Supplementary Material: Budburst timing within a functional trait framework

Figures & Tables

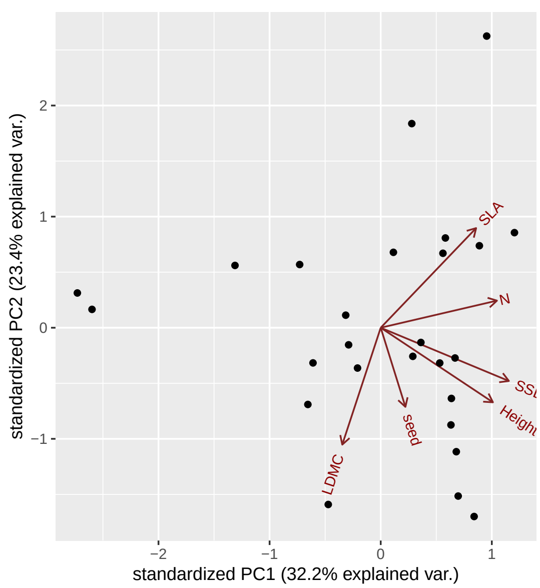

Figure S1: A projection of tree traits across the first and second principle component axis. Arrows represent the direction of vectors for six functional traits. Points represent the 26 species for which complete trait data was available

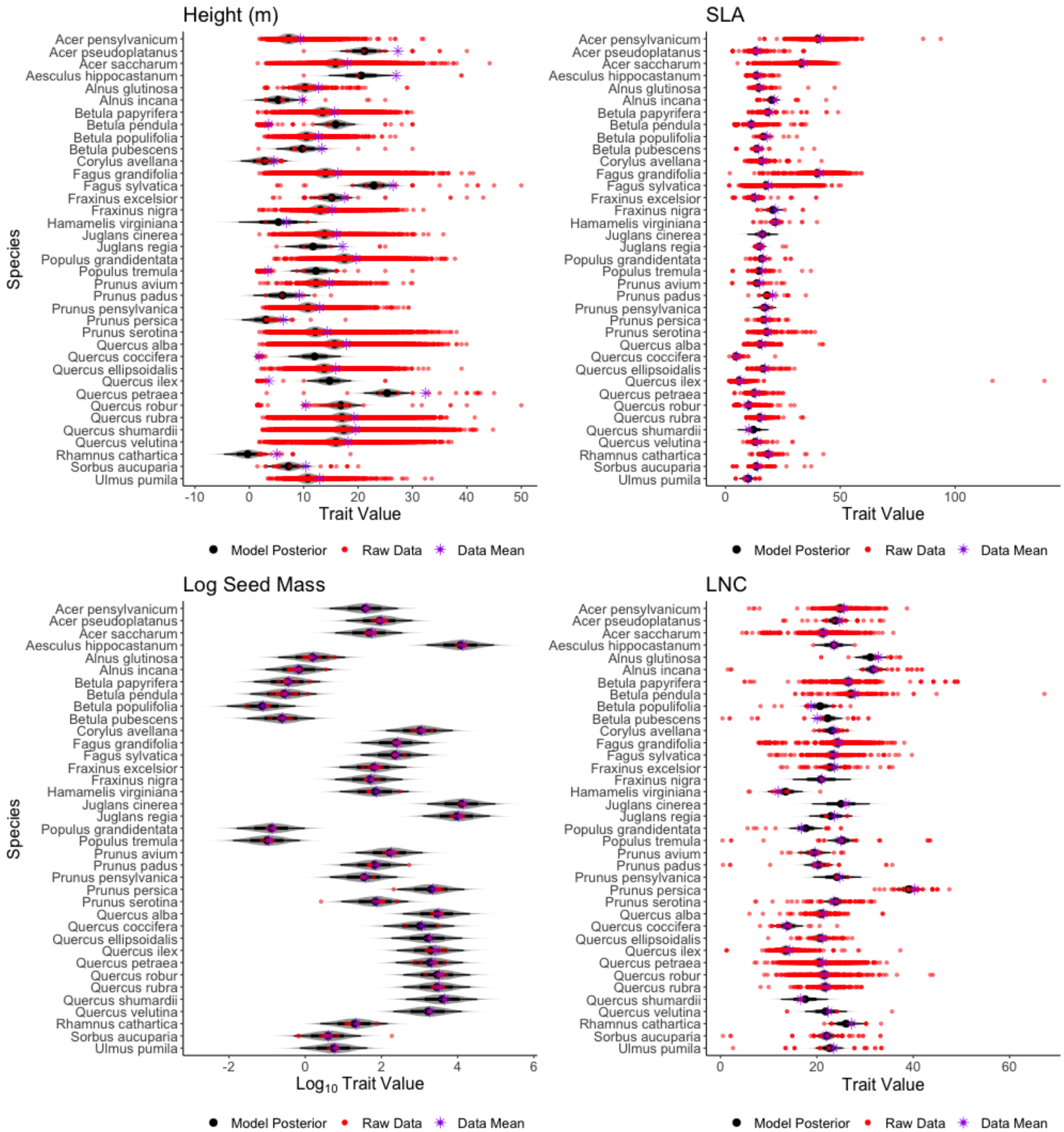

Figure S2: Comparisons of estimated model fits and raw data from joint models of trait effects on budburst phenological cues for 37 species of woody deciduous plants. Four functional traits – a. height, b. SLA, c. seed mass, and d. LNC – were modeled individually, with the calculated trait value being used to jointly model species responses to standardized chilling, forcing, and photoperiod cues. Model posteriors are shown in black, with the thicker line depicting the 66% interval and the thinner black line the 97% interval. Overall species level model posterior distributions were well aligned with the raw data, shown in red, and the species level means from the raw data, denoted as a purple stars.

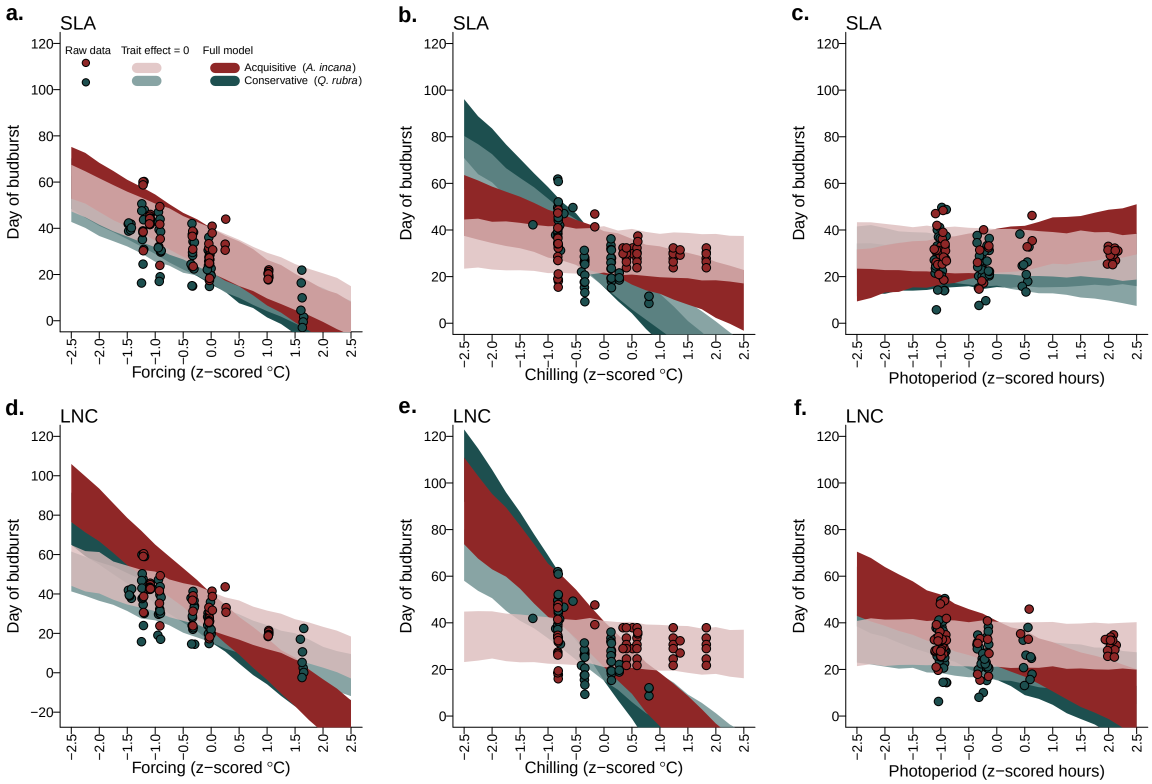

Figure S3: We expected species with traits associated with acquisitive (e.g, low specific leaf area, SLA, and leaf nitrogen content, LNC) versus conservative (e.g., high SLA and LNC) growth strategies would have different budburst responses to phenological cues. Our joint model allows traits of species to influence their responses to cues. We show an example here with an acquisitive species, *Alnus incana* shown in red, and a conservative species, *Quercus rubra* shown in blue, for SLA (**a-c**) and LNC (**d-f**). Our joint model estimated later budburst due to trait effects for both SLA and LNC in response to forcing (**a, d,**) and chilling (**b, e**) and for LNC in response to photoperiod (**f**). Only in response to photoperiod did we estimate the effect of SLA to lead to slightly earlier budburst with longer photoperiods (**c**). The coloured bands represent the 50% uncertainty intervals of the model estimates and points individual trait measurements.

Table S1: Bibliographic information for trait data sources from both BIEN and Try trait databases. Datasets without references or incomplete references are denoted below as 'unreferenced'.

Database	Reference	Trait name	Unit	No. observations	No. Species
bien	Mchugh et al. (2015)	Height	m	26	8
bien	Marx et al. (2016)	Height	m	2	2
bien	Price et al. (2014)	Height	m	27	19
bien	Unreferenced	Height	m	18	16
bien	Kleyer et al. (2008)	Height	m	90	19
bien	Unreferenced	Height	m	10	10
bien	Moles, Angela; unreferenced	Height	m	21	14
bien	Reams, Greg; unreferenced	Height	m	47036	19
bien	Grime, Hodgson, & Hunt; unreferenced	Height	m	5	5
bien	Unreferenced	Height	m	8	5
bien	Pérez-de Lis et al. (2017)	Height	m	18	1
bien	Robinson et al. (2015)	Height	m	120	1
bien	Anderson-teixeira et al. (2015)	Height	m	20	1
try	Bond-Lamberty et al. (2002)	Height	m	2	1
try	Unpublished	Height	m	275	3
try	Wright et al. (2004)	Height	m	28	19
try	Prentice et al. (2011)	Height	m	2	2
try	Schweingruber and Landolt (2010)	Height	m	21	21
try	Unpublished	Height	m	35	2
try	Moles et al. (2004)	Height	m	5	5
try	Cavender-Bares et al. (2006)	Height	m	1	1
try	Diaz et al. (2004)	Height	m	11	10
try	Craine et al. (2009)	LNC	mg/g	287	12
try	Wilson et al. (2000)	LNC	mg/g	44	2
try	Wenxuan et al. (2012)	LNC	mg/g	7	4
try	Yahan et al. (2013)	LNC	mg/g	7	3
try	Wright et al. (2004)	LNC	mg/g	65	32
try	Prentice et al. (2011)	LNC	mg/g	3	2
try	Vergutz et al. (2012)	LNC	mg/g	120	20
try	Atkin et al. (2015)	LNC	mg/g	24	8
try	Marie et al. (2015)	LNC	mg/g	72	22
try	Cornelissen et al. (2003)	LNC	mg/g	2	1
try	Unpublished	LNC	mg/g	3216	37
try	Wang et al. (2017)	LNC	mg/g	6	2
bien	Marx et al. (2016)	Seed mass	mg	3	3
bien	Unreferenced	Seed mass	mg	4	2
bien	Liu et al. (2018)	Seed mass	mg	250	37
bien	Ameztegui et al. (2017)	Seed mass	mg	12	12
bien	Paine et al. (2015)	Seed mass	mg	12	7
try	Wilson et al. (2000)	SLA	mm2 mg-1	44	2
try	Unpublished	SLA	mm2 mg-1	204	3
try	Wright et al. (2004)	SLA	mm2 mg-1	93	33
try	Prentice et al. (2011)	SLA	mm2 mg-1	2	2
try	Kleyer et al. (2008)	SLA	mm2 mg-1	102	18
try	Unpublished	SLA	mm2 mg-1	83	2
try	Atkin et al. (2015)	SLA	mm2 mg-1	40	11
try	Marie et al. (2015)	SLA	mm2 mg-1	86	23
try	Cornelissen et al. (2003)	SLA	mm2 mg-1	615	14
try	Unpublished	SLA	mm2 mg-1	6307	37
try	Wang et al. (2017)	SLA	mm2 mg-1	6	2
try	Shipley and Vu (2002)	SLA	mm2 mg-1	20	2
try	Cavender-Bares et al. (2006)	SLA	mm2 mg-1	42	2
try	Unpublished	SLA	mm2 mg-1	1	1
try	Diaz et al. (2004)	SLA	mm2 mg-1	11	10

Table S2: Summary of model estimates using measurements of tree height for our 37 focal species ($n = 42781$)

	mean	sd	2.5%	50%	97.5%	Rhat
$\mu_{grand.trait}$	12.71	1.96	8.73	12.75	16.46	1.00
$\mu_{k,g}$	32.07	2.63	26.97	32.05	37.30	1.00
μ_{force}	-10.74	2.86	-16.63	-10.66	-5.38	1.01
μ_{chill}	-4.08	4.13	-12.46	-4.02	3.99	1.01
μ_{photo}	1.11	2.18	-3.37	1.14	5.27	1.01
$\beta_{trait.force}$	0.16	0.19	-0.21	0.16	0.55	1.01
$\beta_{trait.chill}$	-0.54	0.28	-1.07	-0.54	0.02	1.01
$\beta_{trait.photo}$	-0.25	0.15	-0.54	-0.25	0.08	1.00
$\sigma_{species}$	5.91	0.76	4.63	5.84	7.57	1.00
σ_{study}	7.53	1.22	5.52	7.40	10.28	1.00
σ_{trait}	5.39	0.02	5.36	5.39	5.43	1.00
σ_{pheno}	15.11	2.05	11.20	15.06	19.36	1.00
σ_{force}	4.96	1.16	3.01	4.85	7.55	1.00
σ_{chill}	8.53	2.10	5.21	8.26	13.38	1.00
σ_{photo}	3.25	0.86	1.79	3.17	5.15	1.00
σ_d	14.18	0.26	13.69	14.18	14.70	1.00

Table S3: Summary of model estimates using measurements of seed mass data for our 37 focal species ($n = 281$).

	mean	sd	2.5%	50%	97.5%	Rhat
$\mu_{grand.trait}$	1.87	0.50	0.89	1.88	2.84	1.00
$\mu_{k,g}$	31.35	2.64	26.32	31.27	36.76	1.00
μ_{force}	-8.17	1.60	-11.35	-8.16	-5.07	1.00
μ_{chill}	-9.41	2.82	-15.21	-9.43	-3.92	1.00
μ_{photo}	-1.26	1.25	-3.72	-1.27	1.19	1.00
$\beta_{trait.force}$	-0.30	0.69	-1.61	-0.31	1.06	1.00
$\beta_{trait.chill}$	-1.09	1.09	-3.28	-1.08	1.01	1.00
$\beta_{trait.photo}$	-0.56	0.58	-1.68	-0.56	0.62	1.00
$\sigma_{species}$	1.62	0.19	1.30	1.61	2.05	1.00
σ_{study}	0.97	0.10	0.77	0.97	1.17	1.00
σ_{trait}	0.25	0.01	0.23	0.25	0.27	1.00
σ_{pheno}	14.84	2.25	10.58	14.79	19.42	1.00
σ_{force}	4.92	0.98	3.22	4.85	7.03	1.00
σ_{chill}	10.67	2.57	6.55	10.33	16.65	1.00
σ_{photo}	3.58	0.86	2.13	3.49	5.52	1.00
σ_d	14.12	0.25	13.66	14.12	14.61	1.00

Table S4: Summary of model estimates using measurements of specific leaf area for our 37 focal species ($n = 7656$).

	mean	sd	2.5%	50%	97.5%	Rhat
$\mu_{grand.trait}$	16.85	1.47	14.03	16.85	19.71	1.01
$\mu_{k,g}$	31.33	2.55	26.45	31.30	36.39	1.00
μ_{force}	-11.40	2.71	-17.29	-11.33	-6.42	1.01
μ_{chill}	-16.66	4.70	-26.35	-16.61	-7.84	1.00
μ_{photo}	1.85	2.47	-3.13	1.98	6.47	1.00
$\beta_{trait.force}$	0.17	0.15	-0.11	0.17	0.47	1.01
$\beta_{trait.chill}$	0.34	0.25	-0.13	0.34	0.83	1.00
$\beta_{trait.photo}$	-0.23	0.14	-0.50	-0.24	0.05	1.00
$\sigma_{species}$	7.78	0.93	6.21	7.70	9.77	1.00
σ_{study}	3.28	0.97	1.87	3.13	5.57	1.00
σ_{trait}	6.17	0.05	6.07	6.16	6.27	1.00
σ_{pheno}	13.92	2.11	10.10	13.79	18.34	1.00
σ_{force}	4.97	1.12	3.07	4.87	7.49	1.00
σ_{chill}	10.57	2.30	6.79	10.33	15.56	1.00
σ_{photo}	3.48	0.81	2.14	3.40	5.36	1.00
σ_{d}	14.17	0.26	13.66	14.17	14.68	1.00

Table S5: Summary of model estimates using measurements of leaf nitrogen content for our 37 focal species ($n = 3853$.)

	mean	sd	2.5%	50%	97.5%	Rhat
$\mu_{grand.trait}$	22.61	1.37	19.91	22.60	25.32	1.01
$\mu_{k,g}$	31.14	2.52	26.33	31.09	36.29	1.00
μ_{force}	-19.33	5.37	-30.02	-19.45	-8.62	1.02
μ_{chill}	-27.10	7.04	-40.56	-27.27	-12.84	1.01
μ_{photo}	-9.40	4.67	-18.09	-9.41	-0.37	1.02
$\beta_{trait.force}$	0.47	0.23	0.01	0.47	0.93	1.02
$\beta_{trait.chill}$	0.72	0.30	0.12	0.72	1.29	1.01
$\beta_{trait.photo}$	0.31	0.19	-0.06	0.31	0.68	1.02
$\sigma_{species}$	5.12	0.61	4.09	5.06	6.48	1.00
σ_{study}	3.55	0.98	2.03	3.44	5.83	1.00
σ_{trait}	5.13	0.06	5.02	5.13	5.25	1.00
σ_{pheno}	14.05	1.97	10.30	13.97	18.23	1.00
σ_{force}	4.59	1.09	2.80	4.47	7.05	1.00
σ_{chill}	8.92	1.97	5.74	8.71	13.44	1.00
σ_{photo}	3.59	0.81	2.25	3.52	5.41	1.00
σ_{d}	14.17	0.26	13.67	14.17	14.67	1.00

References

Ameztegui, A., A. Paquette, B. Shipley, M. Heym, C. Messier, and D. Gravel. 2017. Shade tolerance and the functional trait : demography relationship in temperate and boreal forests. Functional Ecology 31:821–830.

Anderson-teixeira, K. J., J. C. Mcgarvey, H. C. Muller-landau, J. Y. Park, E. B. Gonzalez-akre, V. Herrmann, A. C. Bennett, C. V. So, N. A. Bourg, J. R. Thompson, S. M. Mcmahon, and W. J. Mcshea. 2015. Size-related scaling of tree form and function in a mixed-age forest. Functional Ecology 29:1587–1602.

Atkin, O., K. Bloomfield, P. Reich, M. Tjoelker, G. Asner, D. Bonal, G. Bönisch, M. Bradford, L. Cernusak, E. Cosio, D. Creek, C. K.Y., T. Domingues, J. Dukes, J. Egerton, J. Evans, G. Farquhar, N. Fyllas, P. Gauthier, E. Gloor, T. Gimeno, K. Griffin, R. Guerrieri, M. Heskel, C. Huntingford, F. Ishida, J. Kattge, H. Lambers, M. Liddell, J. Lloyd, C. Lusk, R. Martin, A. Maksimov, T. Maximov, Y. Malhi, B. Medlyn, P. Meir, L. Mercado, N. Mirotchnick, D. Ng, Ü. Niinemets, O. O'Sullivan, O. Phillips, L. Poorter, P. Poot, I. Prentice, N. Salinas, L. Rowland, M. Ryan, S. Sitch, M. Slot, N. Smith, M. Turnbull, M. VanderWel, F. Valladares, E. Veneklaas, L. Weerasinghe, C. Wirth, I. Wright, K. Wythers, J. Xiang, S. Xiang, and J. Zaragoza-Castells. 2015. Global variability in leaf respiration in relation to climate, plant functional types and leaf traits. New Phytologist 206:614–636.

Bond-Lamberty, B., C. Wang, and S. T. Gower. 2002. Aboveground and belowground biomass and sapwood area allometric equations for six boreal tree species of northern Manitoba. Canadian Journal of Forest Research 32:1441–1450.

Cavender-Bares, J., A. Keen, and B. Miles. 2006. Phylogenetic structure of floridian plant communities depends on taxonomic and spatial scale. Ecology 87:109–122.

Cornelissen, J. H. C., B. Cerabolini, P. Castro-Diez, P. Villar-Salvador, G. Montserrat-Marti, J. P. Puyravaud, M. Maestro, M. J. A. Werger, and R. Aerts. 2003. Functional traits of woody plants: correspondence of species rankings between field adults and laboratory-grown seedlings? Journal of Vegetation Science 14:311–322.

Craine, J. M., A. J. Elmore, M. P. M. Aidar, M. Bustamante, T. E. Dawson, E. A. Hobbie, A. Kahmen, M. C. Mack, K. K. Mclauchlan, A. Michelsen, G. B. Nardoto, L. H. Pardo, J. Penuelas, P. B. Reich, E. A. G. Schuur, W. D. Stock, P. H. Templer, R. A. Virginia, J. M. Welker, and I. J. Wright. 2009. Global patterns of foliar nitrogen isotopes and their relationships with climate, mycorrhizal fungi, foliar nutrient concentrations, and nitrogen availability. New Phytologist 183:980–992.

Diaz, S., J. G. Hodgson, K. Thompson, M. Cabido, J. H. C. Cornellissen, A. Jalili, G. Montserrat-Marti, J. P. Grime, F. Zarrinkamar, Y. Asri, S. R. Band, S. Basconcelo, P. Castro-Diez, G. Funes, B. Hamzehee, M. Khoshnevi, N. Pérez-Harguindeguy, M. C. Pérez-Rontomé, F. A. Shirvany, F. Vendramini, S. Yazdani, R. Abbas-Azimi, A. Bogaard, S. Boustani, M. Charles, M. Dehghan, L. de Torres-Espuny, V. Falczuk, J. Guerrero-Campo, A. Hynd, G. Jones, E. Kowsary, F. Kazemi-Saeed, M. Maestro-Martinez, A. Romo-Diez, S. Shaw, B. Siavash, P. Villar-Salvador, and M. R. Zak. 2004. The plant traits that drive ecosystems : Evidence from three continents. Journal of Vegetation Science 15:295–304.

Kleyer, M., R. M. Bekker, I. C. Knevel, J. P. Bakker, K. Thompson, M. Sonnenschein, P. Poschlod, J. M. V. Groenendael, L. Klime, J. Klimesova, S. Klotz, G. M. Rusch, M. Hermy, D. Adriaens, G. Boedeltje, B. Bossuyt, A. Dannemann, P. Endels, L. Götzenberger, J. G. Hodgson, A.-k. Jackel, I. Kühn, D. Kunzmann, W. A. Ozinga, C. Römermann, M. Stadler, J. Schlegelmilch, H. J. Steendam, O. Tackenberg, B. Wilmann, J. H. C. Cornelissen, O. Eriksson, E. Garnier, and B. Peco. 2008. The LEDA Traitbase : a database of life-history traits of the Northwest European flora. Journal of Ecology 96:1266–1274.

Liu, K., S. Eastwood, R.J. a d Flynn, R. Turner, and W. Stuppy. 2018. Kew database.

Marie, V., I. J. Wright, I. C. Prentice, N. H. Batjes, R. Bhaskar, P. M. van Bodegom, W. K. Cornwell, D. Ellsworth, Ü. Niinemets, A. Ordonez, P. B. Reich, and L. S. Santiago. 2015. Global effects of soil and climate on leaf photosyncthetic traits and rates. Global Ecology and Biogeography 24:706–717.

Marx, H. E., D. E. Giblin, P. W. Dunwiddie, and D. C. Tank. 2016. Deconstructing Darwin' s Naturalization using community phylogenetics and functional traits. Diversity and Distributions 22:318–331.

Mchugh, N., J. L. Edmondson, K. J. Gaston, J. R. Leake, and O. S. O. Sullivan. 2015. Modelling short-rotation coppice and tree planting for urban carbon management – a citywide analysis. Journal of Applied Ecology 52:1237–1245.

Moles, A. T., D. S. Falster, M. R. Leishman, and M. Westoby. 2004. Small-seeded species produce more seeds per square metre of canopy per year, but not per individual per lifetime. Journal of Ecology 92:384–396.

Paine, C. E. T., L. Amissah, H. Auge, C. Baraloto, M. Baruffol, N. Bourland, H. Bruelheide, K. Dainou, R. C. de Gouvenain, J.-l. Doucet, S. Doust, P. V. A. Fine, C. Fortunel, J. Haase, K. D. Holl, H. Jactel, X. Li, K. Kitajima, J. Koricheva, C. Martínez-Garza, C. Messier, A. Paquette, C. Philipson, D. Piotto, L. Poorter, J. M. Posada, C. Potvin, K. Rainio, S. E. Russo, M. Ruiz-jaen, M. Scherer-lorenzen, C. O. Webb, S. J. Wright, R. A. Zahawi, and A. Hector. 2015. Globally , functional traits are weak predictors of juvenile tree growth , and we do not know why. Journal of Ecology 103:978–989.

Pérez-de Lis, G., J. M. Olano, V. Rozas, S. Rossi, R. A. Vázquez-Ruiz, and I. García-Gonzalez. 2017. Environmental conditions and vascular cambium regulate carbon allocation to xylem growth in deciduous oaks. Functional Ecology 31:592–603.

Prentice, I. C., T. Meng, H. Wang, S. P. Harrison, J. Ni, and G. Wang. 2011. Evidence of a universal scaling relationship for leaf CO 2 drawdown along an aridity gradient. New Phytologist 190:169–180.

Price, C. A., I. J. Wright, D. D. Ackerly, Ü. Niinemets, P. B. Reich, and E. J. Veneklaas. 2014. Are leaf functional traits 'invariant' with plant size and what is 'invariance' anyway? Functional Ecology 28:1330–1343.

Robinson, K. M., C. Hauzy, N. Loeuille, and B. R. Albrectsen. 2015. Relative impacts of environmental variation and evolutionary history on the nestedness and modularity of tree–herbivore networks. Ecology and Evolution 5:2898–2915.

Schweingruber, F., and W. Landolt. 2010. The xylem database.

Shipley, B., and T.-T. Vu. 2002. Dry matter content as a measure of dry matter concentration in plants and their parts. New Phytologist 153:359–364.

Vergutz, L., S. Manzoni, A. Porporato, R. Novais, and R. Jackson. 2012. A Global Database of Carbon and Nutrient Concentrations of Green and Senesced Leaves. Oak Ridge National Laboratory Distributed Active Archive Center Oak Ridge, Tennessee, U.S.A.

Wang, H., S. P. Harrison, I. C. Prentice, Y. Yang, F. Bai, H. Furstenau Togashi, M. Wang, S. Zhou, and J. Ni. 2017. The China Plant Trait Database. PANGAEA .

Wenxuan, H., C. Yahan, Z. Fang-Jie, L. Tang, J. Rongfeng, and Z. Fusuo. 2012. Floral, climatic and soil pH controls on leaf ash content in China's terrestrial plants. Global Ecology and Biogeography 21:376–382.

Wilson, K. B., D. D. Baldocchi, and P. J. Hanson. 2000. Spatial and seasonal variability of photosynthetic parameters and their relationship to leaf nitrogen in a deciduous forest. Tree Physiology 20:565–578.

Wright, I. J., M. Westoby, P. B. Reich, J. Oleksyn, D. D. Ackerly, Z. Baruch, F. Bongers, J. Cavender-Bares, T. Chapin, J. H. C. Cornellissen, M. Diemer, J. Flexas, J. Gulias, E. Garnier, M. L. Navas, C. Roumet, P. K. Groom, B. B. Lamont, K. Hikosaka, T. Lee, W. Lee, C. Lusk, J. J. Midgley, Ü. Niinemets, H. Osada, H. Poorter, P. Pool, E. J. Veneklaas, L. Prior, V. I. Pyankov, S. C. Thomas, M. G. Tjoelker, and R. Villar. 2004. The worldwide leaf economics spectrum. Nature 428:821–827.

Yahan, C., H. Wenxuan, T. Luying, T. Zhiyao, and F. Jingyun. 2013. Leaf nitrogen and phosphorus concentrations of woody plants differ in responses to climate, soil and plant growth form. Ecography 36:178–184.