

# Supplementary Material: Woody plant phenological responses are strongly associated with key functional traits

Deirdre Loughnan<sup>1</sup>, Faith A M Jones<sup>1,2</sup>, Geoffrey Legault<sup>1</sup>, Daniel Buonaiuto<sup>3,4,5</sup>,  
Catherine Chamberlain<sup>3,4,6</sup>, Ailene Ettinger<sup>7</sup>, Mira Garner<sup>1</sup>, Ignacio Morales-Castilla<sup>8,9</sup>,  
Darwin Sodhi<sup>1</sup>, and E M Wolkovich<sup>1,3,4</sup>

## Additional methods

We used a phylogenetic generalized least-squares regression model (PGLS) to test the relationship between day of budburst and each trait. This analysis allowed us to test for phylogenetic non-independence in the phenology-trait relationship (Freckleton et al., 2002). We obtained a rooted phylogenetic tree by pruning the tree developed by (Smith and Brown, 2018) and performed the PGLS analysis using the mean trait values and mean posterior estimates of the cue responses from our joint model. The PGLS was run using the "Caper" package in R (Orme, 2013).

## Figures & Tables

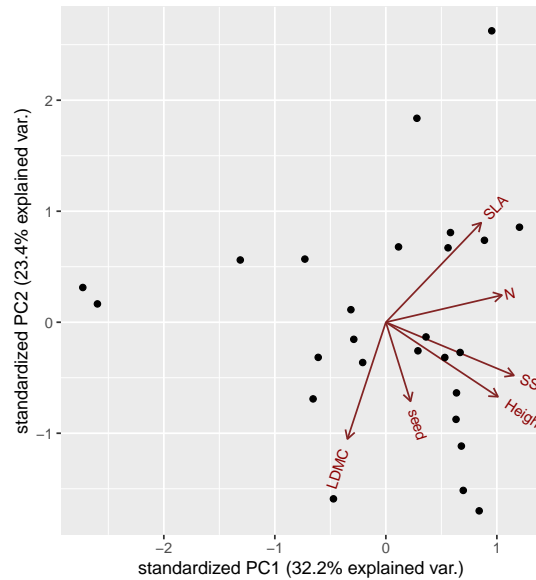


Figure S1: A projection of tree traits across the first and second principle component axis. Arrows represent the direction of vectors for six functional traits. Points represent the 26 species for which complete trait data was available

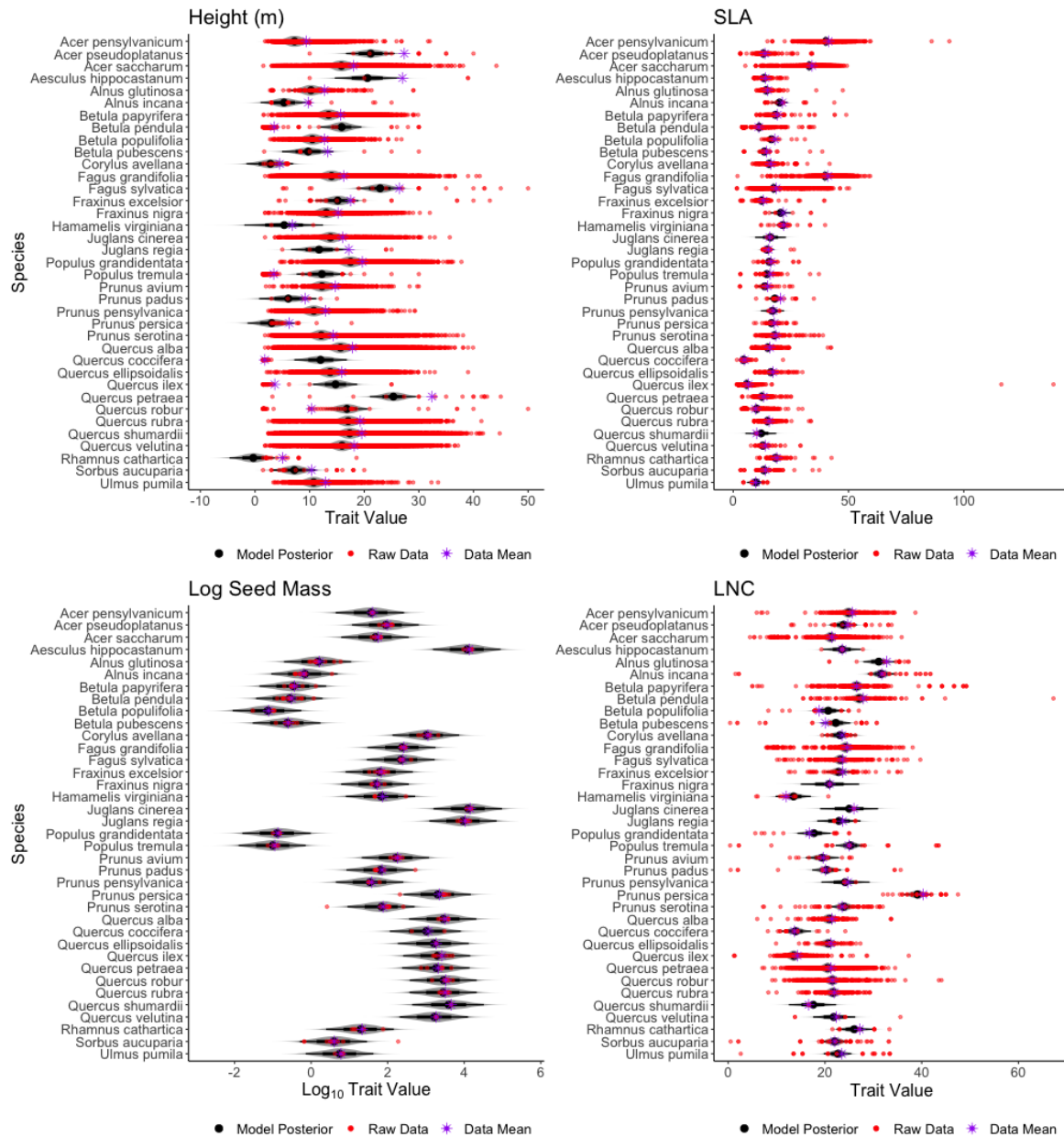


Figure S2: Comparisons of estimated model fits and raw data from joint models of trait effects on budburst phenological cues for 37 species of woody deciduous plants. Four functional traits – a. height, b. SLA, c. seed mass, and d. LNC – were modeled individually, with the calculated trait value being 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.

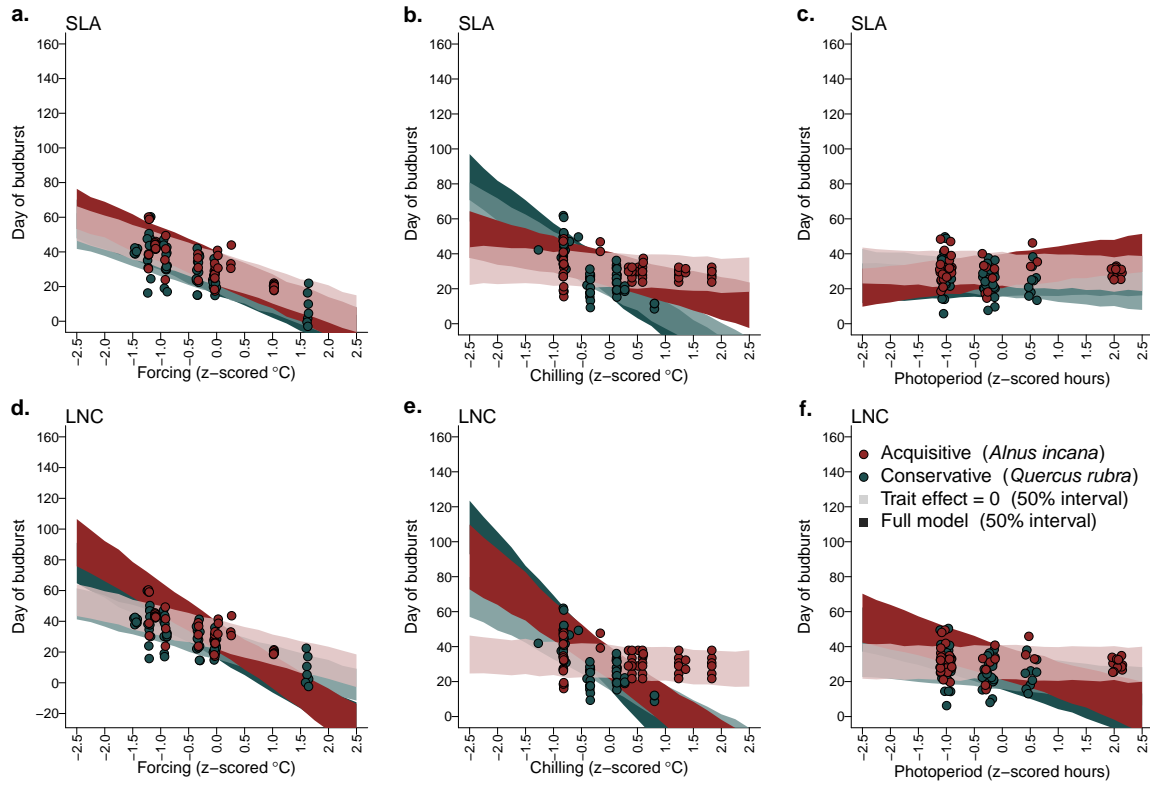


Figure S3: We expected species with traits associated with acquisitive (e.g, low specific leaf area, SLA, and leaf nitrogen content, LNC) versus conservative (e.g., high SLA and LNC) growth strategies would have different budburst responses to phenological cues. Our joint model allows traits of species 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.

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	Unpublished	Height	m	18	16
bien	Kleyer et al. (2008)	Height	m	90	19
bien	Unpublished	Height	m	10	10
bien	Moles, Angela; unpublished	Height	m	21	14
bien	Reams, Greg; unpublished	Height	m	47036	19
bien	Grime, Hodgson, & Hunt; unpublished	Height	m	5	5
bien	Unpublished	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	Unpublished	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	mm <sup>2</sup> mg <sup>-1</sup>	44	2
try	Unpublished	SLA	mm <sup>2</sup> mg <sup>-1</sup>	204	3
try	Wright et al. (2004)	SLA	mm <sup>2</sup> mg <sup>-1</sup>	93	33
try	Prentice et al. (2011)	SLA	mm <sup>2</sup> mg <sup>-1</sup>	2	2
try	Kleyer et al. (2008)	SLA	mm <sup>2</sup> mg <sup>-1</sup>	102	18
try	Unpublished	SLA	mm <sup>2</sup> mg <sup>-1</sup>	83	2
try	Atkin et al. (2015)	SLA	mm <sup>2</sup> mg <sup>-1</sup>	40	11
try	Marie et al. (2015)	SLA	mm <sup>2</sup> mg <sup>-1</sup>	86	23
try	Cornelissen et al. (2003)	SLA	mm <sup>2</sup> mg <sup>-1</sup>	615	14
try	Unpublished	SLA	mm <sup>2</sup> mg <sup>-1</sup>	6307	37
try	Wang et al. (2017)	SLA	mm <sup>2</sup> mg <sup>-1</sup>	6	2
try	Shipley and Vu (2002)	4 SLA	mm <sup>2</sup> mg <sup>-1</sup>	20	2
try	Cavender-Bares et al. (2006)	SLA	mm <sup>2</sup> mg <sup>-1</sup>	42	2
try	Unpublished	SLA	mm <sup>2</sup> mg <sup>-1</sup>	1	1
try	Diaz et al. (2004)	SLA	mm <sup>2</sup> mg <sup>-1</sup>	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	12.71	1.96	8.73	12.75	16.46	1.00
muPhenoSp	32.07	2.63	26.97	32.05	37.30	1.00
muForceSp	-10.74	2.86	-16.63	-10.66	-5.38	1.01
muChillSp	-4.08	4.13	-12.46	-4.02	3.99	1.01
muPhotoSp	1.11	2.18	-3.37	1.14	5.27	1.01
betaTraitxForce	0.16	0.19	-0.21	0.16	0.55	1.01
betaTraitxChill	-0.54	0.28	-1.07	-0.54	0.02	1.01
betaTraitxPhoto	-0.25	0.15	-0.54	-0.25	0.08	1.00
sigma_sp	5.91	0.76	4.63	5.84	7.57	1.00
sigma_study	7.53	1.22	5.52	7.40	10.28	1.00
sigma_traity	5.39	0.02	5.36	5.39	5.43	1.00
sigmaPhenoSp	15.11	2.05	11.20	15.06	19.36	1.00
sigmaForceSp	4.96	1.16	3.01	4.85	7.55	1.00
sigmaChillSp	8.53	2.10	5.21	8.26	13.38	1.00
sigmaPhotoSp	3.25	0.86	1.79	3.17	5.15	1.00
sigmapheno_y	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	1.87	0.50	0.89	1.88	2.84	1.00
muPhenoSp	31.35	2.64	26.32	31.27	36.76	1.00
muForceSp	-8.17	1.60	-11.35	-8.16	-5.07	1.00
muChillSp	-9.41	2.82	-15.21	-9.43	-3.92	1.00
muPhotoSp	-1.26	1.25	-3.72	-1.27	1.19	1.00
betaTraitxForce	-0.30	0.69	-1.61	-0.31	1.06	1.00
betaTraitxChill	-1.09	1.09	-3.28	-1.08	1.01	1.00
betaTraitxPhoto	-0.56	0.58	-1.68	-0.56	0.62	1.00
sigma_sp	1.62	0.19	1.30	1.61	2.05	1.00
sigma_study	0.97	0.10	0.77	0.97	1.17	1.00
sigma_traity	0.25	0.01	0.23	0.25	0.27	1.00
sigmaPhenoSp	14.84	2.25	10.58	14.79	19.42	1.00
sigmaForceSp	4.92	0.98	3.22	4.85	7.03	1.00
sigmaChillSp	10.67	2.57	6.55	10.33	16.65	1.00
sigmaPhotoSp	3.58	0.86	2.13	3.49	5.52	1.00
sigmapheno_y	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	16.85	1.47	14.03	16.85	19.71	1.01
muPhenoSp	31.33	2.55	26.45	31.30	36.39	1.00
muForceSp	-11.40	2.71	-17.29	-11.33	-6.42	1.01
muChillSp	-16.66	4.70	-26.35	-16.61	-7.84	1.00
muPhotoSp	1.85	2.47	-3.13	1.98	6.47	1.00
betaTraitxForce	0.17	0.15	-0.11	0.17	0.47	1.01
betaTraitxChill	0.34	0.25	-0.13	0.34	0.83	1.00
betaTraitxPhoto	-0.23	0.14	-0.50	-0.24	0.05	1.00
sigma_sp	7.78	0.93	6.21	7.70	9.77	1.00
sigma_study	3.28	0.97	1.87	3.13	5.57	1.00
sigma_traity	6.17	0.05	6.07	6.16	6.27	1.00
sigmaPhenoSp	13.92	2.11	10.10	13.79	18.34	1.00
sigmaForceSp	4.97	1.12	3.07	4.87	7.49	1.00
sigmaChillSp	10.57	2.30	6.79	10.33	15.56	1.00
sigmaPhotoSp	3.48	0.81	2.14	3.40	5.36	1.00
sigmapheno_y	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	22.61	1.37	19.91	22.60	25.32	1.01
muPhenoSp	31.14	2.52	26.33	31.09	36.29	1.00
muForceSp	-19.33	5.37	-30.02	-19.45	-8.62	1.02
muChillSp	-27.10	7.04	-40.56	-27.27	-12.84	1.01
muPhotoSp	-9.40	4.67	-18.09	-9.41	-0.37	1.02
betaTraitxForce	0.47	0.23	0.01	0.47	0.93	1.02
betaTraitxChill	0.72	0.30	0.12	0.72	1.29	1.01
betaTraitxPhoto	0.31	0.19	-0.06	0.31	0.68	1.02
sigma_sp	5.12	0.61	4.09	5.06	6.48	1.00
sigma_study	3.55	0.98	2.03	3.44	5.83	1.00
sigma_traity	5.13	0.06	5.02	5.13	5.25	1.00
sigmaPhenoSp	14.05	1.97	10.30	13.97	18.23	1.00
sigmaForceSp	4.59	1.09	2.80	4.47	7.05	1.00
sigmaChillSp	8.92	1.97	5.74	8.71	13.44	1.00
sigmaPhotoSp	3.59	0.81	2.25	3.52	5.41	1.00
sigmapheno_y	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. Heskell, 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. Aïdar, 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. Penúelas, 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. Cornelissen, 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.
- Freckleton, R. P., P. H. Harvey, and M. Pagel. 2002. Phylogenetic analysis and comparative data: A test and review of evidence. *American Naturalist* 160:712–726.
- Kleyer, M., R. M. Bekker, I. C. Knevel, J. P. Bakker, K. Thompson, M. Sonnenschein, P. Poschlod, J. M. V. Groenendaal, 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. Ordóñez, P. B. Reich, and L. S. Santiago. 2015. Global effects of soil and climate on leaf photosynthetic 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.
- Orme, D. 2013. The caper package: comparative analysis of phylogenetics and evolution in R.
- Paine, C. E. T., L. Amissah, H. Auge, C. Baraloto, M. Baruffol, N. Bourland, H. Bruehlheide, 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<sub>2</sub> 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. Albrechtsen. 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.
- Smith, S. A., and J. W. Brown. 2018. Constructing a broadly inclusive seed plant phylogeny. *American Journal of Botany* 105:302–314.
- 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.

- 101 Wang, H., S. P. Harrison, I. C. Prentice, Y. Yang, F. Bai, H. Furstenu Togashi, M. Wang, S. Zhou,  
102 and J. Ni. 2017. The China Plant Trait Database. PANGAEA .
- 103 Wenxuan, H., C. Yahan, Z. Fang-Jie, L. Tang, J. Rongfeng, and Z. Fusuo. 2012. Floral, climatic and  
104 soil pH controls on leaf ash content in China’s terrestrial plants. *Global Ecology and Biogeography*  
105 21:376–382.
- 106 Wilson, K. B., D. D. Baldocchi, and P. J. Hanson. 2000. Spatial and seasonal variability of photo-  
107 synthetic parameters and their relationship to leaf nitrogen in a deciduous forest. *Tree Physiology*  
108 20:565–578.
- 109 Wright, I. J., M. Westoby, P. B. Reich, J. Oleksyn, D. D. Ackerly, Z. Baruch, F. Bongers, J. Cavender-  
110 Bares, T. Chapin, J. H. C. Cornelissen, M. Diemer, J. Flexas, J. Gulias, E. Garnier, M. L. Navas,  
111 C. Roumet, P. K. Groom, B. B. Lamont, K. Hikosaka, T. Lee, W. Lee, C. Lusk, J. J. Midgley,  
112 Ü. Niinemets, H. Osada, H. Poorter, P. Pool, E. J. Veneklaas, L. Prior, V. I. Pyankov, S. C. Thomas,  
113 M. G. Tjoelker, and R. Villar. 2004. The worldwide leaf economics spectrum. *Nature* 428:821–827.
- 114 Yahan, C., H. Wenxuan, T. Luying, T. Zhiyao, and F. Jingyun. 2013. Leaf nitrogen and phosphorus  
115 concentrations of woody plants differ in responses to climate, soil and plant growth form. *Ecography*  
116 36:178–184.