leafout success, including species-level effects, presented on logit scale. Dots and bars show mean and 50% credible intervals. See also Table S3.

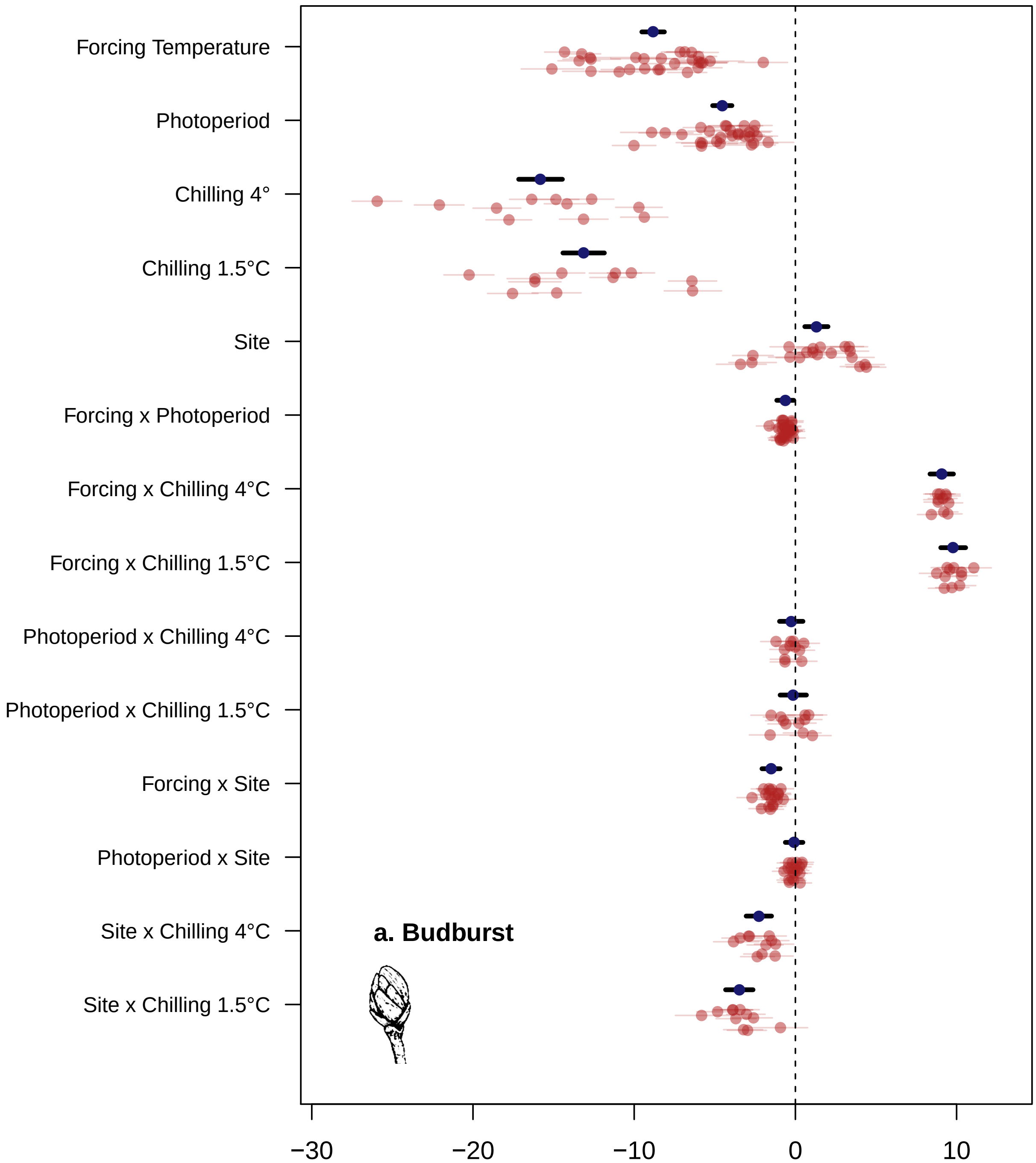

Figure S4: Model estimates of effects of each predictor on budburst day, including species-level effects. Dots and bars show mean and 50% credible intervals.

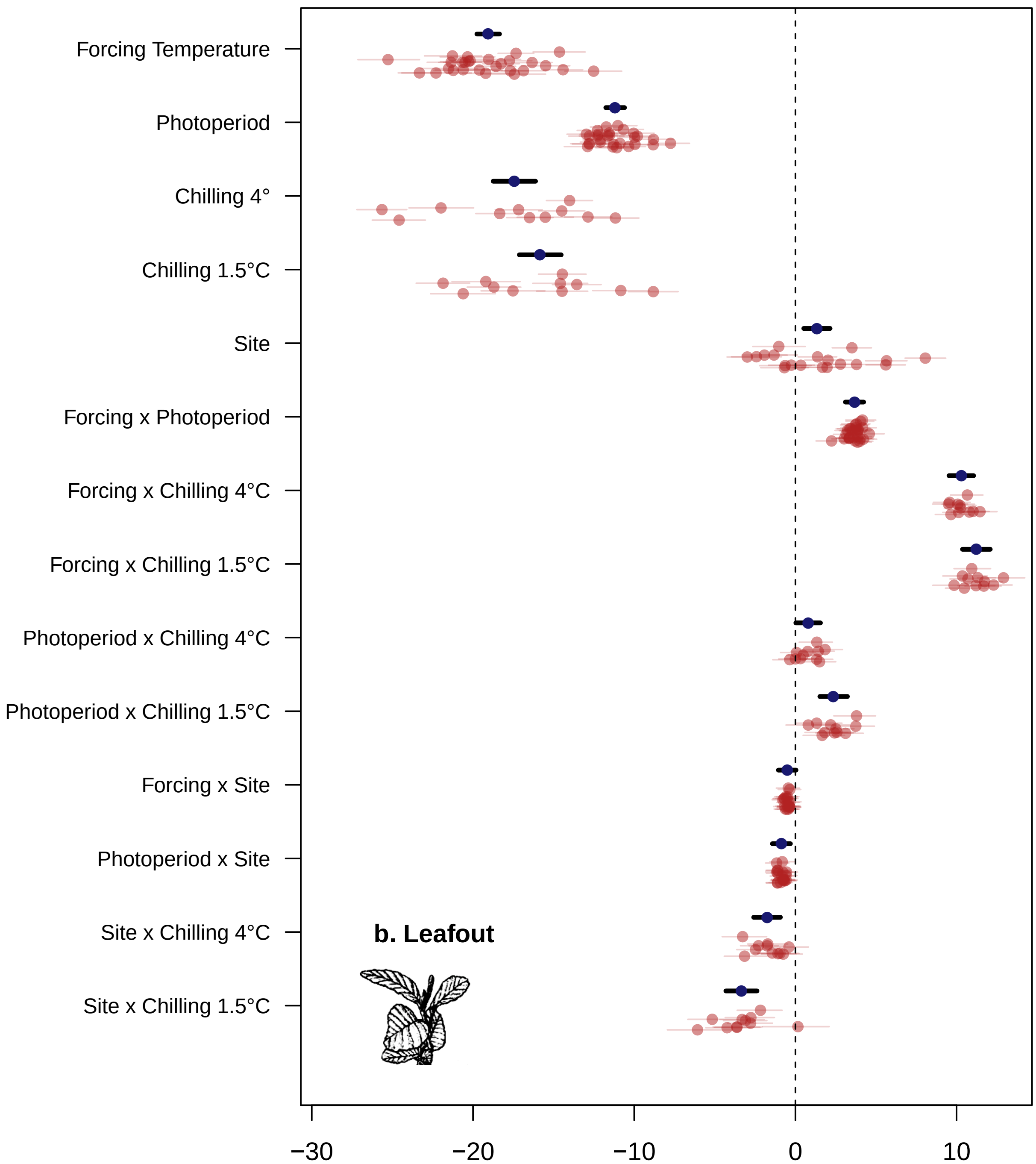

Figure S5: Model estimates of leafout day, including species-level effects. Dots and bars show mean and 50% credible intervals.

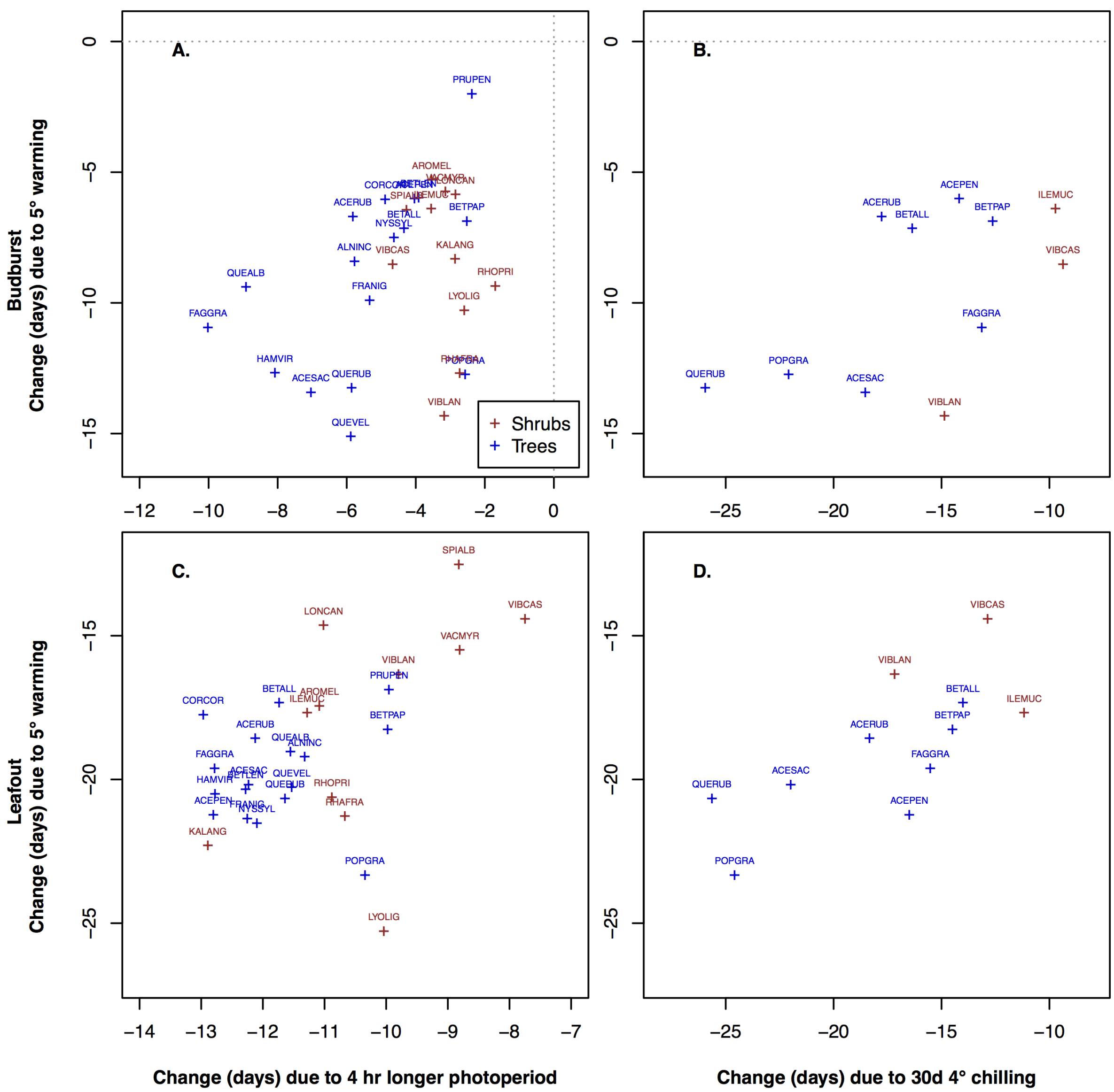

Figure S6: Effects of photoperiod, temperature and chilling across species (shrub species shown in red, tree species in blue): Similar to Fig. 2 from main text, but designed to make species names easier to read by adjusting axes (note that axes vary across rows and columns) and removing bars showing credible intervals.

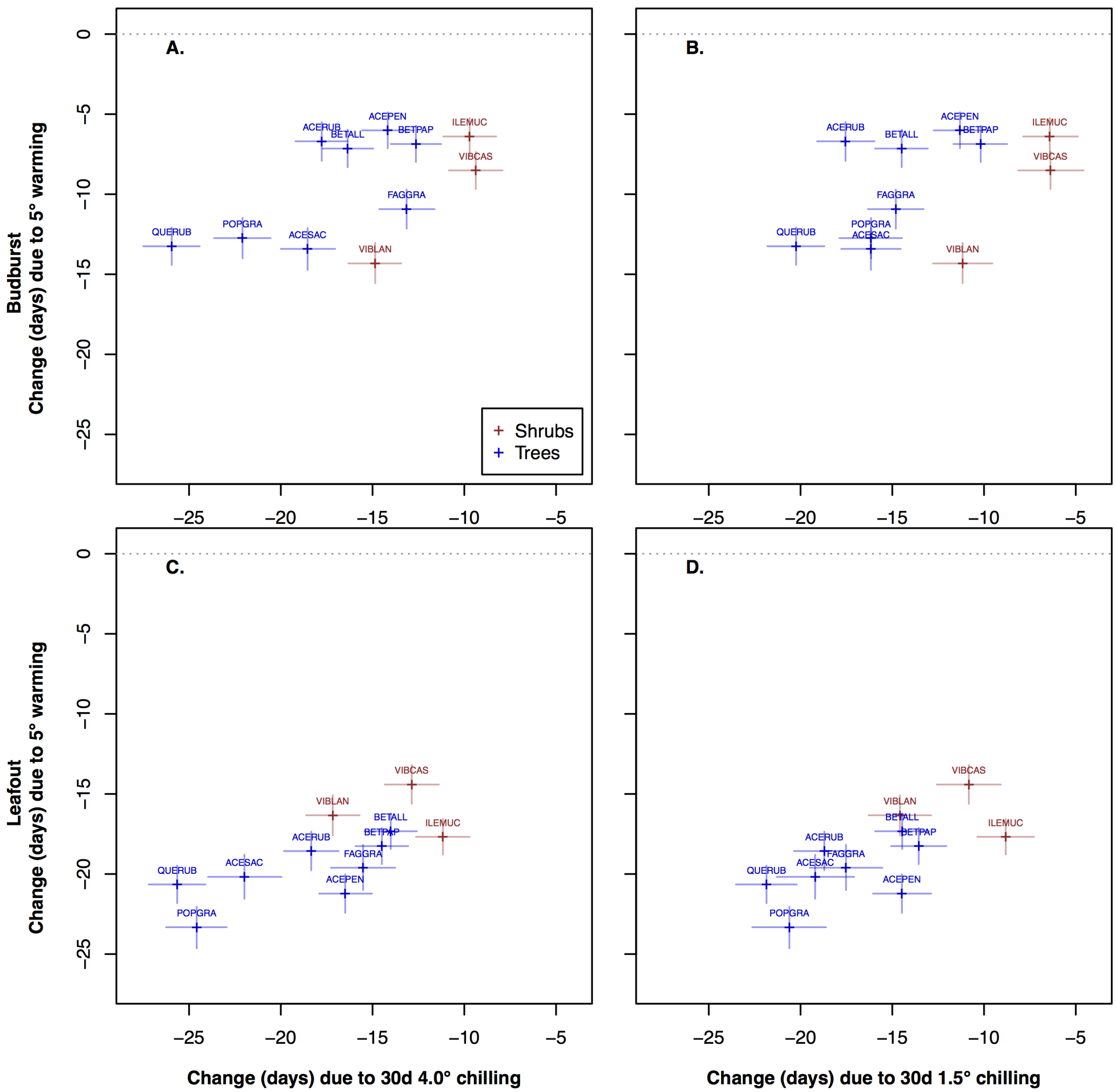

Figure S7: Effects of temperature and chilling across species (shrub species shown in red, tree species in blue): Similar to Fig. 2 from main text, but showing results side-by-side for the two chilling treatments: 4.0°C (left) versus 1.5°C (right) as compared to forcing temperature responses (for photoperiod see S7). Crosses and bars show mean and 50% credible intervals.

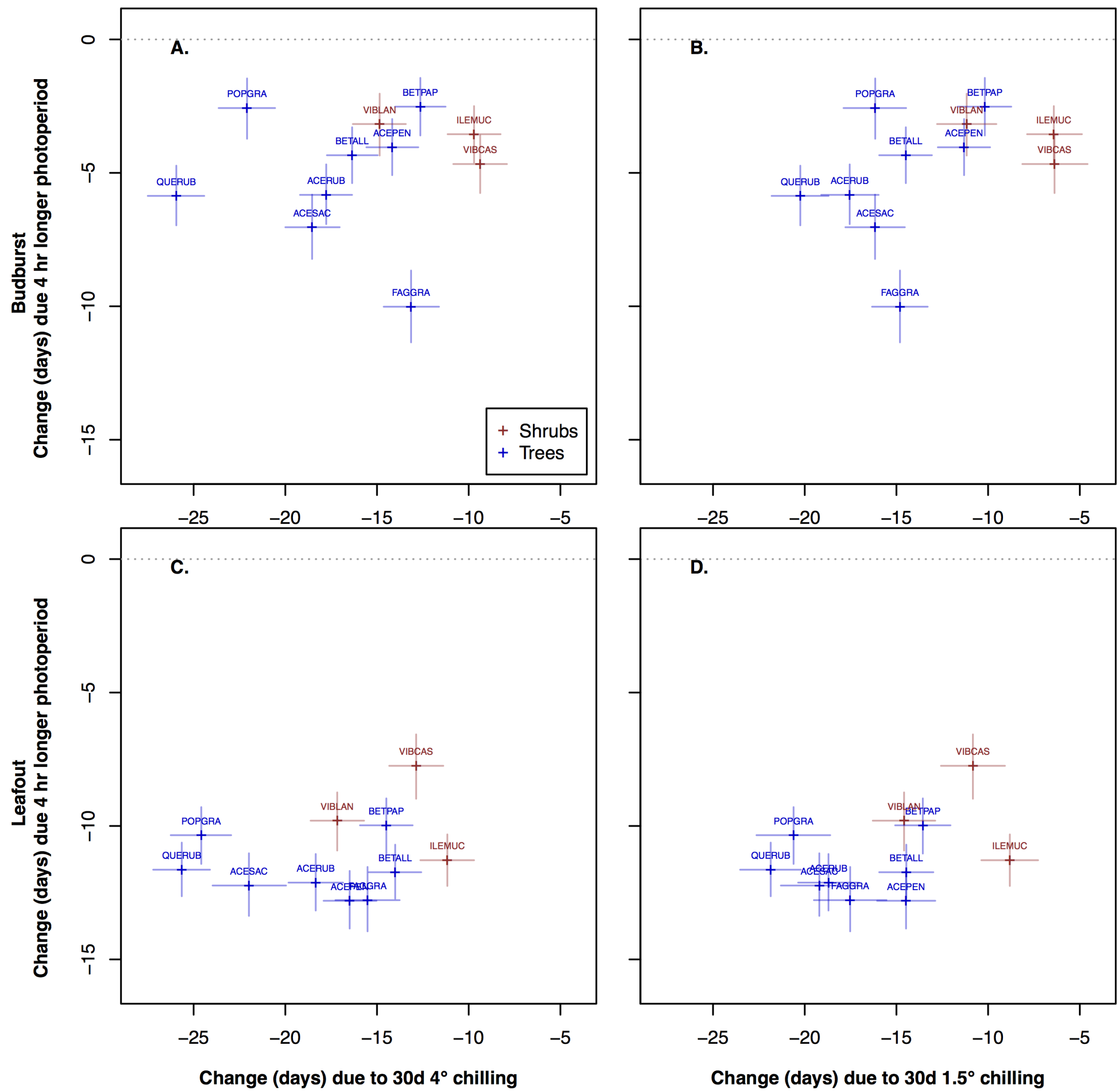

Figure S8: Effects of photoperiod and chilling across species (shrub species shown in red, tree species in blue): Similar to Fig. 2 from main text, but showing results side-by-side for the two chilling treatments: 4.0°C (left) versus 1.5°C (right) as compared to photoperiod responses (for forcing temperature see S6). Crosses and bars show mean and 50% credible intervals.

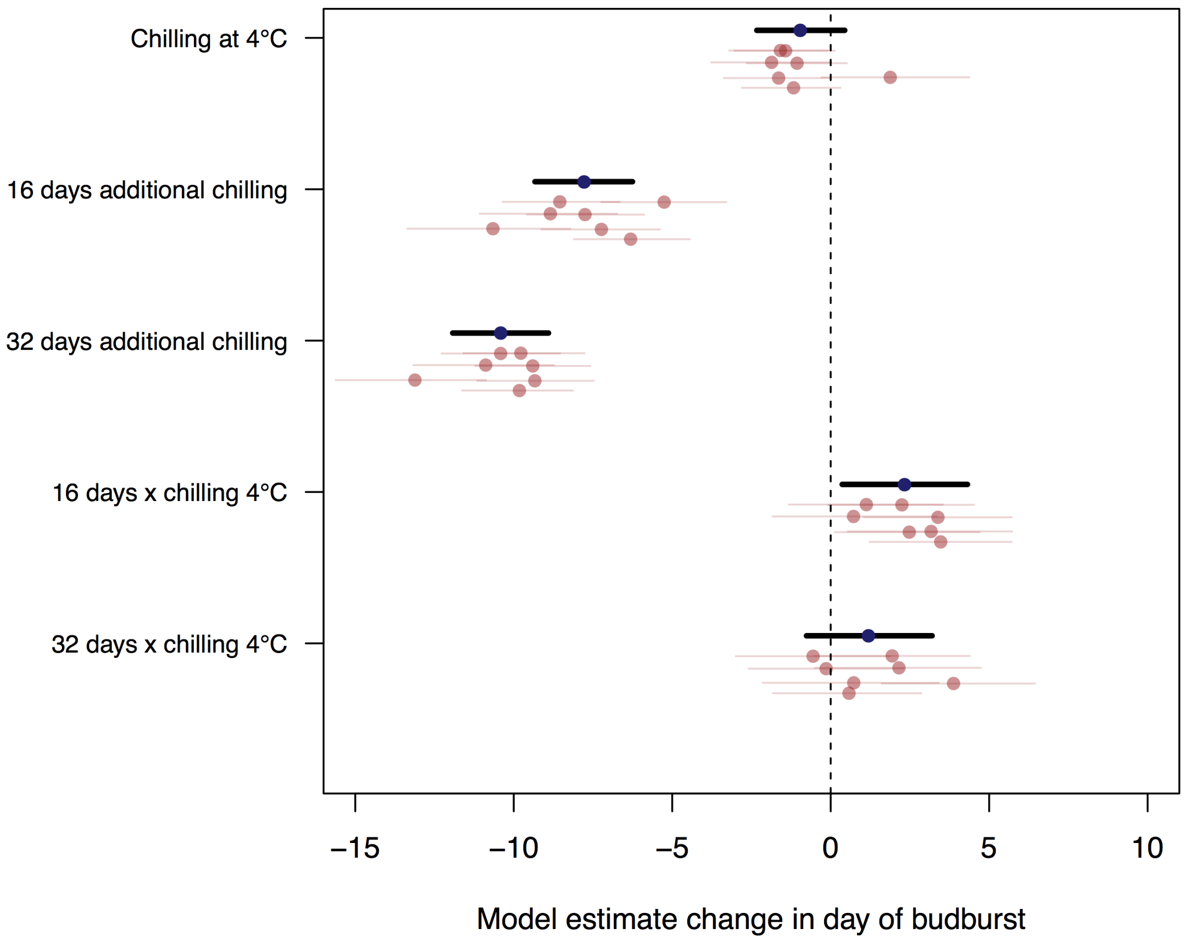

Figure S9: Model estimates of effects chilling temperature (1°C or 4°C) and time (no additional chilling, 16 days additional or 32 days additional chilling) on budburst day (including species-level effects), as assessed from a follow-up experiment conducted in the winter of 2015-2016. Dots and bars show mean and 50% credible intervals. Note that for this experiment the intercept (not shown: 44.7 days) was the estimate for the 1°C treatment.