Supplemental materials: Understanding growing degree days to predict spring phenology under climate change

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Article acceptance date: 13 April 2021

Methods S1: Using simulations to test Bayesian models in Rstan

To test all models, we used data simulations.

Methods S2: Data analysis and model equations

Using Bayesian hierarchical models, we estimated the effects of site (i.e., 'forest' sites modeled as '0' versus 'urban' sites modeled as a '1'), method (i.e., hobo logger climate data modeled as '0' and weather station climate data modeled as '1') and the interaction between site and method effects as predictors with species modeled hierarchically as grouping factors:

$$y_i = \alpha_{species[i]} + \beta_{site_{species[i]}} X_{site} + \beta_{method_{species[i]}} X_{method} + \beta_{sitexmethod_{species[i]}} X_{sitexmethod} + \epsilon_i \quad (1)$$

$$\epsilon_i \sim N(0, \sigma_y)$$

The α and each of the five β coefficients are modeled at the species level, as follows:

$$\begin{aligned} \alpha_{species} &\sim N(\mu_\alpha, \sigma_\alpha) \\ \beta_{site_{species}} &\sim N(\mu_{site}, \sigma_{site}) \\ \beta_{method_{species}} &\sim N(\mu_{method}, \sigma_{method}) \\ \beta_{sitexmethod_{species}} &\sim N(\mu_{sitexmethod}, \sigma_{sitexmethod}) \end{aligned}$$

where i represents each unique observation, *species* is the species, α represents the intercept, β terms represent slope estimates, and y is the number of growing degree days.

Supplemental tables and figures

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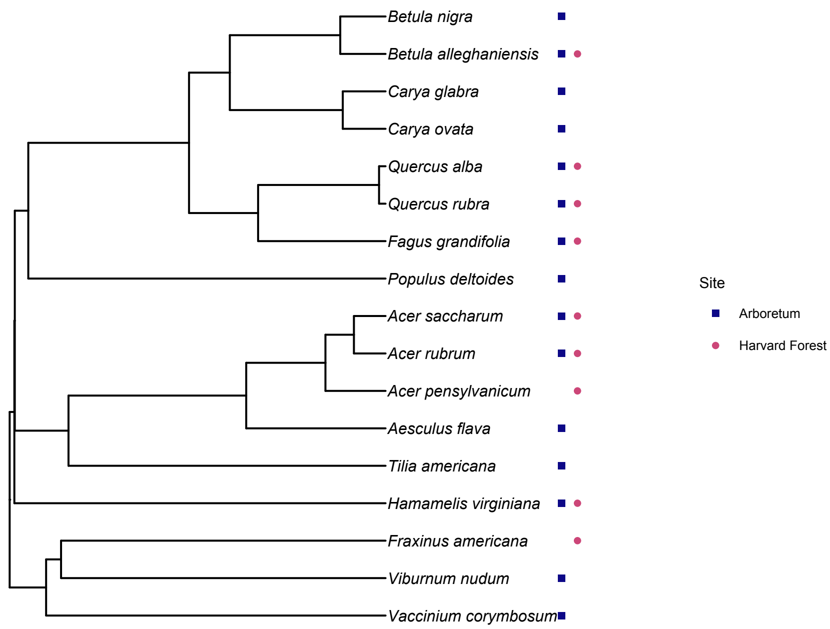

- Figure S1: Phylogeny indicating species across the two sites -

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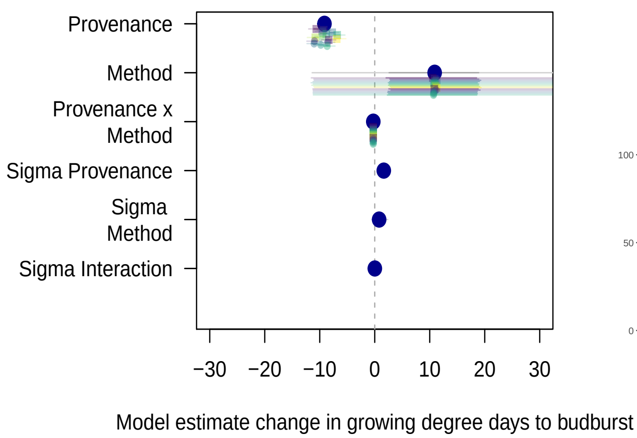
Table S1: **Estimates from noisy weather station simulations**. Using a model with noisy weather station data simulations and testing the effects of site, method and the interaction between site and method results in a large sigma for method. We present posterior means, as well as 50 percent and 95 percent uncertainty intervals from models in which the predictors have been standardized so that they are directly comparable.

	mean	25%	75%	2.5%	97.5%
μ_{α}	307.45	303.99	310.89	297.13	318.19
μ_{site}	0.07	-0.50	0.66	-1.54	1.69
μ_{method}	4.93	2.35	7.60	-3.09	12.52
$\mu_{sitexmethod}$	-0.39	-1.16	0.36	-2.81	1.84
σ_{site}	0.68	0.26	0.98	0.02	1.93
σ_{method}	14.63	12.37	16.33	9.81	22.36
$\sigma_{sitexmethod}$	0.86	0.33	1.23	0.03	2.59
σ_{α}	21.79	18.43	24.37	14.47	33.19
σ_{y}	15.55	15.42	15.67	15.16	15.95
N_{sp}	15.00				

(a)



(b)

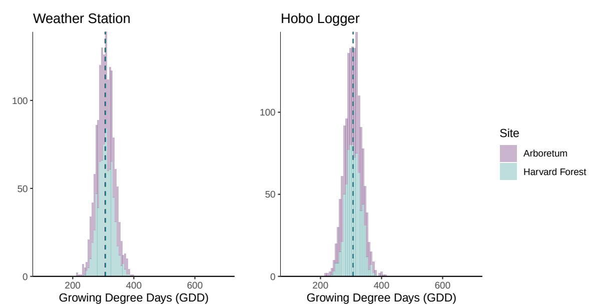


Figure S2: Using simulated data to test provenance latitude, we show (a) histograms of climate data at the Arboretum and Harvard Forest using weather station data and hobo logger data. (b) Histograms of GDDs at the Arboretum and Harvard Forest using weather station data and hobo logger data. (c) Effects of provenance latitude and climate data method (weather station data as ‘1’ or hobo logger data as ‘0’) on simulated growing degree days (GDDs) until budburst using noisy weather station data. More positive values indicate more GDDs are required for budburst whereas more negative values suggest fewer GDDs are required. Dots and lines show means and 50% uncertainty intervals. See Table XX for full model output.

Table S2: **Estimates from noisy hobo logger simulations**. Using a model with noisy hobo logger data simulations and testing the effects of site, method and the interaction between site and method results in a large sigma for method. We present posterior means, as well as 50 percent and 95 percent uncertainty intervals from models in which the predictors have been standardized so that they are directly comparable.

	mean	25%	75%	2.5%	97.5%
μ_{α}	316.41	311.01	321.54	299.27	333.71
μ_{site}	-1.20	-1.78	-0.62	-2.89	0.51
μ_{method}	-6.41	-9.15	-3.68	-14.64	1.86
$\mu_{sitexmethod}$	2.15	1.36	2.91	-0.10	4.47
σ_{site}	1.00	0.42	1.43	0.03	2.73
σ_{method}	15.14	12.73	17.02	10.11	23.17
$\sigma_{sitexmethod}$	1.20	0.48	1.70	0.04	3.31
σ_{α}	31.87	27.47	35.30	22.11	46.96
σ_{y}	15.05	14.91	15.19	14.67	15.46
N_{sp}	15.00				

Table S3: **Estimates from microclimate simulations**. Using a model with microclimate data simulations and testing the effects of site, method and the interaction between site and method results in a small sigma for method. We present posterior means, as well as 50 percent and 95 percent uncertainty intervals from models in which the predictors have been standardized so that they are directly comparable.

	mean	25%	75%	2.5%	97.5%
μ_{α}	322.94	318.50	327.45	310.33	335.58
μ_{site}	-0.32	-0.91	0.30	-2.11	1.42
μ_{method}	-6.78	-8.07	-5.50	-10.55	-3.07
$\mu_{sitexmethod}$	1.05	0.26	1.85	-1.33	3.38
σ_{site}	1.14	0.47	1.65	0.06	3.12
σ_{method}	6.82	5.63	7.72	4.26	10.92
$\sigma_{sitexmethod}$	1.23	0.46	1.77	0.04	3.60
σ_{α}	24.85	21.32	27.48	17.17	36.72
σ_{y}	16.73	16.59	16.87	16.32	17.14
N_{sp}	15.00				

Table S4: **Estimates from urban simulations**. Using a model with urban data simulations and testing the effects of site, method and the interaction between site and method results in a negative effect of site. We present posterior means, as well as 50 percent and 95 percent uncertainty intervals from models in which the predictors have been standardized so that they are directly comparable.

	mean	25%	75%	2.5%	97.5%
μ_{α}	307.37	303.97	310.87	296.13	317.88
μ_{site}	-19.23	-19.81	-18.64	-20.98	-17.50
μ_{method}	0.27	-0.31	0.90	-1.47	1.92
$\mu_{sitexmethod}$	-0.41	-1.21	0.36	-2.59	1.87
σ_{site}	1.15	0.47	1.64	0.05	3.16
σ_{method}	1.03	0.46	1.47	0.05	2.65
$\sigma_{sitexmethod}$	0.77	0.30	1.10	0.02	2.33
σ_{α}	21.55	18.47	23.96	14.96	31.33
σ_{y}	15.56	15.42	15.70	15.17	15.97
N_{sp}	15.00				

Table S5: **Estimates from real data**. Using a model with real data and testing the effects of site, method and the interaction between site and method results in XXX. We present posterior means, as well as 50 percent and 95 percent uncertainty intervals from models in which the predictors have been standardized so that they are directly comparable.

	mean	25%	75%	2.5%	97.5%
μ_{α}	424.96	413.29	437.11	387.75	458.74
μ_{site}	-31.66	-39.63	-23.74	-54.08	-9.28
μ_{method}	-0.50	-7.29	6.22	-19.96	20.45
$\mu_{sitexmethod}$	-40.35	-48.17	-32.56	-63.08	-17.80
σ_{site}	21.46	11.46	29.44	1.25	49.34
σ_{method}	17.09	7.80	24.21	0.88	43.70
$\sigma_{sitexmethod}$	25.62	16.26	33.80	2.66	52.91
σ_{α}	62.95	53.51	71.16	40.91	93.12
σ_{y}	71.54	69.73	73.28	66.63	76.75
N_{sp}	18.00				

Table S6: **Estimates from an urban effect and noisy weather station simulations**. Using a model with an urban effect and noisy weather station data simulations and testing the effects of site, method and the interaction between site and method results in XXX. We present posterior means, as well as 50 percent and 95 percent uncertainty intervals from models in which the predictors have been standardized so that they are directly comparable.

	mean	25%	75%	2.5%	97.5%
μ_{α}	306.04	302.37	309.82	294.54	316.85
μ_{site}	-17.13	-20.24	-14.11	-26.63	-7.89
μ_{method}	5.65	3.45	7.87	-1.17	12.40
$\mu_{sitexmethod}$	-13.47	-14.65	-12.27	-16.97	-10.01
σ_{site}	18.38	15.64	20.55	12.45	27.44
σ_{method}	12.16	10.23	13.76	7.95	18.51
$\sigma_{sitexmethod}$	3.69	2.06	5.07	0.31	8.34
σ_{α}	21.03	17.96	23.41	14.71	31.42
σ_{y}	20.36	20.18	20.54	19.86	20.85
N_{sp}	15.00				

Table S7: **Estimates from provenance latitude simulations**. Using a model with provenance latitude simulations and testing the effects of site, method and the interaction between site and method results in XXX. We present posterior means, as well as 50 percent and 95 percent uncertainty intervals from models in which the predictors have been standardized so that they are directly comparable.

	mean	25%	75%	2.5%	97.5%
μ_{α}	625.44	601.53	654.55	542.03	686.12
μ_{site}	-9.14	-9.47	-8.81	-10.14	-8.12
μ_{method}	10.90	2.61	18.91	-11.39	35.01
$\mu_{sitexmethod}$	-0.26	-0.45	-0.06	-0.82	0.26
σ_{site}	1.65	1.32	1.89	0.97	2.76
σ_{method}	0.80	0.31	1.13	0.03	2.39
$\sigma_{sitexmethod}$	0.02	0.01	0.03	0.00	0.05
σ_{α}	96.80	77.58	113.07	53.04	159.98
σ_{y}	15.60	15.45	15.74	15.18	16.01
N_{sp}	15.00				