Supplementary Material: Budburst timing within a functional trait framework

Figures & Tables

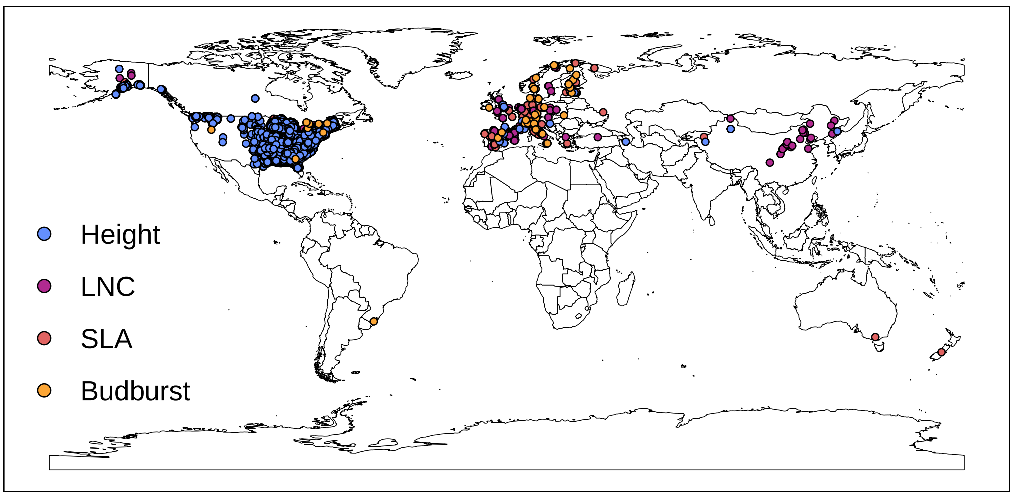

Figure S1: We obtained data from the TRY and BIEN plant trait databases and the OSPREE database of plant phenology experiments for temperate tree species. Following our cleaning of the data and selection of uncorrelated traits, our final dataset included 37 species from 24 unique datasources for the trait data and 34 unique studies for the budburst data. Our data is focused on temperate ecosystems globally with most data originating from North America and Europe.

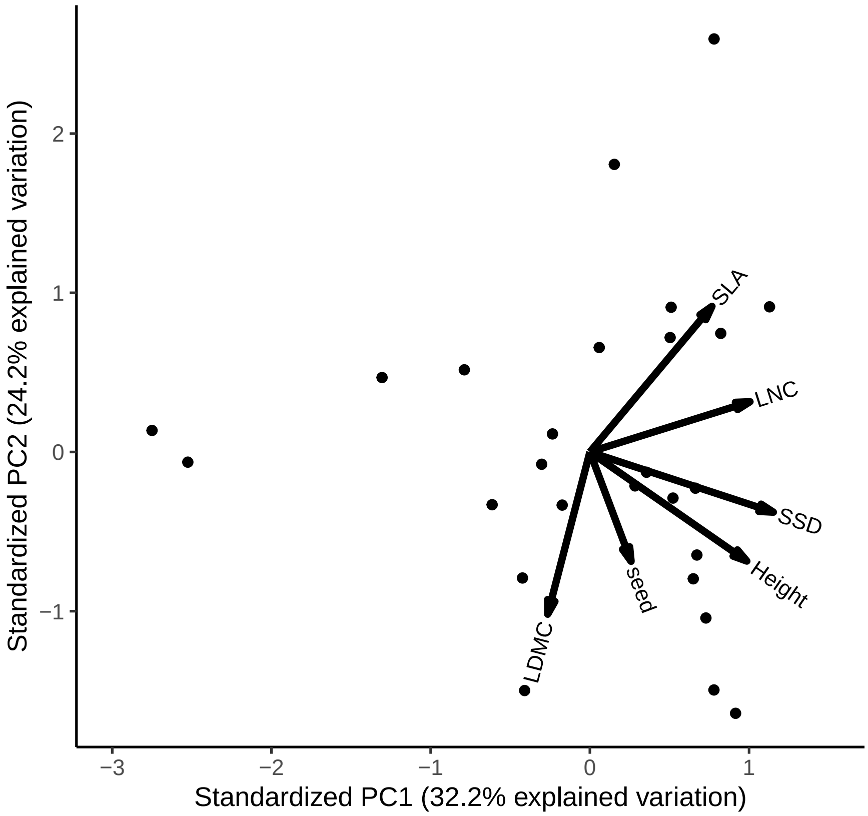

Figure S2: A projection of tree traits across the first and second principle component axis. Arrows represent the direction of vectors for the six functional traits with complete trait data. Points represent the 26 species for which complete trait data was available.

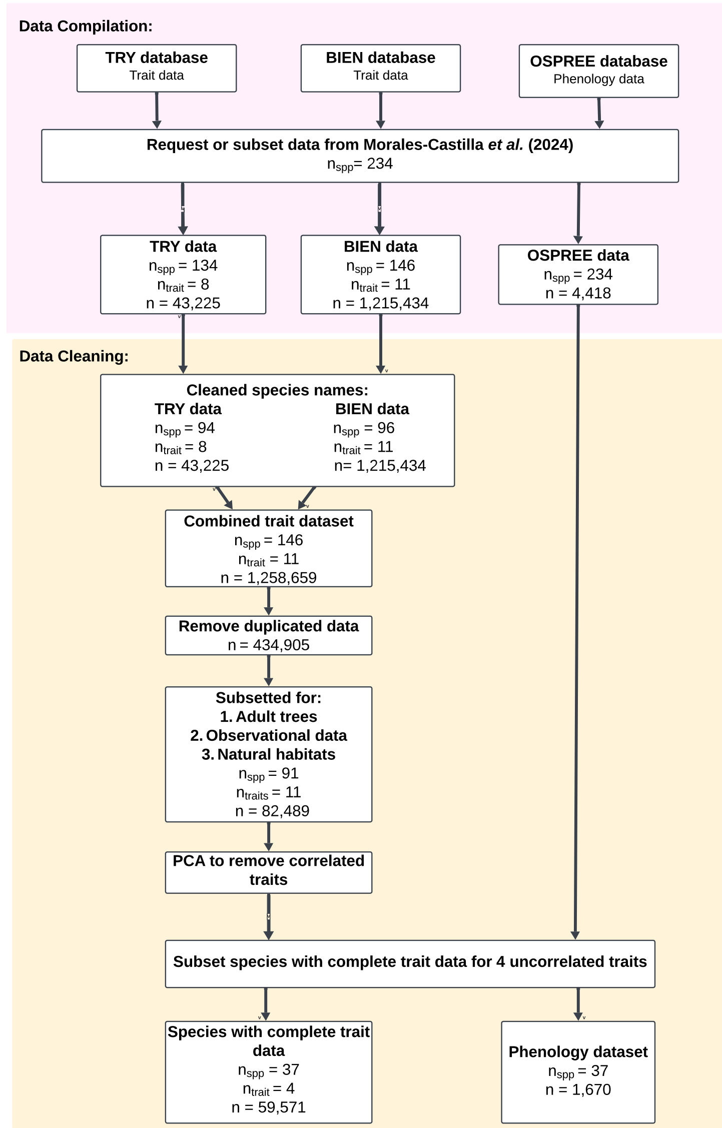

Figure S3: Our initial aim was to include all species from (analyzed by Morales-Castilla *et al.*, 2024), however trait data was only available for a subset of these species. Data was cleaned extensively, with each step depicted by a box, and subset to only include traits for adult trees growing under natural conditions for which we had a complete suite of trait values.

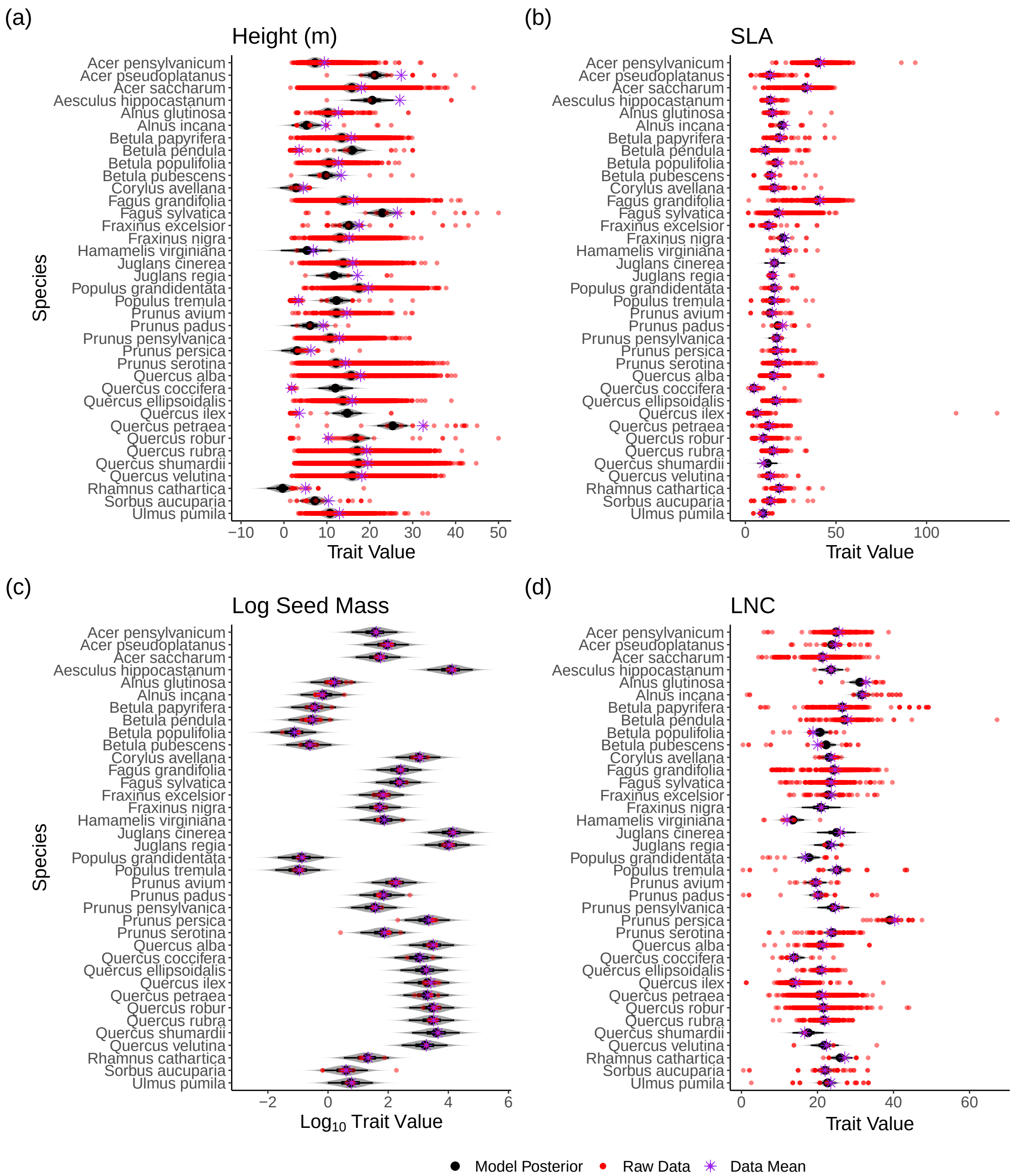

Figure S4: Comparisons of estimated model fits and raw data from joint models of trait effects on budburst phenological cues for 37 species of woody deciduous plants. Four functional traits—(a) height, (b) SLA, (c) seed mass, and (d) LNC— were modeled individually, with the calculated trait value being 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 50% uncertainty interval and the thinner black line the 95% uncertainty 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.

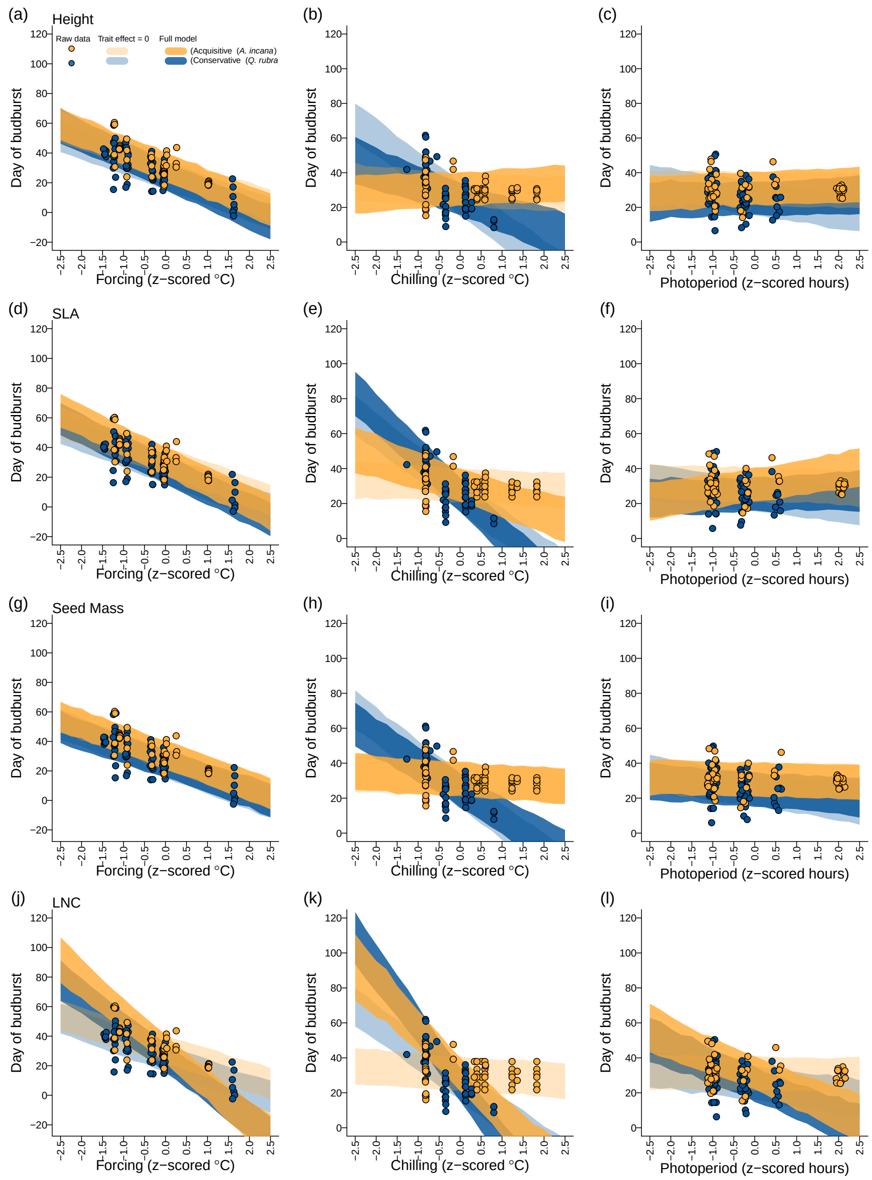

Figure S5: Here we show the relationship between traits and the three phenological cues using as an example an acquisitive species, *Alnus incana* shown in blue, and a conservative species, *Quercus rubra* shown in yellow. The posterior estimates from our height (a-c), SLA (d-f), seed mass (g-i), and LNC (j-l) models were used to estimate the day of budburst for the two species. The effect of height on budburst timing was smallest in response to forcing (a), while the greatest effect of height on budburst was in response to chilling (b), followed by photoperiod (c). The greatest effect of SLA on budburst was only in relation to photoperiod (f). Seed mass had a negligible effect on our estimates budburst (g-i). But LNC had a considerable effect on budburst timing in relation to each cue (j-l). The strength of the relationships can be assessed by comparing the colored bands, with the lighter bands depicting the estimated 50% uncertainty interval without the effect of traits ($\mu_{k,g}$ equal to zero) and darker bands the estimated budburst with the effects of traits included. Points represent the raw budburst data.

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 & 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 & 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 estimates from our model of height ($n = 42781$) using data from 37 focal species. Values represent the mean estimate for model parameters as well as the 50% and 90% uncertainty interval (UI). The strength of the relationship can be assessed by comparing across UI, with parameters with intervals that cross zero depicting weak relationships

	mean	5%	25%	75%	95%
$\mu_{grand.trait}$	12.7	9.4	11.4	14.0	15.8
$\mu_{k,g}$	32.1	27.8	30.3	33.9	36.5
μ_{force}	-10.7	-15.5	-12.6	-8.8	-6.2
μ_{chill}	-4.1	-10.8	-6.8	-1.4	2.6
μ_{photo}	1.1	-2.6	-0.3	2.5	4.6
$\beta_{trait.force}$	0.2	-0.2	0.0	0.3	0.5
$\beta_{trait.chill}$	-0.5	-1.0	-0.7	-0.3	-0.1
$\beta_{trait.photo}$	-0.2	-0.5	-0.4	-0.1	0.0
$\sigma_{species}$	5.9	4.8	5.4	6.4	7.3
σ_{study}	7.5	5.8	6.7	8.3	9.7
σ_{trait}	5.4	5.4	5.4	5.4	5.4
σ_{pheno}	15.1	11.8	13.8	16.4	18.6
σ_{force}	5.0	3.3	4.1	5.7	7.1
σ_{chill}	8.5	5.6	7.0	9.8	12.4
σ_{photo}	3.2	2.0	2.6	3.8	4.8
σ_{d}	14.2	13.8	14.0	14.3	14.6

Table S3: Summary of estimates from our model of specific leaf area (SLA, $n = 7656$) using data from 37 focal species. Values represent the mean estimate for model parameters as well as the 50% and 90% uncertainty interval (UI). The strength of the relationship can be assessed by comparing across UI, with parameters with intervals that cross zero depicting weak relationships

	mean	5%	25%	75%	95%
$\mu_{grand.trait}$	16.8	14.5	15.8	17.8	19.3
$\mu_{k,g}$	31.3	27.2	29.6	33.0	35.6
μ_{force}	-11.4	-16.2	-13.1	-9.6	-7.2
μ_{chill}	-16.7	-24.6	-19.8	-13.3	-9.1
μ_{photo}	1.9	-2.4	0.2	3.6	5.8
$\beta_{trait.force}$	0.2	-0.1	0.1	0.3	0.4
$\beta_{trait.chill}$	0.3	-0.1	0.2	0.5	0.7
$\beta_{trait.photo}$	-0.2	-0.5	-0.3	-0.1	0.0
$\sigma_{species}$	7.8	6.4	7.1	8.4	9.4
σ_{study}	3.3	2.0	2.6	3.8	5.1
σ_{trait}	6.2	6.1	6.1	6.2	6.3
σ_{pheno}	13.9	10.7	12.4	15.3	17.6
σ_{force}	5.0	3.3	4.2	5.6	7.0
σ_{chill}	10.6	7.2	8.9	12.0	14.8
σ_{photo}	3.5	2.3	2.9	3.9	5.0
σ_{d}	14.2	13.8	14.0	14.3	14.6

Table S4: Summary of estimates from our model of seed mass ($n = 281$) using data from 37 focal species. Values represent the mean estimate for model parameters as well as the 50% and 90% uncertainty interval (UI). The strength of the relationship can be assessed by comparing across UI, with parameters with intervals that cross zero depicting weak relationships

	mean	5%	25%	75%	95%
$\mu_{grand.trait}$	1.9	1.0	1.5	2.2	2.7
$\mu_{k,g}$	31.4	27.1	29.6	33.1	35.8
μ_{force}	-8.2	-10.8	-9.2	-7.1	-5.6
μ_{chill}	-9.4	-14.0	-11.2	-7.5	-4.8
μ_{photo}	-1.3	-3.4	-2.1	-0.4	0.8
$\beta_{trait.force}$	-0.3	-1.4	-0.8	0.1	0.9
$\beta_{trait.chill}$	-1.1	-2.9	-1.8	-0.4	0.7
$\beta_{trait.photo}$	-0.6	-1.5	-0.9	-0.2	0.4
$\sigma_{species}$	1.6	1.3	1.5	1.7	2.0
σ_{study}	1.0	0.8	0.9	1.0	1.1
σ_{trait}	0.2	0.2	0.2	0.3	0.3
σ_{pheno}	14.8	11.2	13.3	16.3	18.6
σ_{force}	4.9	3.4	4.2	5.5	6.7
σ_{chill}	10.7	7.1	8.8	12.1	15.4
σ_{photo}	3.6	2.3	3.0	4.1	5.1
σ_d	14.1	13.7	14.0	14.3	14.5

Table S5: Summary of estimates from our model of leaf nitrogen content (LNC, $n = 3853$) using data from 37 focal species. Values represent the mean estimate for model parameters as well as the 50% and 90% uncertainty interval (UI). The strength of the relationship can be assessed by comparing across UI, with parameters with intervals that cross zero depicting weak relationships

	mean	5%	25%	75%	95%
$\mu_{grand.trait}$	22.6	20.4	21.7	23.5	24.9
$\mu_{k,g}$	31.1	27.1	29.4	32.8	35.3
μ_{force}	-19.3	-27.9	-22.9	-15.8	-10.5
μ_{chill}	-27.1	-38.5	-31.7	-22.4	-15.4
μ_{photo}	-9.4	-17.0	-12.5	-6.2	-1.9
$\beta_{trait.force}$	0.5	0.1	0.3	0.6	0.8
$\beta_{trait.chill}$	0.7	0.2	0.5	0.9	1.2
$\beta_{trait.photo}$	0.3	0.0	0.2	0.4	0.6
$\sigma_{species}$	5.1	4.2	4.7	5.5	6.2
σ_{study}	3.6	2.2	2.9	4.1	5.3
σ_{trait}	5.1	5.0	5.1	5.2	5.2
σ_{pheno}	14.0	10.9	12.7	15.3	17.4
σ_{force}	4.6	3.0	3.8	5.2	6.6
σ_{chill}	8.9	6.1	7.5	10.1	12.5
σ_{photo}	3.6	2.4	3.0	4.1	5.0
σ_d	14.2	13.8	14.0	14.3	14.6

Stan model code

```
data {
  int<lower = 1> n_spec;
  int<lower = 1> N;
  int<lower = 1, upper = n_spec> trait_species[N];
  int<lower = 1> n_study;
  int<lower = 1, upper = n_study> study[N];
  vector[N] yTraiti;

  int<lower = 1> Nph;
  int<lower = 1, upper = n_spec> phenology_species[Nph];
  vector[Nph] yPhenoi;
  vector[Nph] forcei;
  vector[Nph] chilli;
  vector[Nph] photoi;
}

parameters{

  real mu_grand;
  vector[n_spec] muSp;
  vector[n_study] muStudy;
  real<lower = 0> sigma_traity;
  real<lower = 0> sigma_sp;
  real<lower = 0> sigma_study;

  real alphaForceSp[n_spec];
  real muForceSp;
  real<lower = 0> sigmaForceSp;
  real alphaChillSp[n_spec];
  real muChillSp;
  real<lower = 0> sigmaChillSp;
  real alphaPhotoSp[n_spec];
  real muPhotoSp;
  real<lower = 0> sigmaPhotoSp;
  real alphaPhenoSp[n_spec];
  real muPhenoSp;
  real<lower = 0> sigmaPhenoSp;
  real betaTraitxForce;
  real betaTraitxChill;
  real betaTraitxPhoto;
  real<lower = 0> sigmapheno_y;
}

transformed parameters{

  vector[N] y_hat;
  vector[n_spec] mu_grand_sp;

  real betaForceSp[n_spec];
```

```
  real betaPhotoSp[n_spec];
  real betaChillSp[n_spec];

  for(i in 1:n_spec){
    mu_grand_sp[i] = mu_grand + muSp[i];
  }
  for (i in 1:N){
    y_hat[i] = mu_grand + muSp[trait_species[i]] + muStudy[study[i]];
  }

  for (isp in 1:n_spec){
    betaForceSp[isp] = alphaForceSp[isp] + betaTraitxForce * (mu_grand_sp[isp]);
  }
  for (isp in 1:n_spec){
    betaPhotoSp[isp] = alphaPhotoSp[isp] + betaTraitxPhoto * (mu_grand_sp[isp]);
  }
  for (isp in 1:n_spec){
    betaChillSp[isp] = alphaChillSp[isp] + betaTraitxChill * (mu_grand_sp[isp]);
  }
}

model{
  yTraiti ~ normal(y_hat, sigma_traity);
  muSp ~ normal(0, sigma_sp);
  muStudy ~ normal(0, sigma_study);
  mu_grand ~ normal(20,10);
  sigma_sp ~ normal(4,5);
  sigma_study ~ normal(2,5);
  sigma_traity ~ normal(3,5);

  for (i in 1:Nph){
    yPhenoi[i] ~ normal(alphaPhenoSp[phenology_species[i]] +
    betaForceSp[phenology_species[i]] * forcei[i] +
    betaPhotoSp[phenology_species[i]] * photoi[i] +
    betaChillSp[phenology_species[i]] * chilli[i],
    sigmapheno_y);
  }

  alphaPhenoSp ~ normal(muPhenoSp, sigmaPhenoSp);
  alphaForceSp ~ normal(muForceSp, sigmaForceSp);
  alphaChillSp ~ normal(muChillSp, sigmaChillSp);
  alphaPhotoSp ~ normal(muPhotoSp, sigmaPhotoSp);

  muPhenoSp ~ normal(40,10);
  sigmaPhenoSp ~ normal(5,5);

  sigmapheno_y ~ normal(10,5);

  muForceSp ~ normal(-15,10);
  sigmaForceSp ~ normal(5,5);

  muChillSp ~ normal(-15,10);
```

```
  sigmaChillSp ~ normal(5,5);

  muPhotoSp ~ normal(-15,10);
  sigmaPhotoSp ~ normal(5,5);

  betaTraitxForce ~ normal(0,1);
  betaTraitxPhoto ~ normal(0,1);
  betaTraitxChill ~ normal(0,1);

}
```

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