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SUPPLEMENTARY INFORMATION

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Title: **Day length unlikely to constrain climate-driven shifts in leaf-out times of northern woody plants**

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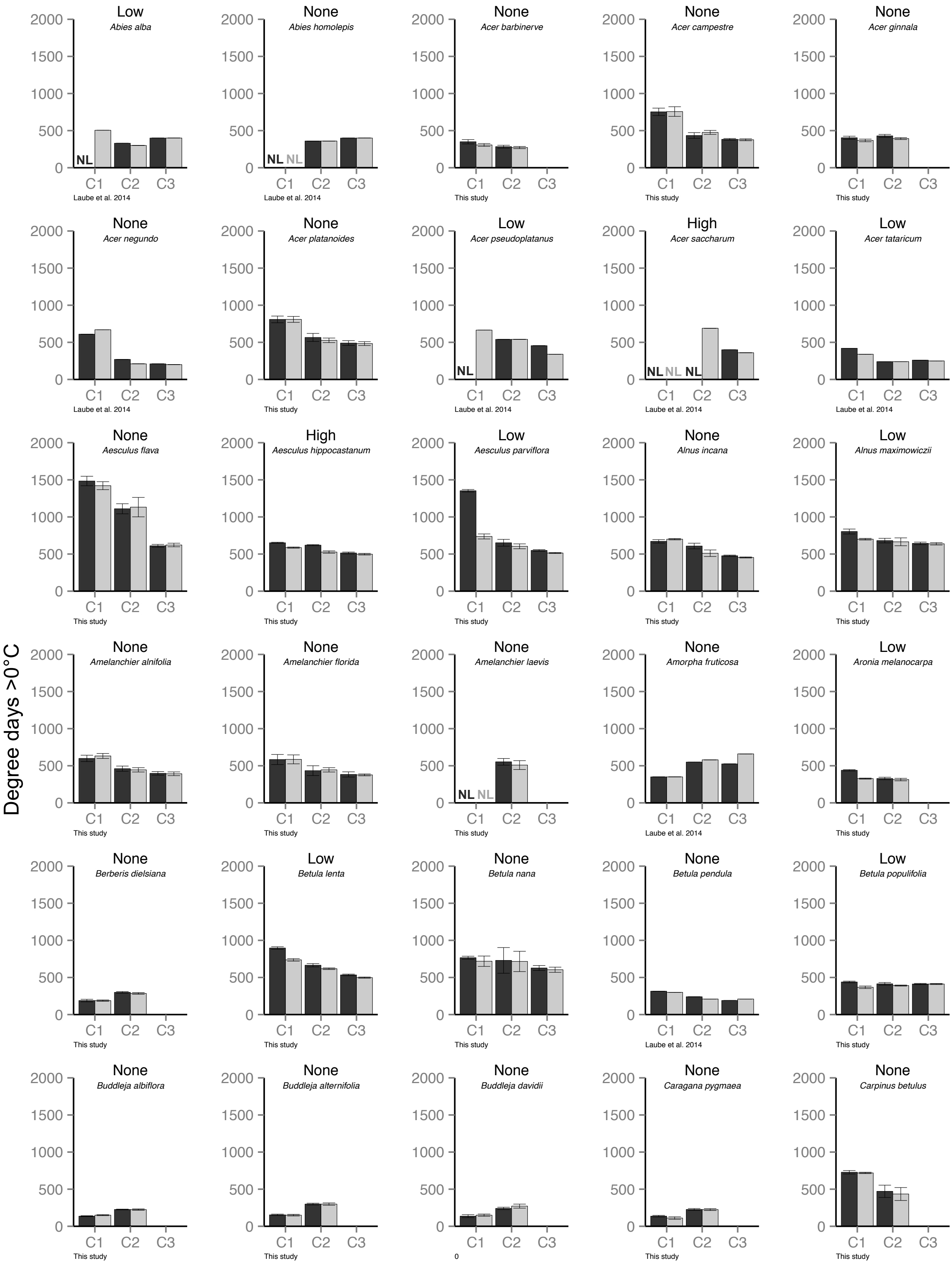
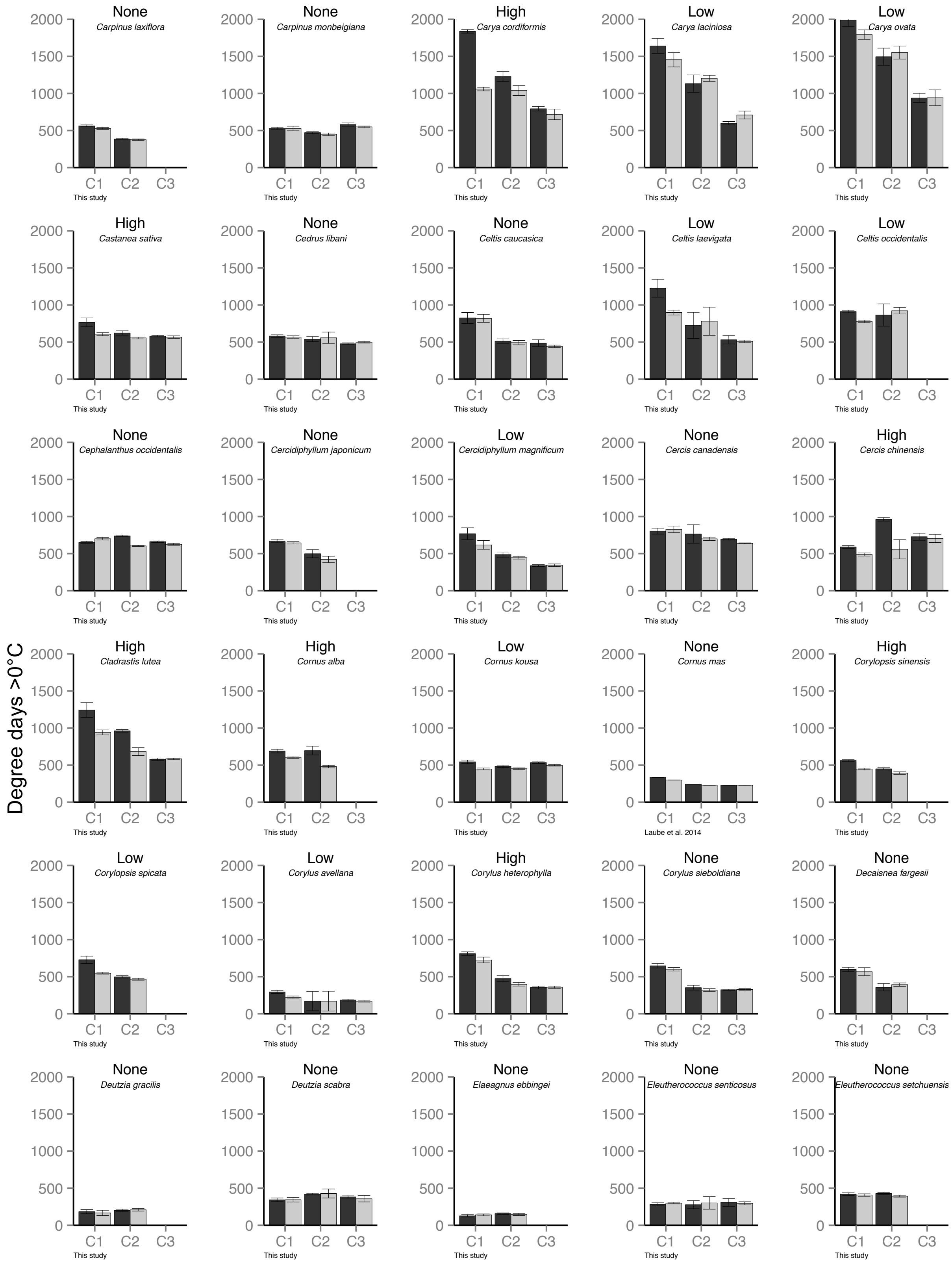


Figure S1 partial



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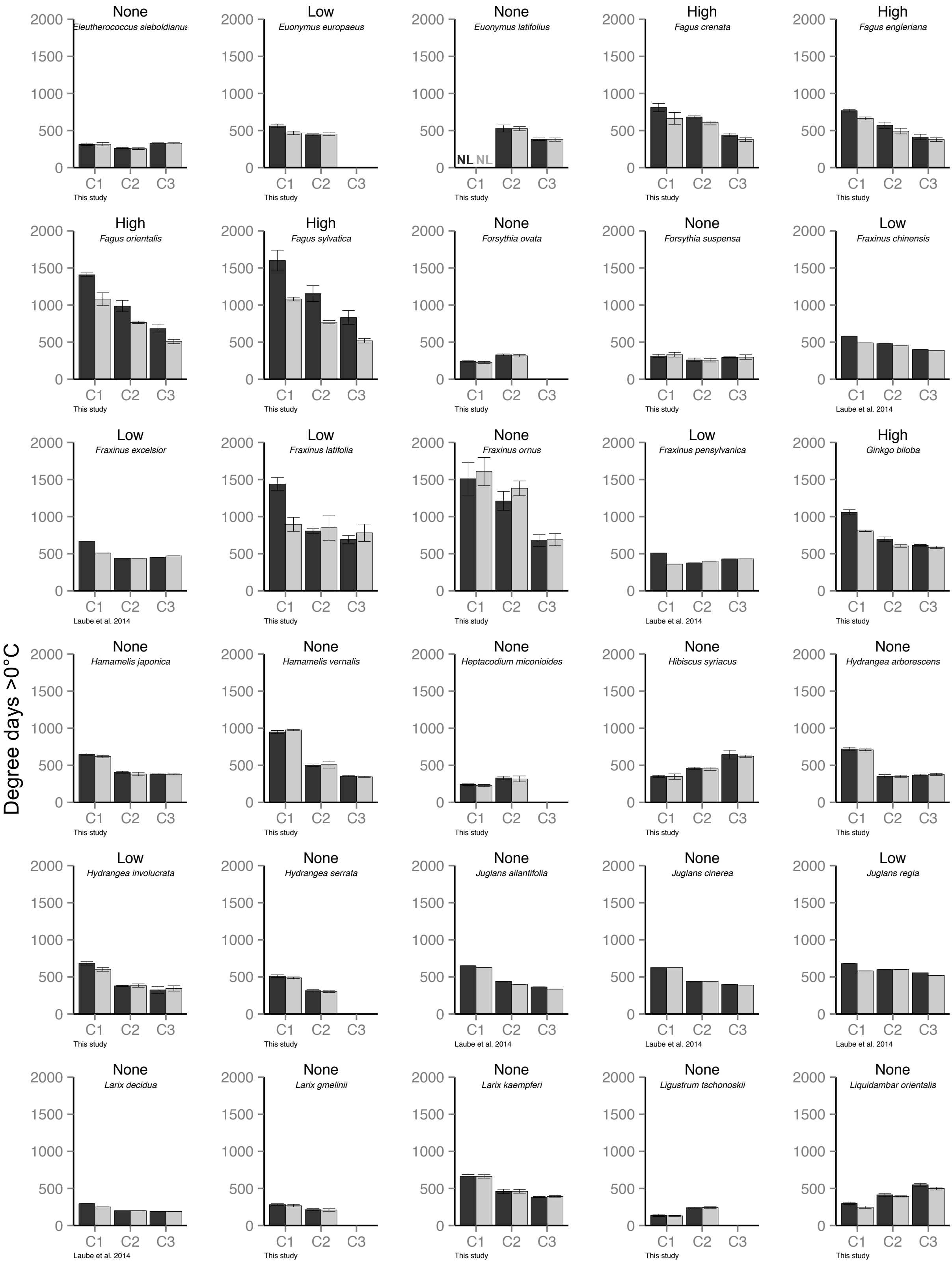

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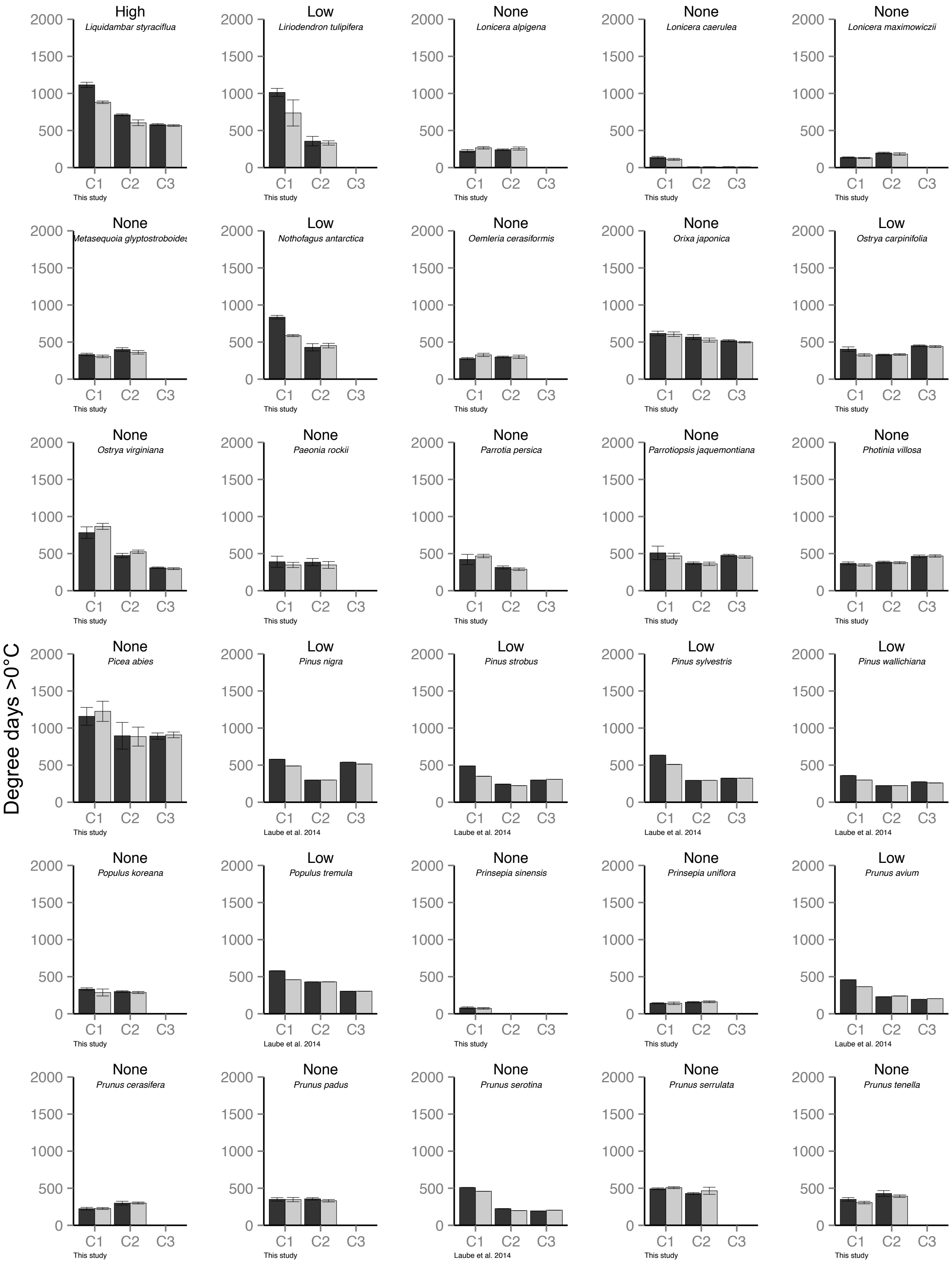

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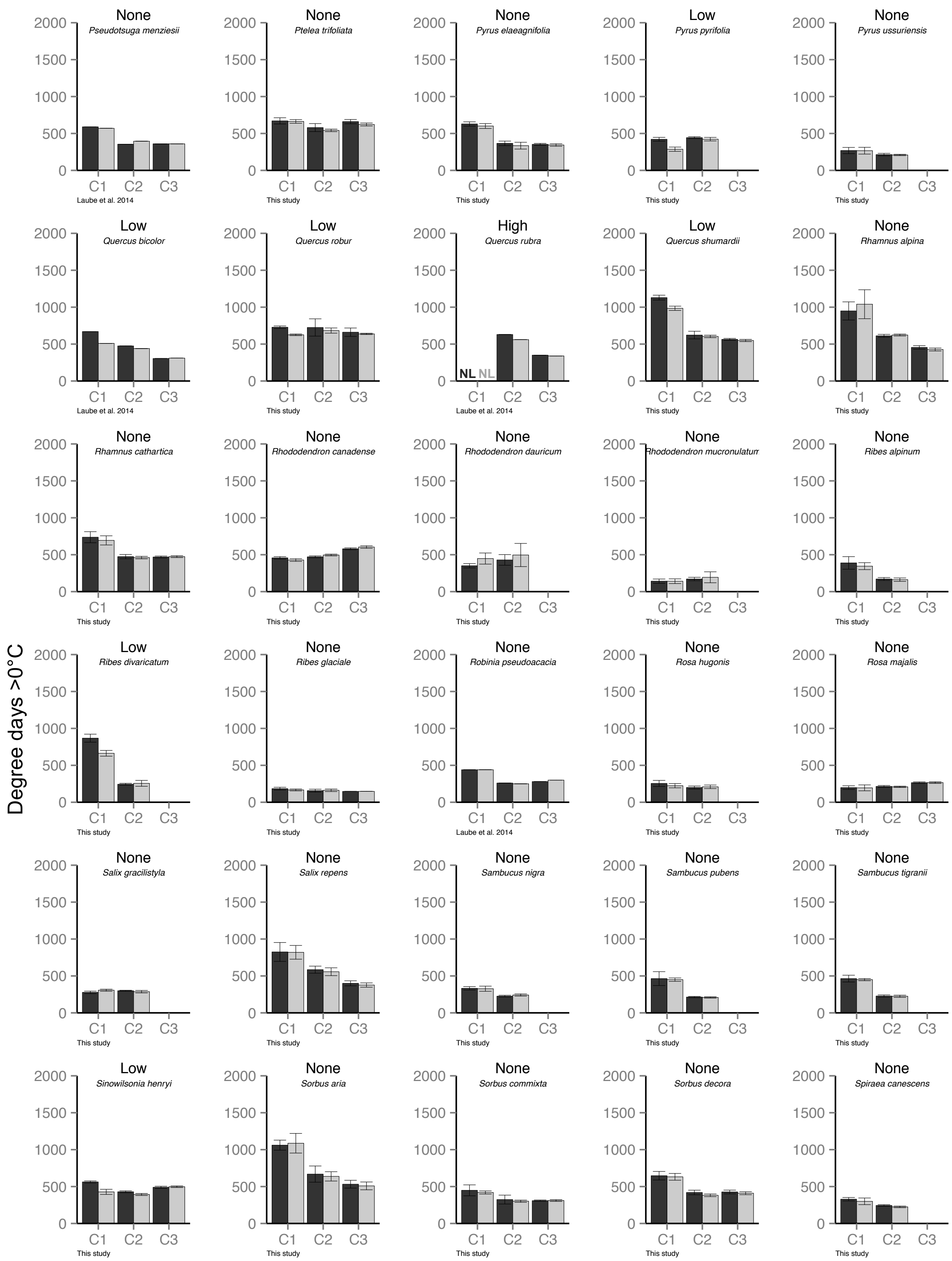

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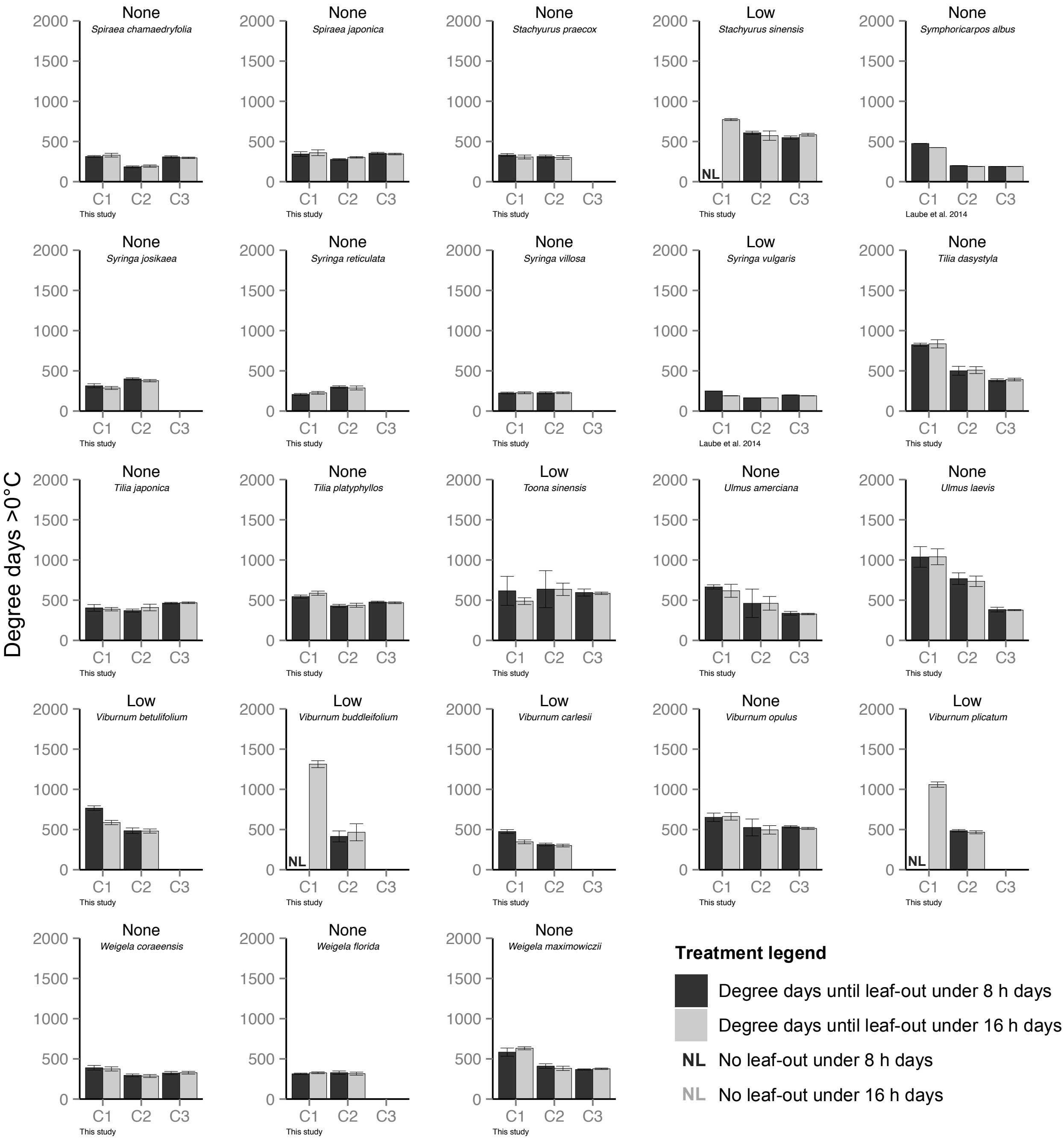

Figure S1 | Photoperiod requirements of 173 temperate woody species. The importance of photoperiod in regulating leaf-out (none, low, or high photoperiodism) was inferred from twig cutting experiments conducted in this study and in Laube *et al.*[12]. Graphs show forcing requirements (median growing degree days >0°C outdoors and in climate chamber ± SD) until leaf-out under short day length (8 h/d, black bars) and long day length (16 h/d, grey bars) at three different cutting dates (this study: C1 = 21 Dec 2013, C2 = 10 Feb 2014, C3 = 21 March 2014; Laube *et al.*[12]: C1 = 14 Dec 2011, C2 = 30 Jan 2012, C3 = 14 March 2012). *NL* indicates that no leaf-out occurred under 8-h (*NL* in black) or 16-h (*NL* in grey) day length. Some species leafed out before the last cutting date (C3), which is indicated by missing bars for the C3 treatment.

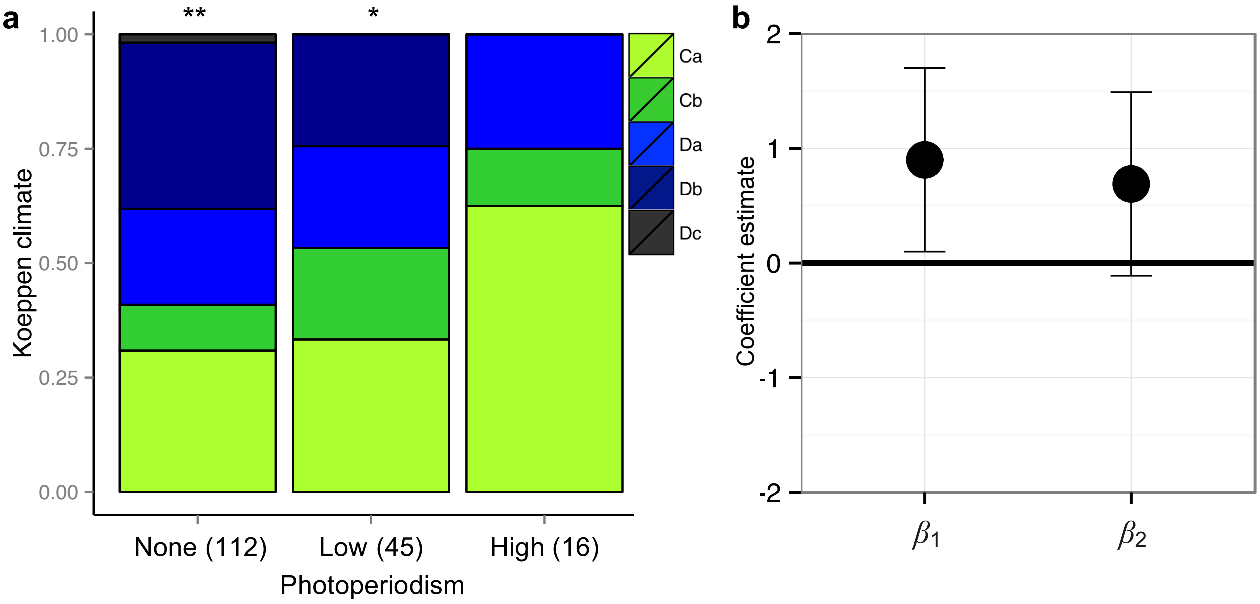

Figure S2 | Species with photoperiod requirements are native to milder climates. a, For each photoperiod category we show the relative proportion of species' Koeppen-Geiger temperature regimes (Ca = mild winter and hot summer periods, Cb = mild winter and warm summer periods, Da = cold winter and hot summer periods, Db = cold winter and warm summer periods, Dc = cold winter and cold summer periods). Asterisks above bars indicate which group differed significantly from the group containing species with high photoperiod requirements (*$P < 0.05$, **$P < 0.01$). Sample sizes are shown in brackets below the graph. **b,** Estimated coefficient values (effective posterior means and 95% credible intervals) for the effect of spring photoperiodism on species' winter (β_1) and summer (β_2) temperature regime. Winter climate and summer temperature were included as binary variables of whether the species is native to (i) mild (Koeppen letter C) or cold winter climates (Koeppen letter D); and (ii) hot (Koeppen letter a) or colder summer climates (Koeppen letters b/c). Model controls for phylogenetic autocorrelation and species' maximum growth height (see Supplementary Methods). Values reflect standardized data and can be interpreted as relative effect sizes.

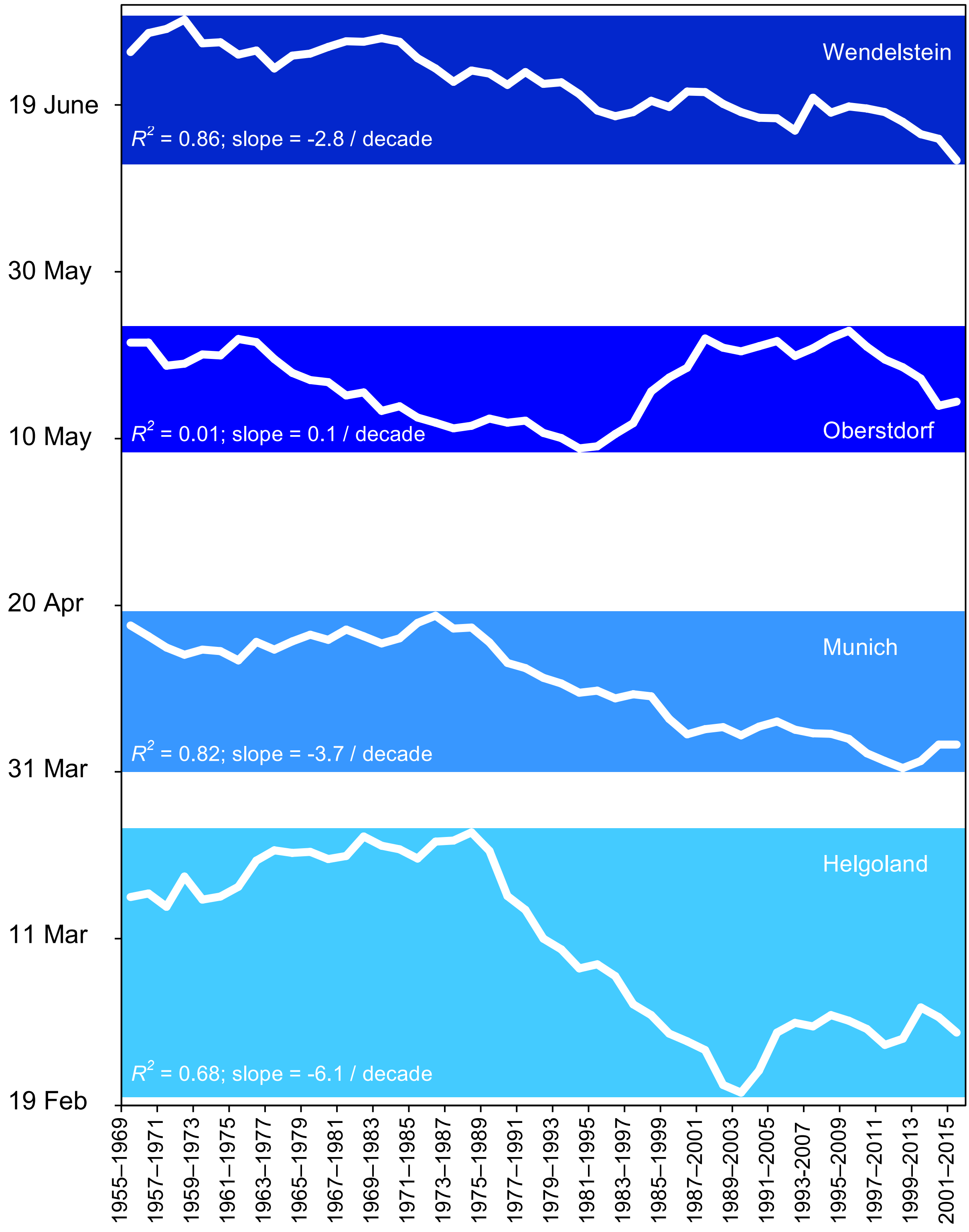

Figure S3 | Last frost events between 1955 and 2015 at four German weather stations with a 15-year moving window. Last frost events were defined as the latest day in spring with a minimum temperature below 0°C. Data for Helgoland (40 m a.s.l.; 54°10'N, 07°53'E), Munich (501 m a.s.l.; 48°08'N, 11°31'E), Oberstdorf (806 m a.s.l.; 47°25'N, 10°17'E), and Wendelstein (1832 m a.s.l.; 47°42'N, 12°00'E).

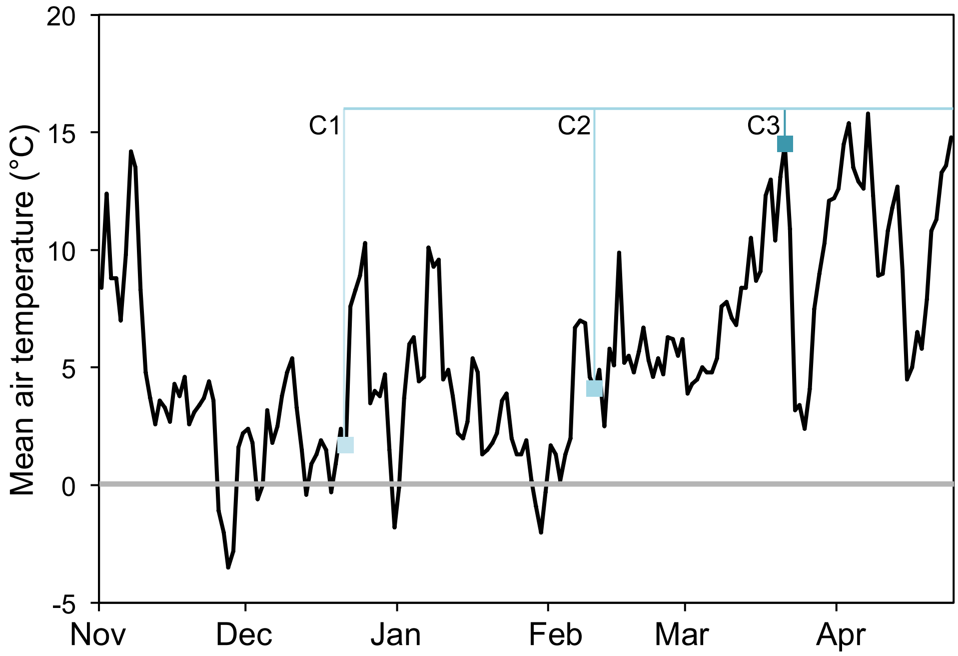

Figure S4 | Mean air temperature during the study period (Nov 2013 – Apr 2014) outside (black line) and in climate chambers (blue lines). C1 – C3: Daily mean air temperature in the climate chambers for different chilling treatments. C1: low chilling = 38 chill days, C2: intermediate chilling = 72 chill days, C3: high chilling = 88 chill days. Chill days were calculated as number of days with a mean air temperature <5°C from 1 November until start of the respective climate chamber treatment (C1, C2, C3).

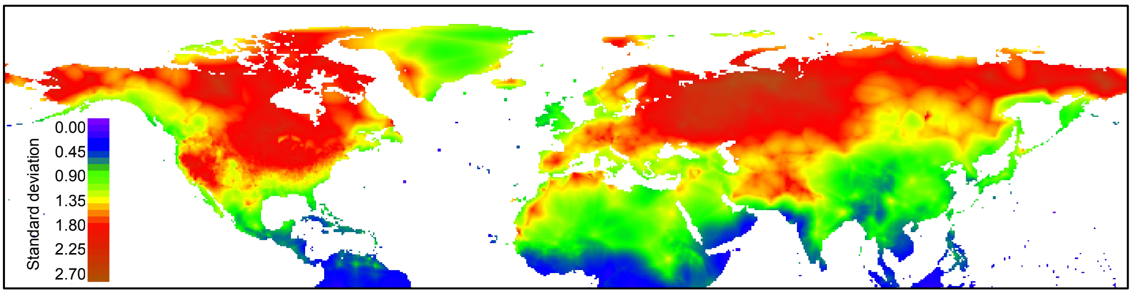

Figure S5 | Inter-annual spring temperature variability (T variability). T variability was calculated as the standard deviation of mean spring temperatures (March, April, and May) from 1901 to 2013. Data on monthly average temperatures during this period were available from the CRU database (5-arc minute spatial resolution data)[35].

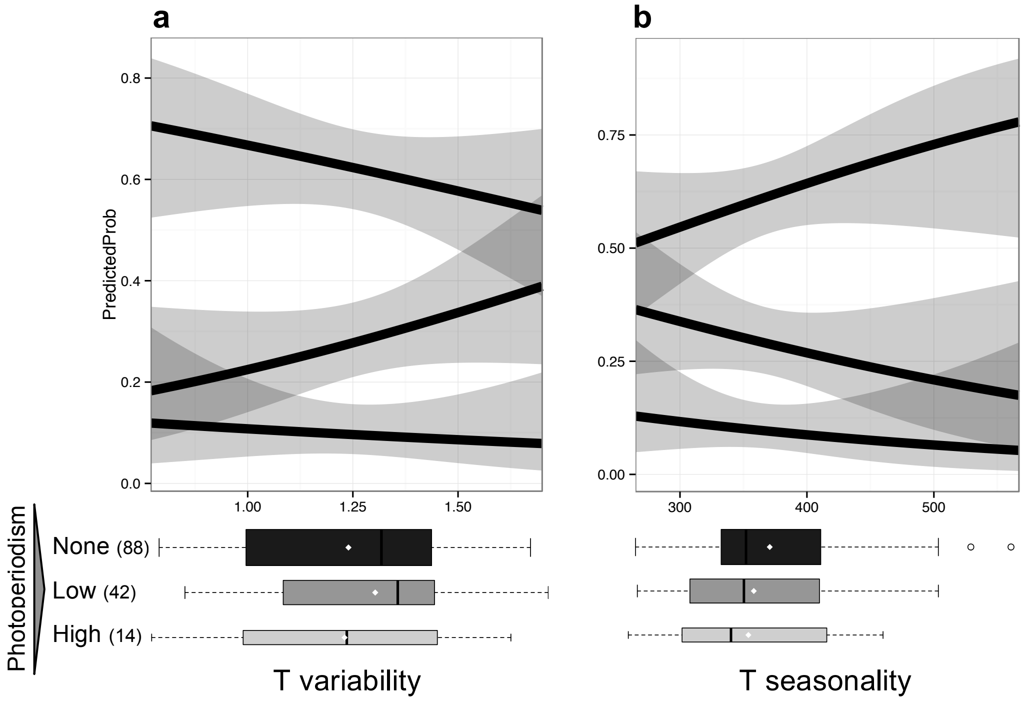

Figure S6 | Relationships between species' spring photoperiodism and the between-year spring temperature variability (a) and temperature seasonality (b) in their native ranges. **a**, Probability of species-specific photoperiod sensitivity as a function of median spring T variability in a species' native range (0.5 quantile; $P = 0.43$; univariate GLM). **b**, Probability of species-specific photoperiod sensitivity as a function of maximum T seasonality in a species' native range (0.95 quantile; $P = 0.67$; univariate GLM). Envelopes around each line show 95% confidence intervals. Boxplots for species' median T variability and maximum T seasonality when they were grouped according to photoperiod requirements are shown below the graph. Photoperiod requirements: None = No sensitivity; Low = Sensitivity to day length during early dormancy; High = Sensitivity to day length also in late dormancy (see Supplementary Fig. 1).

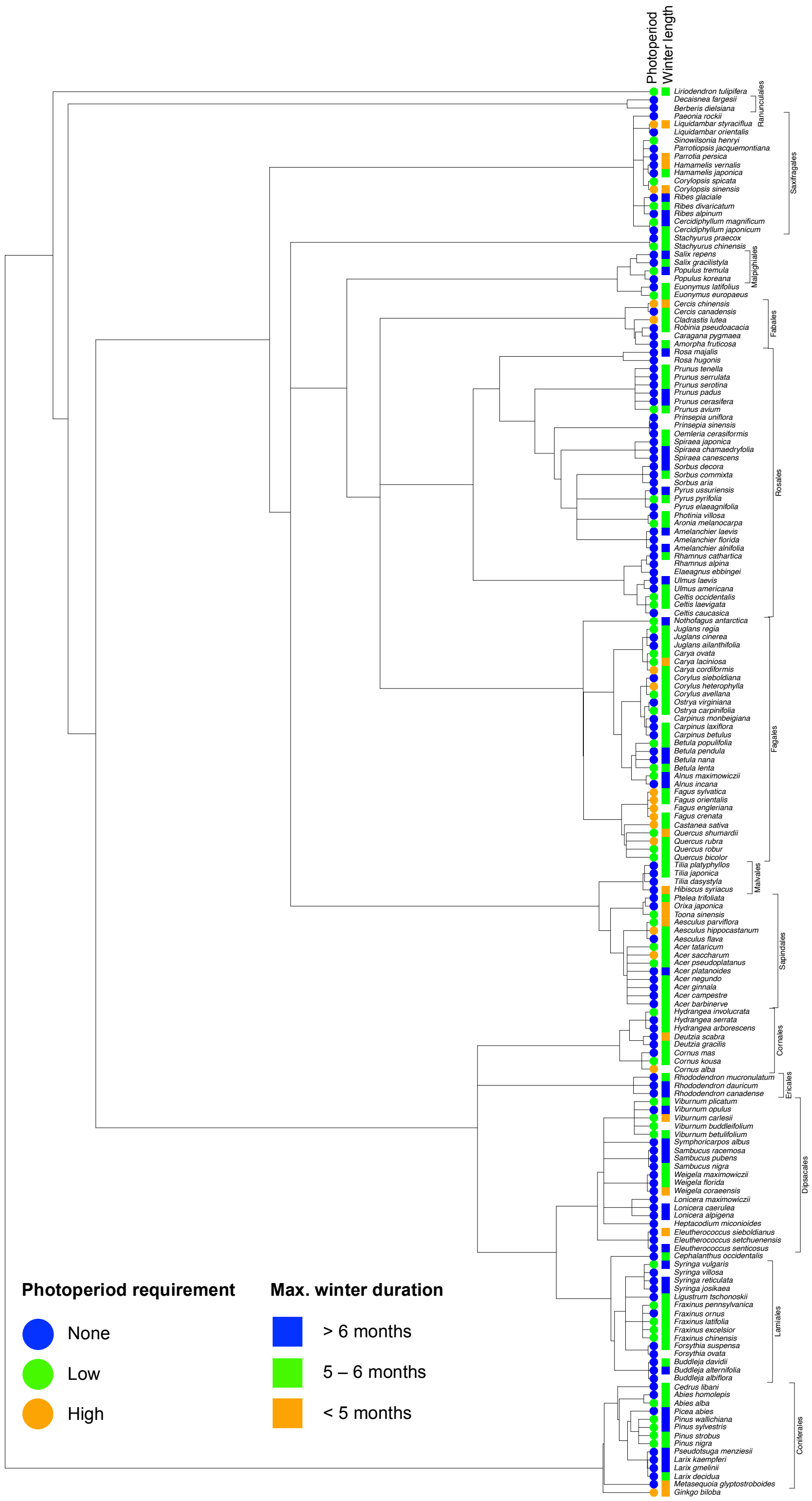

Figure S7 | PHYLOMATIC tree modified from Panchen *et al.*[42] containing the 173 woody species for which photoperiod requirements were studied. Species' photoperiod requirements and their maximum winter duration (0.95 quantile for the number of months with an average temperature below 5°C) are indicated by colored circles and squares, respectively.

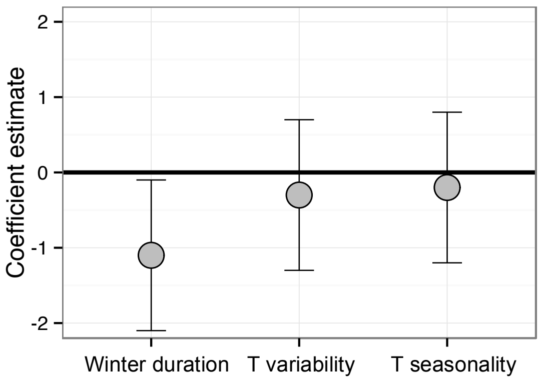

Figure S8 | Effect of species' climate parameters on variation in spring photoperiodism. Coefficient values (effective posterior means and 95% credible intervals) for relationships between species' photoperiodism and their winter duration (0.95 quantile), inter-annual spring temperature variability (T variability; 0.5 quantile), and temperature seasonality (T seasonality; 0.95 quantile). Note that in this model, photoperiod is treated as dependent variable (ordinal logistic regression). Models account for phylogenetic structure in the data and species' maximum growth height (see Supplementary Methods). Values reflect standardized data and can be interpreted as relative effect sizes. Sample sizes: N = 88 species (None), 42 (Low), 14 (High photoperiodism).

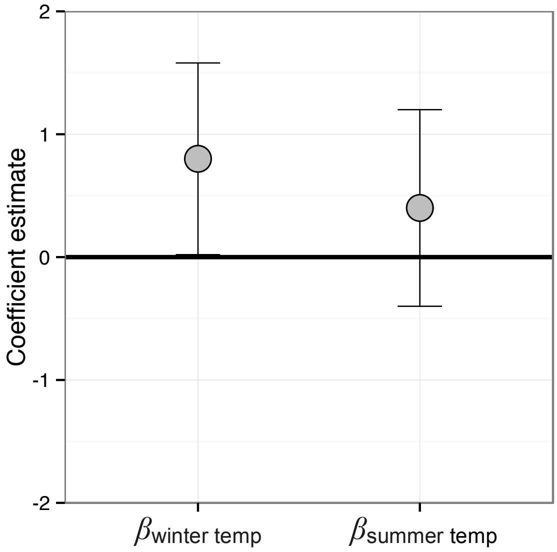

Figure S9 | The effect of winter and summer temperature regime on species-level variation in photoperiodism for 173 species using the Koeppen-Geiger climate classification. Coefficient values (effective posterior means and 95% credible intervals) for relationships between winter and summer climate and species' photoperiodism. Winter climate was included as a binary variable capturing whether a species is native to mild (Koeppen letter C) or cold winter climates (Koeppen letter D). Summer climate was included as a binary variable capturing whether a species is native to hot (Koeppen letter a) or colder summer climates (Koeppen letters b/c). The dependent variable (species' photoperiodism) was included as ordinal variable (no, low, high photoperiod requirements). To control for phylogenetic autocorrelation and a possible effect of species' growth habit, the model includes random genus and family effects and a fixed effect of species' maximum growth height (see Supplementary Methods). Values reflect standardized data and can be interpreted as relative effect sizes.

Table S1 | Photoperiod requirements, standard deviations in leaf-out dates / thermal requirements, maximum winter duration, predominant climate, and maximum growth height of 173 temperate woody species. The importance of photoperiod in regulating leaf-out (*Photo*) was inferred from twig cutting experiments conducted in this study and a previous study[12]. Species-specific standard deviations in leaf-out dates (*SD DOY*) or thermal requirements (*SD GDD*; growing degree days >0° from 1 Jan until leaf-out) were calculated on the basis of leaf-out dates available from the Munich Botanical Garden from 2012 to 2015. *Climate* refers to the predominant Koeppen-Geiger climate type in a species' native range. Maximum winter duration (*WD*) refers to species' 0.95 quantile for the number of months with an average temperature below 5°C in their native ranges. *Height* refers to the mature (maximum) recorded height of a species.

Genus	Species	Photo	SD DOY	SD GDD	Climate	WD	Height
Abies	*alba*	Low	5.56	42.35	Dfb	6	40
Abies	*homolepis*	None	-	-	Cfa	6	25
Acer	*barbinerve*	None	13.49	11.29	Dwb	5	8
Acer	*campestre*	None	10.61	21.07	Cfb	5	20
Acer	*ginnala*	None	13.96	24.22	Dfa	6	15
Acer	*negundo*	None	11.46	14.15	Dfa	5	15
Acer	*platanoides*	None	11.41	38.97	Dfb	7	30
Acer	*pseudoplatanus*	Low	-	-	Dfb	6	30
Acer	*saccharum*	High	10.34	9.17	Dfa	6	40
Acer	*tataricum*	Low	-	-	Dfa	6	15
Aesculus	*flava*	None	8.83	19.91	Cfa	5	30
Aesculus	*hippocastanum*	High	10.37	33.61	Csa	6	30
Aesculus	*parviflora*	Low	17.46	39.03	Cfa	4	4
Alnus	*incana*	None	9.6	15.64	Dfb	8	20
Alnus	*maximowiczii*	Low	9.27	42.17	Dfa	8	9
Amelanchier	*alnifolia*	None	10.18	20.57	Dfb	8	4
Amelanchier	*florida*	None	9.11	14.41	Dfb	-	4
Amelanchier	*laevis*	None	9.54	10.29	Dfb	7	8
Amorpha	*fruticosa*	None	5.1	21.67	Cfa	5	3
Aronia	*melanocarpa*	Low	12.01	22.49	Dfb	6	3
Berberis	*dielsiana*	None	14.72	10.89	Dwa	-	2
Betula	*lenta*	Low	11.73	44.74	Dfa	5	25
Betula	*nana*	None	11	11.24	Dfc	9	1
Betula	*pendula*	None	8.66	16.48	Dfb	7	30

Table S1 continued.

Genus	Species	Photo	SD DOY	SD GDD	Climate	WD	Height
Betula	*populifolia*	Low	9.18	15.06	Dfb	6	9
Buddleja	*albiflora*	None	13.03	31.09	BWk	-	4
Buddleja	*alternifolia*	None	13.15	10.98	BWk	8	5
Buddleja	*davidii*	None	-	-	Cwb	5	5
Caragana	*pygmaea*	None	14.08	25.66	Dwb	-	0.5
Carpinus	*betulus*	None	12.01	15.05	Dfb	5	25
Carpinus	*laxiflora*	None	12.12	22.2	Cfa	5	30
Carpinus	*monbeigiana*	None	12.07	22.94	Cwb	-	16
Carya	*cordiformis*	High	8.38	45.57	Cfa	5	35
Carya	*laciniosa*	Low	5.32	52.92	Dfa	4	30
Carya	*ovata*	Low	4.57	49.08	Dfa	5	27
Castanea	*sativa*	High	9.91	17.06	Cfb	5	30
Cedrus	*libani*	None	13.77	56.34	Csa	5	40
Celtis	*caucasica*	None	-	-	Csa	-	15
Celtis	*laevigata*	Low	5.68	21.43	Cfa	5	24
Celtis	*occidentalis*	Low	10.39	30.81	Dfa	5	24
Cephalanthus	*occidentalis*	None	4.19	73.28	Cfa	5	6
Cercidiphyllum	*japonicum*	None	11.76	26.9	Cfa	6	45
Cercidiphyllum	*magnificum*	Low	9.61	10.96	Dfa	8	10
Cercis	*canadensis*	None	6.38	29.72	Cfa	5	9
Cercis	*chinensis*	High	7.72	27.42	Cwa	4	3.5
Cladrastis	*lutea*	High	10.41	24.9	Cfa	5	15
Cornus	*alba*	High	11.79	10.51	Dwa	-	3
Cornus	*kousa*	Low	9.54	11.38	Cfa	5	12
Cornus	*mas*	None	9.83	14.97	Cfb	5	5
Corylopsis	*sinensis*	High	9.98	9.97	Cfa	3	1.8
Corylopsis	*spicata*	Low	10.87	11.38	Cfa	-	2.4
Corylus	*avellana*	Low	10.74	19.2	Cfb	6	8
Corylus	*heterophylla*	High	10.28	29.62	Cfa	6	7
Corylus	*sieboldiana*	None	12.12	31.29	Cfa	6	5
Decaisnea	*fargesii*	None	13.57	27.98	Cfa	-	8
Deutzia	*gracilis*	None	13.99	20.6	Cfa	5	0.6
Deutzia	*scabra*	None	11.43	19.42	Cfa	4	4
Elaeagnus	*ebbingei*	None	11.32	18.87	-	-	3
Eleutherococcus	*senticosus*	None	13.38	15.76	Dwb	7	2
Eleutherococcus	*setchuenensis*	None	11.32	15.46	Dwb	-	4
Eleutherococcus	*sieboldianus*	None	11.00	22.99	Cfa	4	2

Table S1 continued.

Genus	Species	Photo	SD DOY	SD GDD	Climate	WD	Height
Euonymus	*europaeus*	Low	11.73	16.88	Cfb	5	6
Euonymus	*latifolius*	None	9.2	16.95	Dfb	6	3
Fagus	*crenata*	High	11.7	42.67	Dfa	6	35
Fagus	*engleriana*	High	10.8	32.4	Cwa	-	17
Fagus	*orientalis*	High	-	-	Cfa	6	45
Fagus	*sylvatica*	High	6.85	30.26	Cfb	6	40
Forsythia	*ovata*	None	13.2	3.62	Dwa	-	1.5
Forsythia	*suspensa*	None	12.14	11.13	Cfa	5	5
Fraxinus	*chinensis*	Low	11.62	44.04	Dwa	6	25
Fraxinus	*excelsior*	Low	6.78	60.31	Dfb	6	35
Fraxinus	*latifolia*	Low	5.51	43.32	Csb	5	25
Fraxinus	*ornus*	None	4.99	24.87	Cfa	5	25
Fraxinus	*pennsylvanica*	Low	3.87	52.37	Dfa	6	20
Ginkgo	*biloba*	High	10.23	43.61	Cfa	4	35
Hamamelis	*japonica*	None	12.12	22.54	Dfa	6	4
Hamamelis	*vernalis*	None	11.86	22.17	Dfa	4	4
Heptacodium	*miconioides*	None	12.69	14.23	Cfa	-	8
Hibiscus	*syriacus*	None	10.42	39.63	Cfa	3	4
Hydrangea	*arborescens*	None	10.34	15.49	Dfa	5	3
Hydrangea	*involucrata*	Low	11.24	11.01	Cfa	5	1
Hydrangea	*serrata*	None	13.96	14.52	Dfb	6	1.2
Juglans	*ailanthifolia*	None	13.07	70.66	Dfa	6	20
Juglans	*cinerea*	None	-	-	Dfa	6	24
Juglans	*regia*	Low	8.74	19.63	Cfb	5	25
Larix	*decidua*	None	12.39	6.61	Dfb	6	45
Larix	*gmelinii*	None	12.92	13.89	Dwb	8	30
Larix	*kaempferi*	None	12.01	12.6	Dfa	7	40
Ligustrum	*tschonoskii*	None	12.26	19.3	Cfa	6	3
Liquidambar	*orientalis*	None	9.11	16.37	Csa		40
Liquidambar	*styraciflua*	High	8.42	18.87	Cfa	3	35
Liriodendron	*tulipifera*	Low	13.67	20.31	Cfa	5	40
Lonicera	*alpigena*	None	-	-	Dfc	7	2
Lonicera	*caerulea*	None	15.44	20.49	Dfc	8	1
Lonicera	*maximowiczii*	None	14.45	24.21	Dwb	-	4
Metasequoia	*glyptostroboides*	None	12.28	23.49	Cwa	3	45
Nothofagus	*antarctica*	Low	14.24	26.78	Cfb	7	25
Oemleria	*cerasiformis*	None	15.5	42.43	Csb	5	5

Table S1 continued.

Genus	Species	Photo	SD DOY	SD GDD	Climate	WD	Height
Orixa	*japonica*	None	13.4	5.72	Cwa	4	3
Ostrya	*carpinifolia*	Low	9.31	14.49	Cfb	6	20
Ostrya	*virginiana*	None	10.54	14.17	Dfa	6	18
Paeonia	*rockii*	None	13.77	18.67	Cwa	-	3
Parrotia	*persica*	None	12.12	18.77	Csa	3	15
Parrotiopsis	*jacquemontiana*	None	9.56	12.52	Dwa	-	6
Photinia	*villosa*	None	9.95	5.89	Cwa	5	15
Picea	*abies*	None	7.77	27.56	Dfb	8	55
Pinus	*nigra*	Low	-	-	Cfa	5	40
Pinus	*strobus*	Low	-	-	Dfb	6	50
Pinus	*sylvestris*	Low	-	-	Dfb	8	30
Pinus	*wallichiana*	Low	-	-	Dsb	7	40
Populus	*koreana*	None	14.45	10.64	Dfa	-	15
Populus	*tremula*	Low	-	-	Dfb	8	20
Prinsepia	*sinensis*	None	24.76	8.08	Dwb	-	2
Prinsepia	*uniflora*	None	11.62	21.36	Dwa	-	2
Prunus	*avium*	Low	-	-	Cfb	6	25
Prunus	*cerasifera*	None	13.5	11.87	Dfa	7	15
Prunus	*padus*	None	12.29	12.27	Dfb	8	15
Prunus	*serotina*	None	12.44	9.03	Cfa	6	30
Prunus	*serrulata*	None	11.69	16.56	Cfa	5	12
Prunus	*tenella*	None	13.52	26.2	Dfb	6	1.5
Pseudotsuga	*menziesii*	None	-	-	Csb	8	70
Ptelea	*trifoliata*	None	-	-	Cfa	5	8
Pyrus	*elaeagnifolia*	None	12.71	32.72	Csa	-	6
Pyrus	*pyrifolia*	Low	11.81	11.17	Cwa	5	15
Pyrus	*ussuriensis*	None	16.38	16.43	Dwa	7	15
Quercus	*bicolor*	Low	8.66	46.62	Dfa	5	25
Quercus	*robur*	Low	9.32	27.39	Cfb	6	40
Quercus	*rubra*	High	11.73	49.14	Dfa	6	35
Quercus	*shumardii*	Low	10.23	33.49	Cfa	3	35
Rhamnus	*alpina*	None	7.33	32.11	Dfb	-	4
Rhamnus	*cathartica*	None	7.77	25.99	Cfb	6	6
Rhododendron	*canadense*	None	9.81	11.59	Dfb	7	1.2
Rhododendron	*dauricum*	None	12.87	17.44	Dwb	9	2
Rhododendron	*mucronulatum*	None	24.79	51.45	Dwb	6	2
Ribes	*alpinum*	None	12.5	7.93	Dfb	7	1.5

Table S1 continued.

Genus	Species	Photo	SD DOY	SD GDD	Climate	WD	Height
Ribes	*divaricatum*	Low	7.8	17.96	Dsb	6	3
Ribes	*glaciale*	None	5.51	11.3	Cwb	8	3
Robinia	*pseudoacacia*	None	6.65	29.42	Cfa	5	25
Rosa	*hugonis*	None	12.5	20.19	-	-	2
Rosa	*majalis*	None	13.5	10.5	Dfb	8	2
Salix	*gracilistyla*	None	13.52	8.14	Cfa	5	6
Salix	*repens*	None	8.81	17.79	Dfb	7	1
Sambucus	*nigra*	None	15.26	9.94	Dfb	6	6
Sambucus	*pubens*	None	13.33	11.98	Dfb	8	6
Sambucus	*racemosa*	None	13.38	3.84	Dfb	7	3
Sinowilsonia	*henryi*	Low	8.04	17.89	Cwa	-	8
Sorbus	*aria*	None	-	-	Cfb	-	10
Sorbus	*commixta*	None	12.61	10.69	Dfb	6	10
Sorbus	*decora*	None	8.26	21.84	Dfb	8	10
Spiraea	*canescens*	None	13.5	11.87	Dwb	7	4
Spiraea	*chamaedryfolia*	None	13.53	19.07	Dfa	7	1.5
Spiraea	*japonica*	None	13.15	16.97	Cwa	6	1.8
Stachyurus	*chinensis*	Low	11.03	46.21	Cfb	5	4
Stachyurus	*praecox*	None	15.2	34.01	Cfa	5	1.5
Symphoricarpos	*albus*	None	-	-	Csb	7	2
Syringa	*josikaea*	None	13.64	5.44	Dfb	7	4
Syringa	*reticulata*	None	11.9	13.26	Dwb	7	6
Syringa	*villosa*	None	14.01	14.08	Dwa	-	4
Syringa	*vulgaris*	Low	12.48	4.83	Dfb	7	7
Tilia	*dasystyla*	None	9.95	28.13	Dfa	-	30
Tilia	*japonica*	None	9.91	11.92	Cfa	6	20
Tilia	*platyphyllos*	None	9.43	16.91	Cfb	6	30
Toona	*sinensis*	Low	12.28	47.31	Cwa	2	25
Ulmus	*americana*	None	10.44	17.14	Dfa	6	30
Ulmus	*laevis*	None	8.96	37.07	Dfb	7	30
Viburnum	*betulifolium*	Low	-	-	Cfa	6	3
Viburnum	*buddleifolium*	Low	14.18	22.55	Cfa	-	5
Viburnum	*carlesii*	Low	13.15	13.53	Cfa	4	2
Viburnum	*opulus*	None	10.75	20.61	Dfb	7	5
Viburnum	*plicatum*	Low	11.81	15.87	Cfa	5	3
Weigela	*coraeensis*	None	14.55	26.27	Dfa	4	5
Weigela	*florida*	None	10.05	14.75	Dwa	6	2.5
Weigela	*maximowiczii*	None	13.45	11.55	Dfa	6	1.5