Supporting Information: Differences between flower and leaf phenological responses to environmental variation drive shifts in spring phenological sequences of temperate woody plants

Tables

Species	Family	flower-leaf sequence	pollination	bud type	habit
Acer pensylvanicum	Sapindaceae	flowers with/after leaves	wind/insect	mixed	understory tree
Acer rubrum	Sapindaceae	flowers before leaves	wind/insect	separate	canopy tree
Acer saccharum	Sapindaceae	flowers before/with leaves	wind/insect	mixed	canopy tree
Betula alleghaniensis	Betulaceae	flowers before leaves	wind	separate	canopy tree
Corylus cornuta	Betulaceae	flowers before leaves	wind	separate	shrub
Comptonia peregrina	Myrtaceae	flowers before leaves	wind	separate	shrub
Ilex mucronata	Aquifoliaceae	flowers with leaves	insect	mixed	shrub
Ilex verticillata	Aquifoliaceae	flowers after leaves	insect	mixed	shrub
Prunus pensylvanica	Rosaceae	flowers with leaves	insect	mixed	understory tree
Prunus virginiana	Rosaceae	flowers with/after leaves	insect	mixed	shrub
Vaccinium corymbosum	Ericaceae	flowers after leaves	insect	separate	shrub
Viburnum acerifolium	Adoxaceae	flowers after leaves	insect	mixed	shrub

Table S1: Descriptive flower-leaf sequences classifications and functional traits for 12 temperate woody species collected from Harvard Forest (Petersham, MA, USA) and included in the lab experiment.

		Harvard Forest	sd	Chamber: 30 days	Chamber: 60 days
1	Utah Model	979.64	248.34	720.00	1440.00
2	Chill Hours	1170.71	273.07	720.00	1440.00
3	Dynamic Model	86.56	16.64	21.25	43.50

Table S2: Comparisons between the average amount of chilling accumulated by woody plants at Harvard Forest (Petersham, MA, USA) between 15 October and 15 April in the field (Harvard Forest) and our experimental treatments (Chamber: 30 days, Chamber: 60 days) using three alternative methods for calculating chilling (Utah Model, Chill hours, Dynamic Model, (see Luedeling & Brown, 2011) for details).

	Estimate	Est.Error	Q2.5	Q25	Q75	Q97.5
Intercept	70.81	9.18	52.99	64.94	76.88	88.08
Chill	-30.41	5.40	-40.45	-33.89	-27.15	-19.25
Light	5.87	5.13	-4.17	2.42	9.16	15.92
Force	-17.76	5.21	-28.21	-21.10	-14.29	-8.22
Chill:Light	-5.17	4.35	-13.62	-8.03	-2.31	3.56
Chill:Force	12.37	4.84	2.62	9.26	15.51	21.85
Light:Force	-12.62	4.10	-20.50	-15.37	-9.87	-4.79

Table S3: Mean ('Estimate') and quantile ('Q') estimates of effects of forcing temperature, chilling duration, and photoperiod and all two-way interactions (change in day of phenological event/ change in environmental cue; 4 weeks chilling/6°C forcing/4 hours photoperiod) on leaf budburst of 10 woody plant species from Bayesian hierarchical models.

	Estimate	Est.Error	Q2.5	Q25	Q75	Q97.5
Intercept	77.53	9.92	58.14	71.05	83.88	97.18
Chill	-21.23	7.42	-35.35	-26.14	-16.32	-6.07
Light	-5.72	5.70	-18.28	-9.01	-2.03	4.86
Force	-18.98	6.51	-32.09	-23.02	-14.93	-6.37
Chill:Light	-0.88	6.11	-13.59	-4.72	3.21	10.55
Chill:Force	7.01	6.62	-6.35	2.98	11.11	20.31
Light:Force	-5.61	6.42	-19.08	-9.51	-1.46	6.37

Table S4: Mean ('Estimate') and quantile ('Q') estimates of effects of forcing temperature, chilling duration, and photoperiod and all two-way interactions (change in day of phenological event/change in environmental cue; 4 weeks chilling/6°C forcing/4 hours photoperiod) on flowering of 10 woody plant species from Bayesian hierarchical models.

	Species	Estimate	error	Q2.5	Q25	Q75	Q97.5	phase	sequence
1	A. pensylvanicum	-10.71	3.92	-17.87	-13.48	-8.19	-2.28	leaf budburst	first
2	A. pensylvanicum	-17.43	6.15	-30.48	-20.68	-14.00	-5.59	flowering	second
3	A. rubrum	-16.76	7.25	-33.11	-20.21	-13.09	-2.88	flowering	first
4	A. rubrum	-28.39	6.22	-40.52	-32.69	-24.08	-16.20	leaf budburst	second
5	C. peregrina	-13.28	3.33	-19.62	-15.50	-11.17	-6.60	flowering	first
6	C. peregrina	-15.47	3.69	-23.06	-17.82	-13.01	-8.53	leaf budburst	second
7	C. cornuta	-15.55	4.50	-24.71	-18.13	-12.87	-6.79	flowering	first
8	C. cornuta	-19.82	4.04	-28.13	-22.41	-17.10	-11.99	leaf budburst	second
9	I. mucronata	-10.44	3.81	-17.42	-13.09	-8.05	-2.45	leaf budburst	first
10	I. mucronata	-16.05	4.06	-24.19	-18.58	-13.47	-7.94	flowering	second
11	I. verticillata	-8.66	3.73	-15.58	-11.19	-6.19	-1.12	leaf budburst	first
12	I. verticillata	-20.43	10.72	-43.88	-25.92	-14.18	-2.14	flowering	second
13	P. pensylvanica	-10.24	4.14	-18.67	-12.99	-7.50	-2.14	leaf budburst	first
14	P. pensylvanica	-13.85	4.02	-21.59	-16.46	-11.40	-5.39	flowering	second
15	P. virginiana	-26.68	5.11	-37.14	-30.02	-23.09	-17.20	leaf budburst	first
16	P. virginiana	-23.69	7.67	-40.07	-28.74	-17.84	-10.95	flowering	second
17	V. corymbosum	-7.06	3.85	-14.45	-9.62	-4.56	0.66	leaf budburst	first
18	V. corymbosum	-13.10	3.60	-20.30	-15.49	-10.79	-5.99	flowering	second
19	V. acerifolium	-12.68	3.78	-19.97	-15.14	-10.29	-5.10	leaf budburst	first
20	V. acerifolium	-21.60	8.52	-39.63	-26.63	-16.00	-6.85	flowering	second

Table S5: Mean ('Estimate') and quantile ('Q') estimates of effects of forcing temperature and all two-way interactions (change in day of phenological event/ Δ environmenta/6 °C) on budburst and flowering of 10 woody plant species from Bayesian hierarchical models under long photoperiod and long chilling duration experimental treatments.

Figures

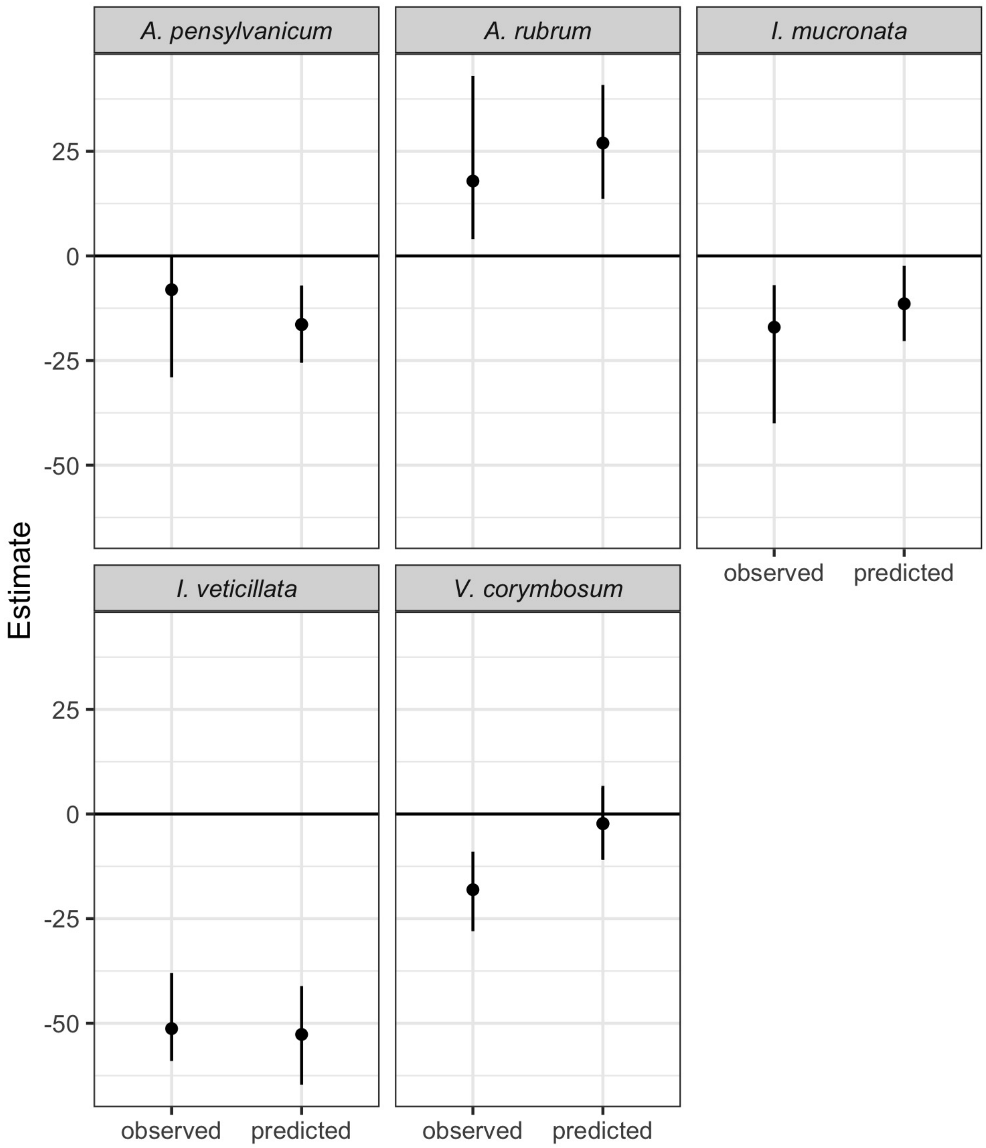

Figure S1: A comparison of the estimated mean flower-leaf sequence interphases (days between phenophase) for six woody plant species under artificial conditions designed to approximate "average" field conditions and observed mean FLS interphases in the field at Harvard Forest in Pertersham MA. Dots represent means FLS interphase in both datasets, and lines represent the 50% credible intervals and the full range of observations for our model predictions and Harvard Forest data respectively. Harvard Forest phenological records are from O'Keefe (2015).

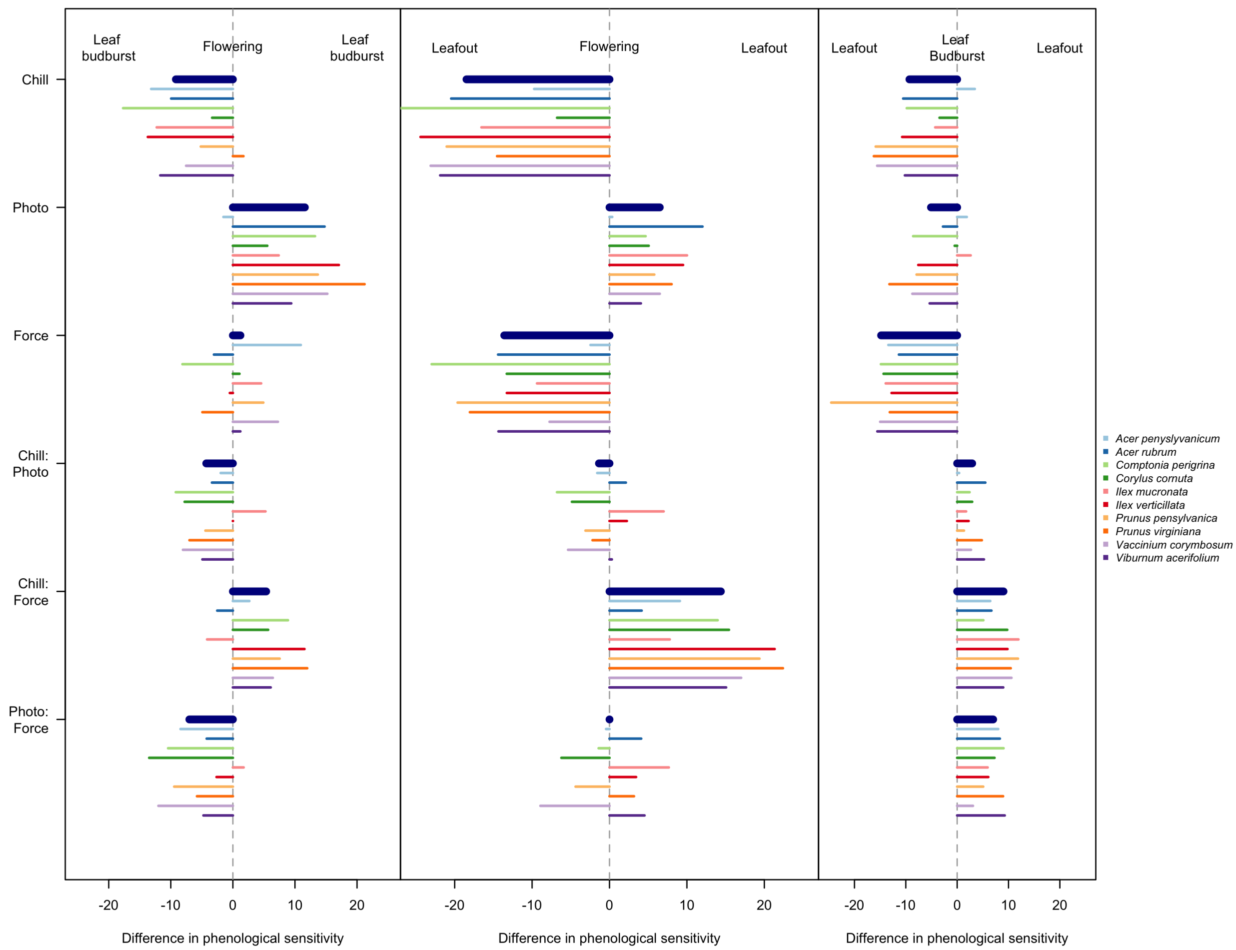

Figure S2: The difference in mean effects of forcing temperature, chilling duration, and photoperiod between leaf budburst, leafout and flowering phenology of 10 temperate woody plant species collected from Harvard Forest (Petersham, MA, USA). Stronger advances in phenology are shown as negative numbers, and delays in phenology as positive numbers. The thicker blue bars depict the main effects for all species and thinner bars indicate the species-specific differences in the responses among phases.

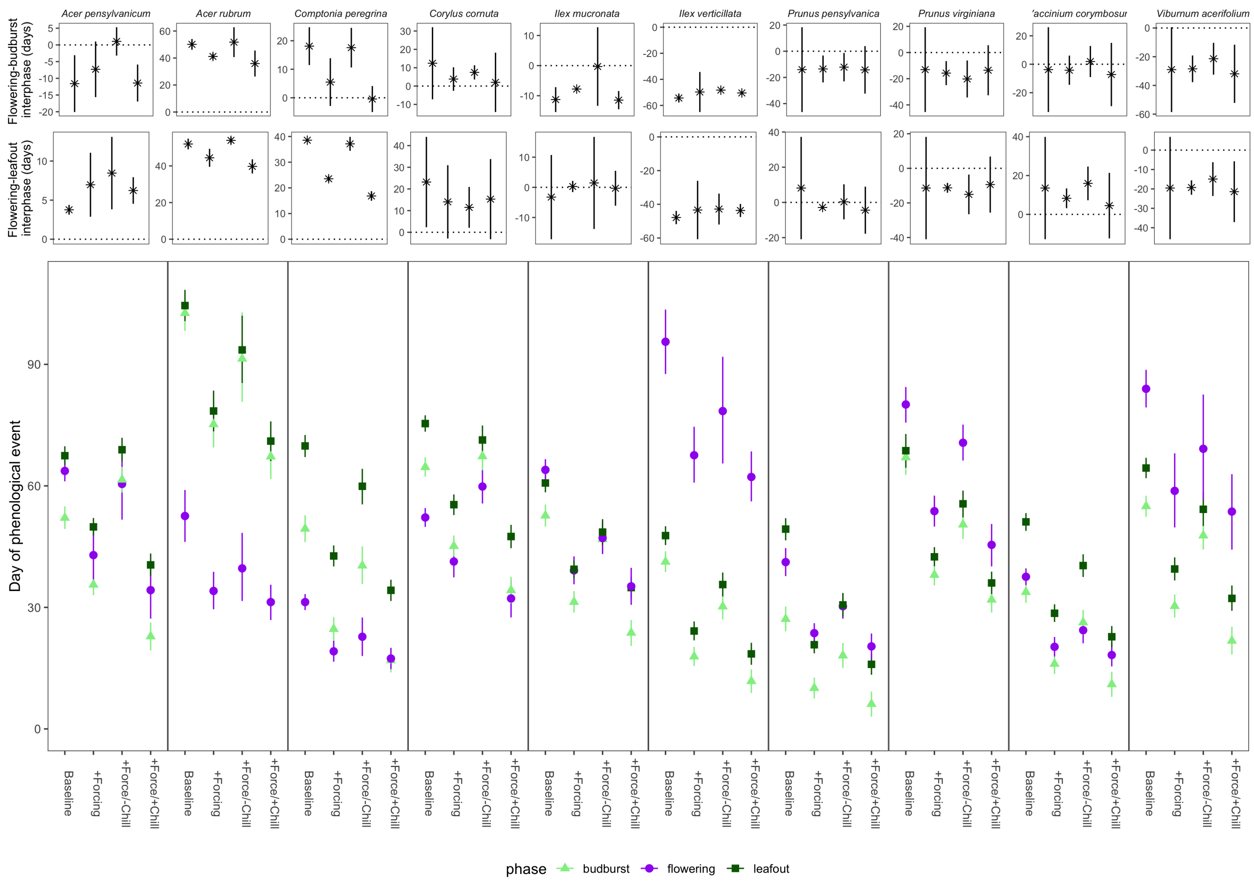

Figure S3: Projected shifts in flower-leaf sequences under current environmental conditions (Baseline) and three climate change scenarios (increase forcing, increase forcing/decrease chilling, increase forcing/increase chilling) predict that FLS for 10 common temperate woody plant species. The top two rows show the mean time between flowering and vegetative phenological events (shapes) with 50% credible intervals (lines). The bottom row shows the predicted event day for each phase. Predictions are based on posterior estimates from Bayesian hierarchical models comparing flowering (circles), leaf budburst (triangles) and leafout (squares) phenological responses to variable chilling duration and forcing temperatures. Shapes represent the mean estimates and lines represent the 50% credible intervals.

Supplemental Methods

Simulations

To better understand the patterns of phenological sensitivity generated by the forcing hierarchy hypothesis (FHH) and the differential sensitivity hypothesis (DSH) respectively, we simulated the underlying physiology of each hypothesis, and used these simulations to generate flower and leaf phenology under two levels of chilling, forcing, and photoperiod in a fully factorial experimental design.

For the FHH we assigned flowering and leafing a critical heat sum threshold (F*) above which the phenological event would take place. We did this using a growing degree model with a base temperature of 5°C (Fu *et al.*, 2014). For the FHH simulations, we assigned flowering an F* of 200 GDDs and leafing an F* of 400 GDDs. In this scenario, higher chilling and photoperiod reduced the F* value for each phenophase by 100 and 20 respectively.

For the DSH we assigned flowering and leafing identical F* values of 400. As in the previous scenario, we let increased chilling and photoperiod reduce the F* values, but these cues reduced the F* for leafing by 200 and 0 respectively and for flowering by 100 and 20.

We also included a third scenario that included both initial F* differences of the FHH (flowering: 200 and leafing: 400) and the differential response to chilling and photoperiod of the DSH (flowering: -100 chilling, -20 photoperiod, leafing -200 chilling, 0 photoperiod).

References

Fu, Y., Zhang, H., Dong, W. & Yuan, W. (2014) Comparison of phenology models for predicting the onset of growing season over the northern hemisphere. *PLOS ONE* **9**, e109544–.

Luedeling, E. & Brown, P.H. (2011) A global analysis of the comparability of winter chill models for fruit and nut trees. *International Journal of Biometeorology* **55**, 411–421.

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