of large-scale citizen science data and long-term study data for phenology modeling

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Supplementary materials

Supplementary images S1 - S11 and Table S1

Figure S1: Sensitivity test results from using a 15 versus 30 day cutoff between the 'yes' and most recent 'no' in the USA-NPN dataset. Each point represents the value of a single parameter for one of eight models for 33 species and phenophases in the USA-NPN dataset. Note only 33 comparisons were possible here as the stricter 15 day cutoff resulted in three of the species not having sufficient observations.

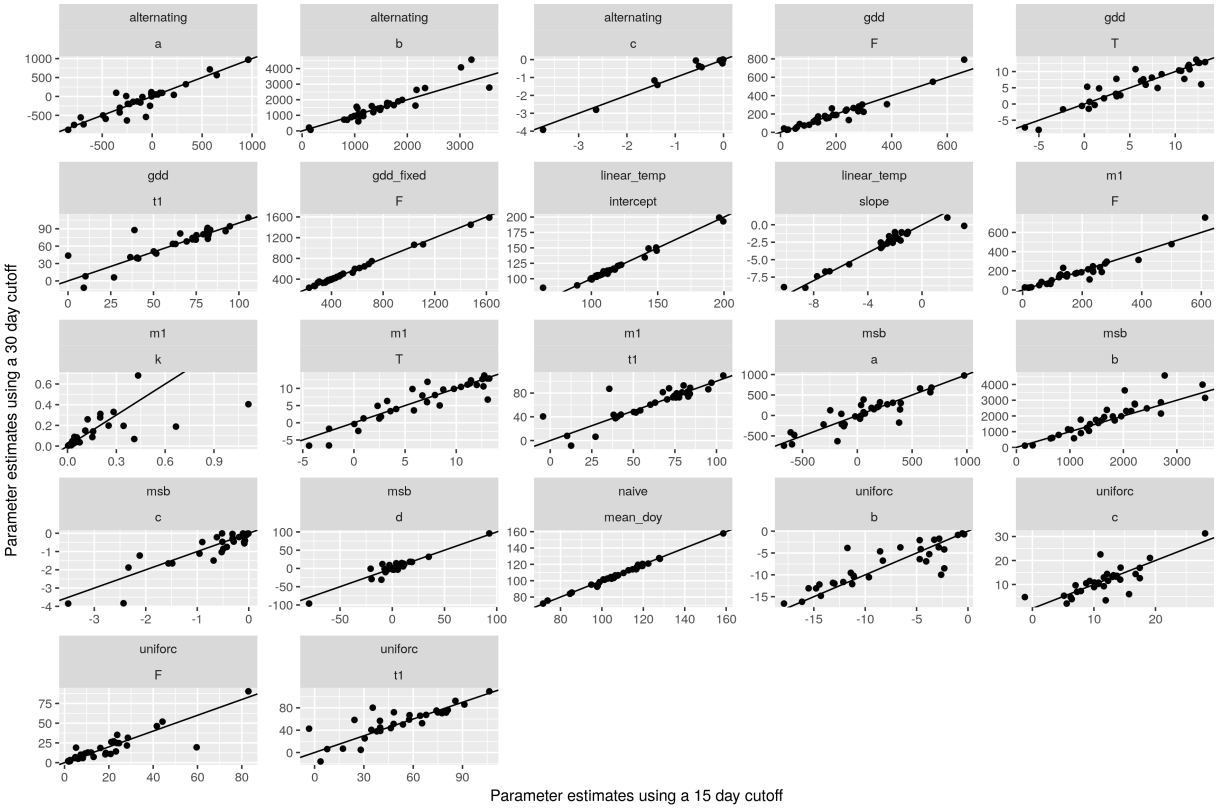
alternating
a
alternating
b
alternating
c
gdd
F
gdd
T
gdd
t1
gdd_fixed
F
linear_temp
intercept
linear_temp
slope
m1
F
m1
k
m1
T
m1
t1
msb
a
msb
b
msb
c
msb
d
naive
mean_doy
uniforc
b
uniforc
c
uniforc
F
uniforc
t1
Parameter estimates using a 30 day cutoff
Parameter estimates using a 15 day cutoff

Figure S1

Figure S2: Comparisons of parameter estimates between NPN and LTER derived models. As in Figure 2 in the main text, but using a threshold of 15 instead of 30 days between the first 'yes' and most recent 'no' in the USA-NPN dataset. See methods for details.

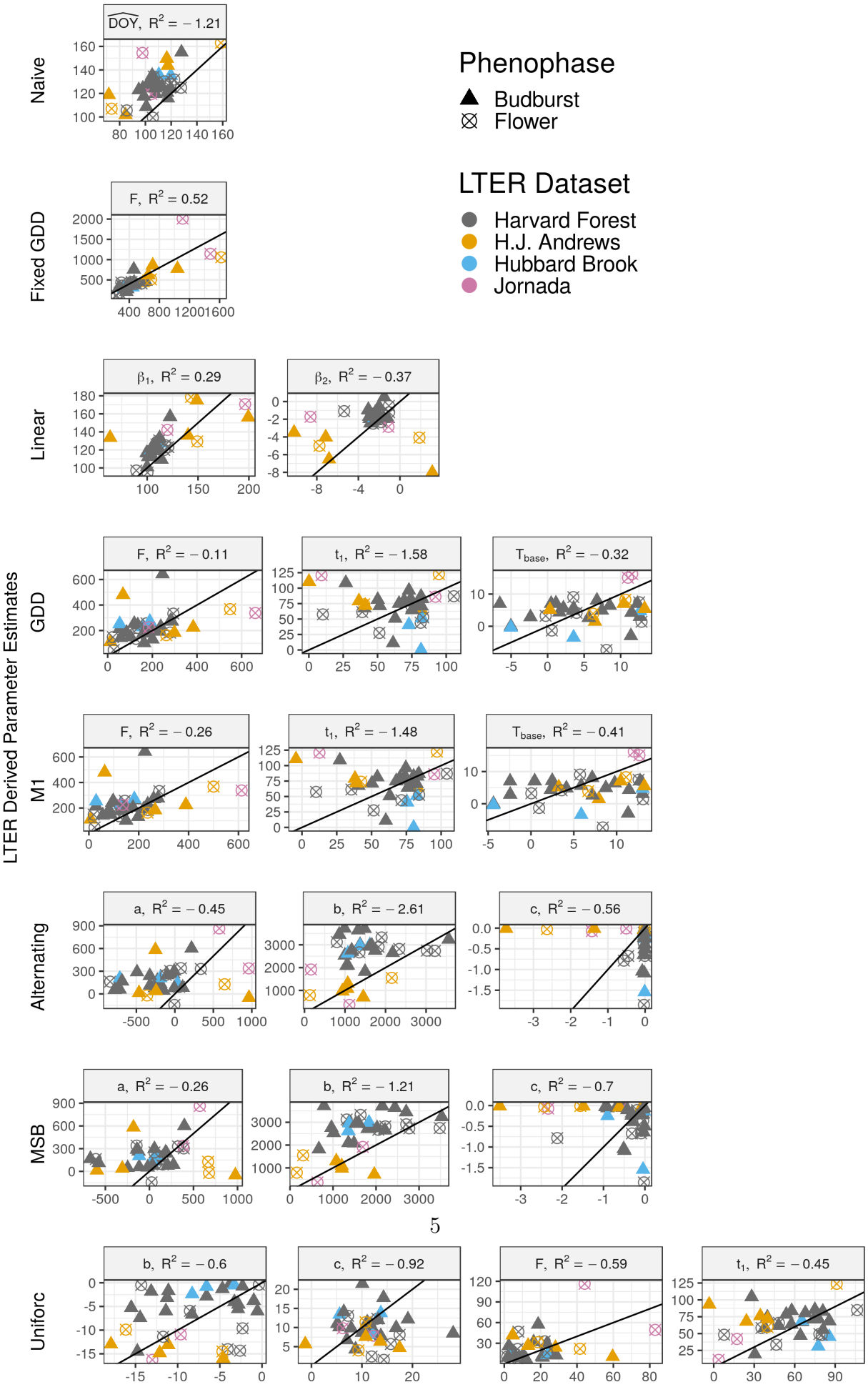
LTER Derived Parameter Estimates
Naive
Fixed GDD
Linear
GDD
M1
Alternating
MSB
Uniforc
DOY, R² = −1.21
F, R² = 0.52
β1, R² = 0.29
β2, R² = −0.37
F, R² = −0.11
t1, R² = −1.58
Tbase, R² = −0.32
F, R² = −0.26
t1, R² = −1.48
Tbase, R² = −0.41
a, R² = −0.45
b, R² = −2.61
c, R² = −0.56
a, R² = −0.26
b, R² = −1.21
c, R² = −0.7
b, R² = −0.6
c, R² = −0.92
F, R² = −0.59
t1, R² = −0.45
Phenophase
Budburst
Flower
LTER Dataset
Harvard Forest
H.J. Andrews
Hubbard Brook
Jornada

Figure S2

Figure S3: Comparison of predicted day of year (DOY) of all phenological events between NPN and LTER-derived models. As in Figure 3 in the main text, but using a threshold of 15 instead of 30 days between the first 'yes' and most recent 'no' in the USA-NPN dataset. See methods for details.

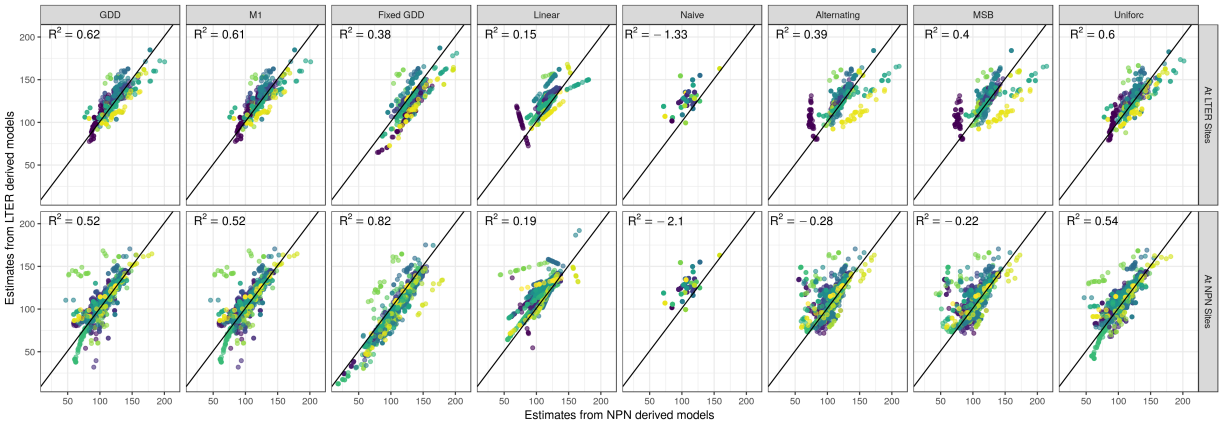
GDD
M1
Fixed GDD
Linear
Naive
Alternating
MSB
Uniforc
R2 = 0.62
R2 = 0.61
R2 = 0.38
R2 = 0.15
R2 = −1.33
R2 = 0.39
R2 = 0.4
R2 = 0.6
R2 = 0.52
R2 = 0.52
R2 = 0.82
R2 = 0.19
R2 = −2.1
R2 = −0.28
R2 = −0.22
R2 = 0.54
At LTER Sites
At NPN Sites
Estimates from LTER derived models
Estimates from NPN derived models
50
100
150
200

Figure S3

Figure S4: Differences in prediction error between NPN and LTER-derived models. As in Figure 4 in the main text, but using a threshold of 15 instead of 30 days between the first 'yes' and most recent 'no' in the USA-NPN dataset. See methods for details.

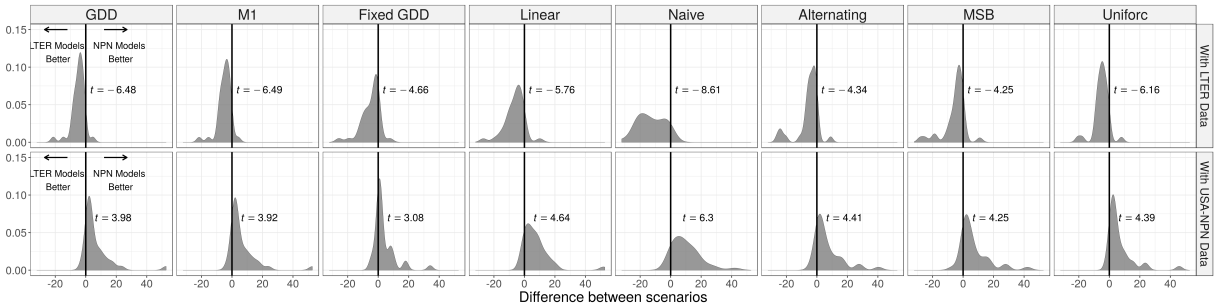
GDD
M1
Fixed GDD
Linear
Naive
Alternating
MSB
Uniforc
LTER Models Better
NPN Models Better
t = −6.48
t = −6.49
t = −4.66
t = −5.76
t = −8.61
t = −4.34
t = −4.25
t = −6.16
t = 3.98
t = 3.92
t = 3.08
t = 4.64
t = 6.3
t = 4.41
t = 4.25
t = 4.39
With LTER Data
With USA-NPN Data
0.15
0.10
0.05
0.00
-20
0
20
40
Difference between scenarios

Figure S4

Figure S5: RMSE for specific species and phenophases using all combinations of models and data sources. Red X's mark the best performing models for each respective dataset.

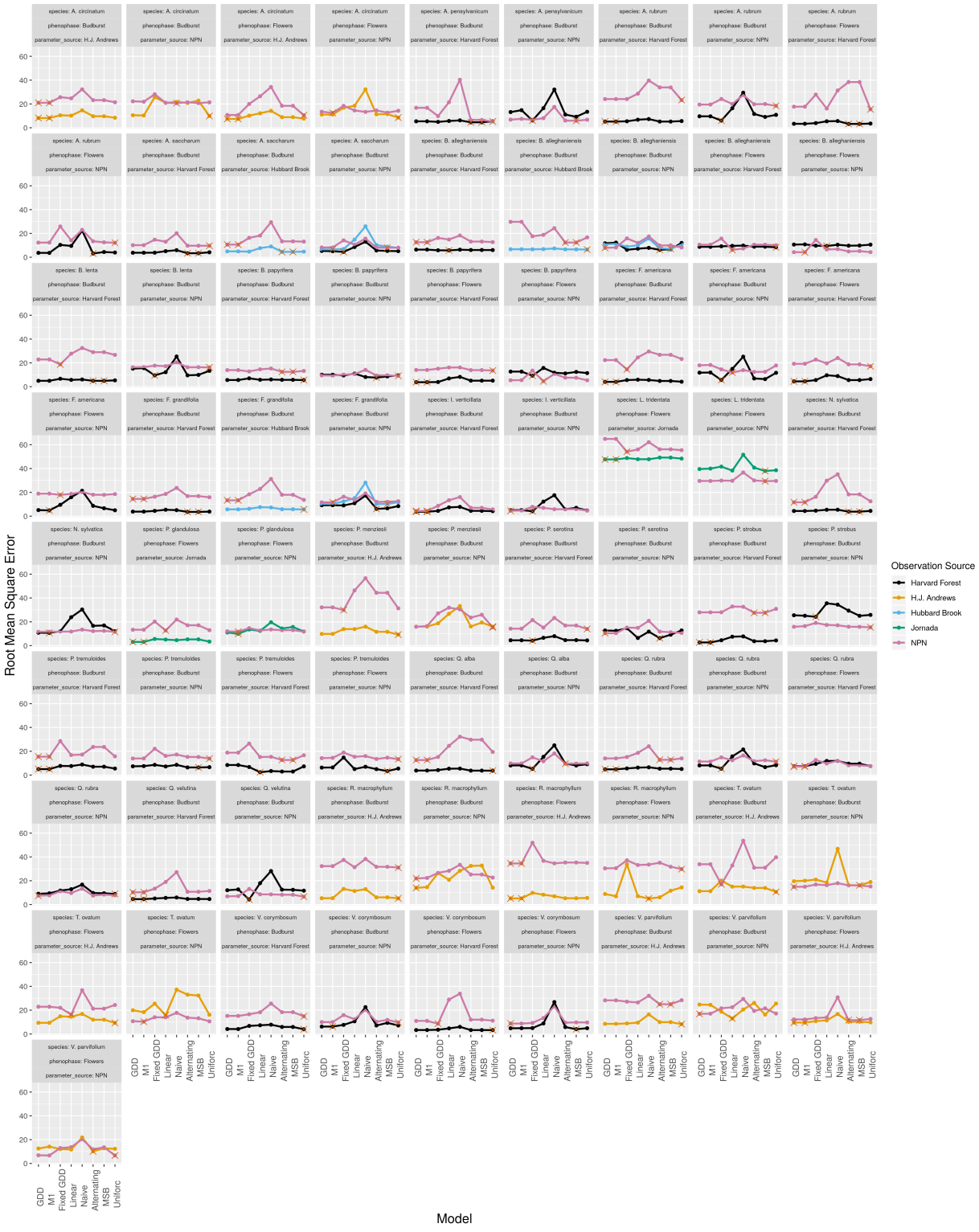
Root Mean Square Error
Model
Observation Source
Harvard Forest
H.J. Andrews
Hubbard Brook
Jornada
NPN
GDD
M1
Fixed GDD
Linear
Naive
Alternating
MSB
Uniforc

Figure S5

Figure S6: Pearson correlation coefficients for specific species and phenophases using all combinations of models and data sources. Note that since all predictions from each Naive model are the same the Pearsons correlation cannot be calculated here. Red X's mark the best performing models for each respective dataset.


Pearson Correlation
Model
Observation Source
Harvard Forest
H.J. Andrews
Hubbard Brook
Jornada
NPN
GDD
M1
Fixed GDD
Linear
Naive
Alternating
MSB
Uniforc

Figure S6

Figure S7: RMSE of all species and phenophases of the four scenarios described in the text. These values were calculated using held out test data.

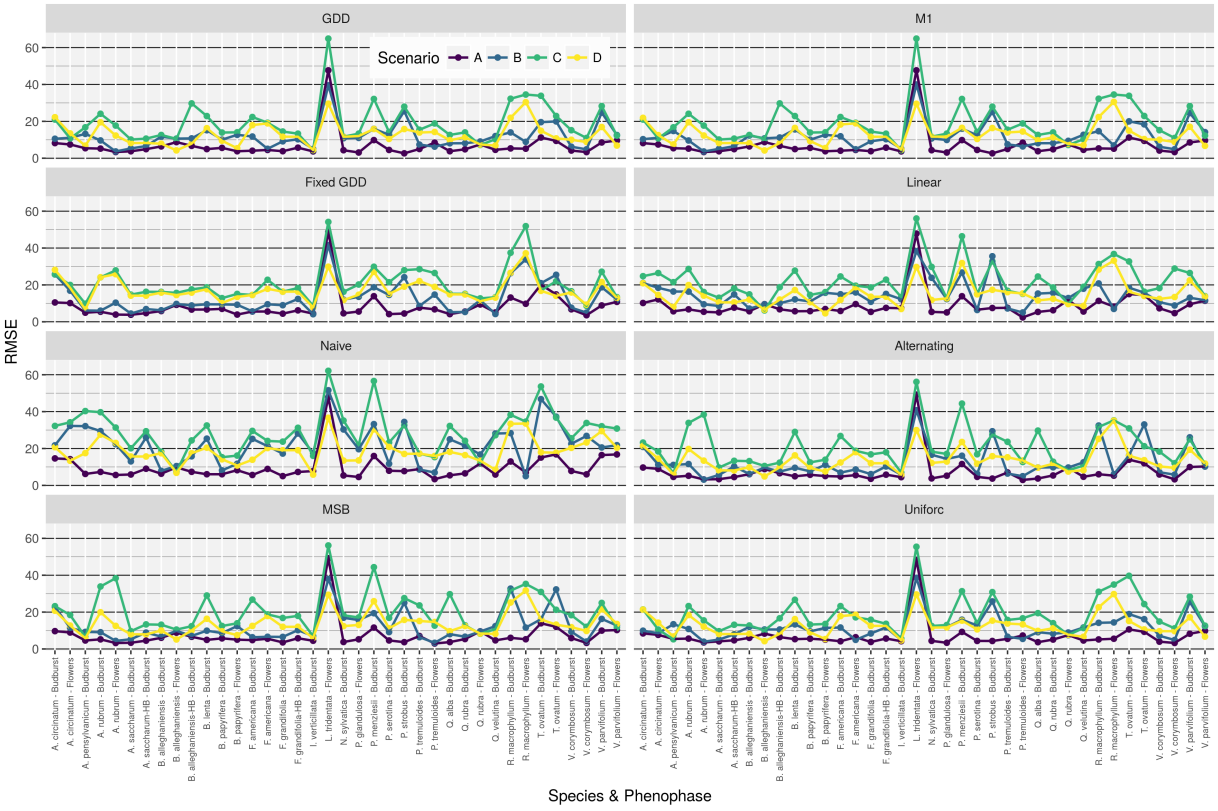
GDD
M1
Fixed GDD
Linear
Naive
Alternating
MSB
Uniforc
Scenario A B C D
RMSE
0
20
40
60
A. circinatum - Budburst
A. circinatum - Flowers
A. pensylvanicum - Budburst
A. rubrum - Budburst
A. rubrum - Flowers
A. saccharum - Budburst
A. saccharum-HB - Budburst
B. alleghaniensis - Budburst
B. alleghaniensis - Flowers
B. alleghaniensis-HB - Budburst
B. lenta - Budburst
B. papyrifera - Budburst
B. papyrifera - Flowers
F. americana - Budburst
F. americana - Flowers
F. grandifolia - Budburst
F. grandifolia-HB - Budburst
I. verticillata - Budburst
L. tridentata - Flowers
N. sylvatica - Budburst
P. glandulosa - Flowers
P. menziesii - Budburst
P. serotina - Budburst
P. strobus - Budburst
P. tremuloides - Budburst
P. tremuloides - Flowers
Q. alba - Budburst
Q. rubra - Budburst
Q. rubra - Flowers
Q. velutina - Budburst
R. macrophyllum - Budburst
R. macrophyllum - Flowers
T. ovatum - Budburst
T. ovatum - Flowers
V. corymbosum - Budburst
V. corymbosum - Flowers
V. parvifolium - Budburst
V. parvifolium - Flowers
Species & Phenophase

Figure S7

Figure S8: Distribution of parameters of the Naive, GDD, Fixed GDD, and Linear models for the three species common to the Hubbard Brook, Harvard, and USA-NPN datasets. The phenophase is budburst for all three species. Vertical lines indicate either the mean (solid) or median (dashed) of the respective distribution. Note the heading for each sub figure.

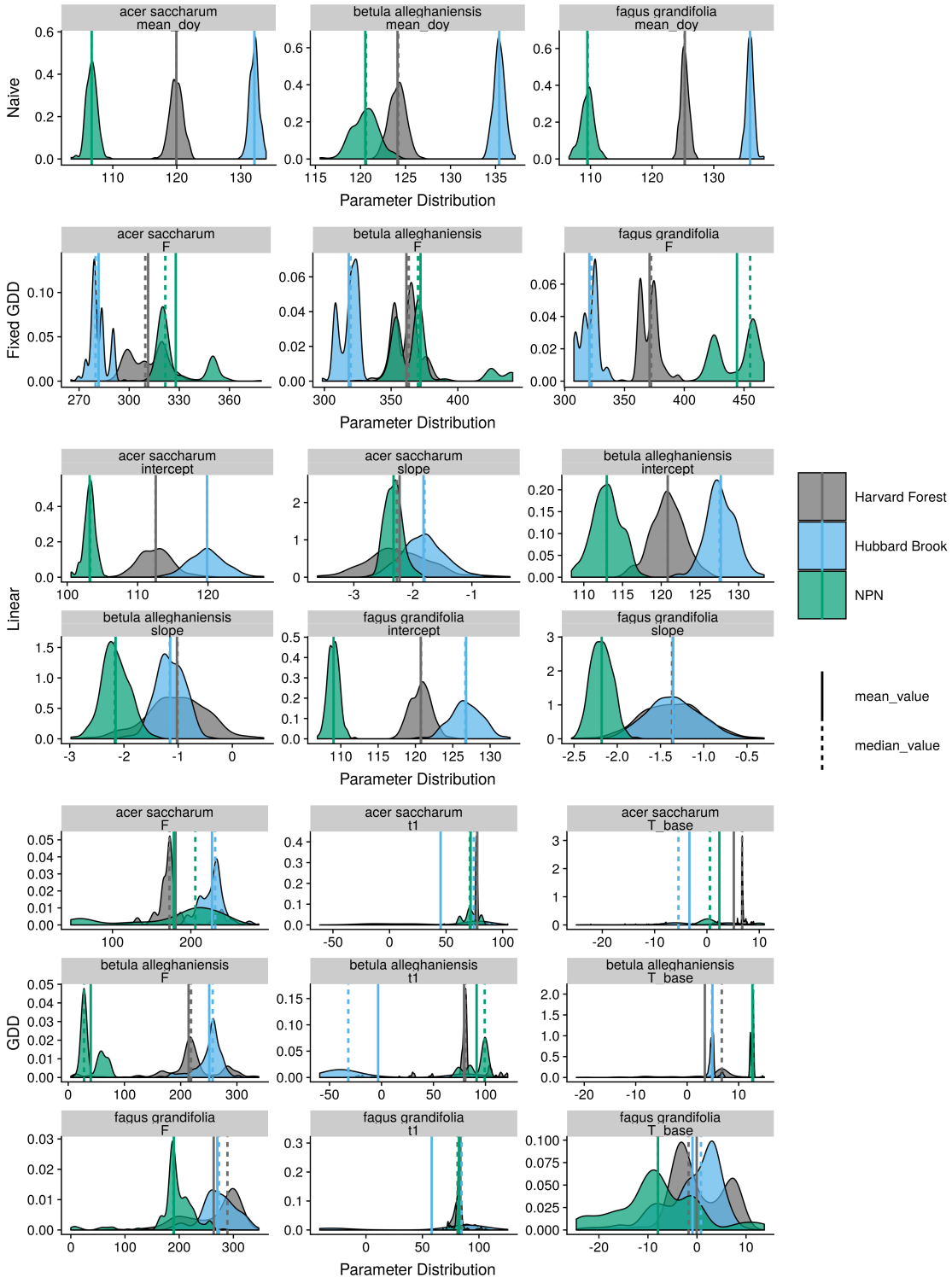
acer saccharum
mean_doy
betula alleghaniensis
mean_doy
fagus grandifolia
mean_doy
Naive
Parameter Distribution
acer saccharum
F
betula alleghaniensis
F
fagus grandifolia
F
Fixed GDD
Parameter Distribution
acer saccharum
intercept
acer saccharum
slope
betula alleghaniensis
intercept
betula alleghaniensis
slope
fagus grandifolia
intercept
fagus grandifolia
slope
Linear
Parameter Distribution
Harvard Forest
Hubbard Brook
NPN
mean_value
median_value
acer saccharum
F
acer saccharum
t1
acer saccharum
T_base
betula alleghaniensis
F
betula alleghaniensis
t1
betula alleghaniensis
T_base
fagus grandifolia
F
fagus grandifolia
t1
fagus grandifolia
T_base
GDD
Parameter Distribution

Figure S8

Figure S9: As in Figure S4, but for the Alternating and Uniforc models.

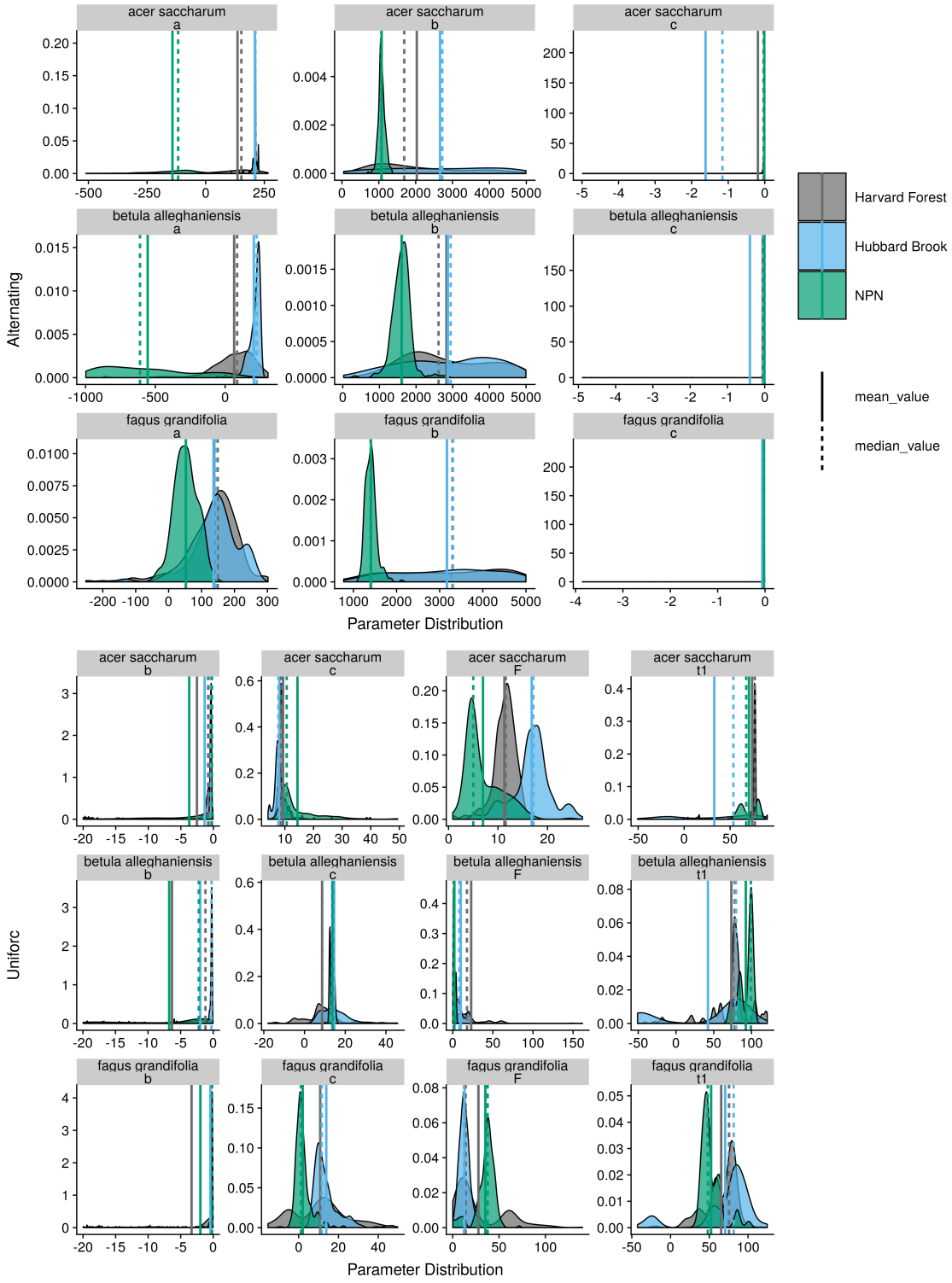
acer saccharum
a
b
c
betula alleghaniensis
a
b
c
fagus grandifolia
a
b
c
Alternating
Parameter Distribution
Harvard Forest
Hubbard Brook
NPN
mean_value
median_value
acer saccharum
b
c
F
t1
betula alleghaniensis
b
c
F
t1
fagus grandifolia
b
c
F
t1
Uniforc
Parameter Distribution

Figure S9

Figure S10: As in Figure S4, but for 4 selected species to show the difference in parameter distributions between LTER and USA-NPN derived models. The phenophase for the four species is budburst. These 4 species are representative of the analysis, and for the remaining comparisons the reader is pointed to the script 'analysis/plot_select_species_parameters.R' in the code repository to generate additional figures.

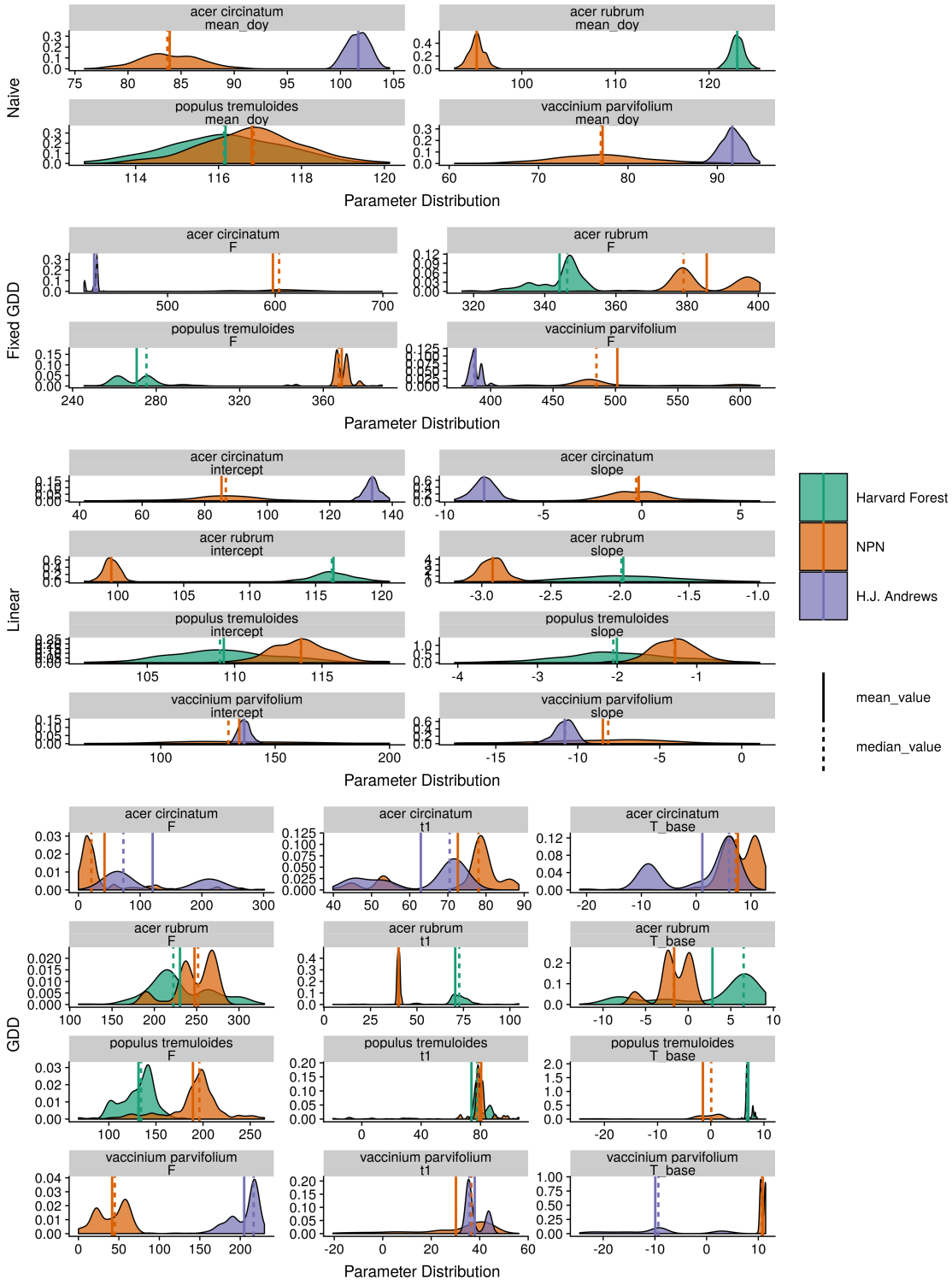
Naive
acer circinatum
mean_doy
acer rubrum
mean_doy
populus tremuloides
mean_doy
vaccinium parvifolium
mean_doy
Parameter Distribution
Fixed GDD
acer circinatum
F
acer rubrum
F
populus tremuloides
F
vaccinium parvifolium
F
Parameter Distribution
Linear
acer circinatum
intercept
acer circinatum
slope
acer rubrum
intercept
acer rubrum
slope
populus tremuloides
intercept
populus tremuloides
slope
vaccinium parvifolium
intercept
vaccinium parvifolium
slope
Parameter Distribution
Harvard Forest
NPN
H.J. Andrews
mean_value
median_value
GDD
acer circinatum
F
acer circinatum
t1
acer circinatum
T_base
acer rubrum
F
acer rubrum
t1
acer rubrum
T_base
populus tremuloides
F
populus tremuloides
t1
populus tremuloides
T_base
vaccinium parvifolium
F
vaccinium parvifolium
t1
vaccinium parvifolium
T_base
Parameter Distribution

Figure S10

Figure S11: As in Figure S6, but for the Alternating and Uniforc models.

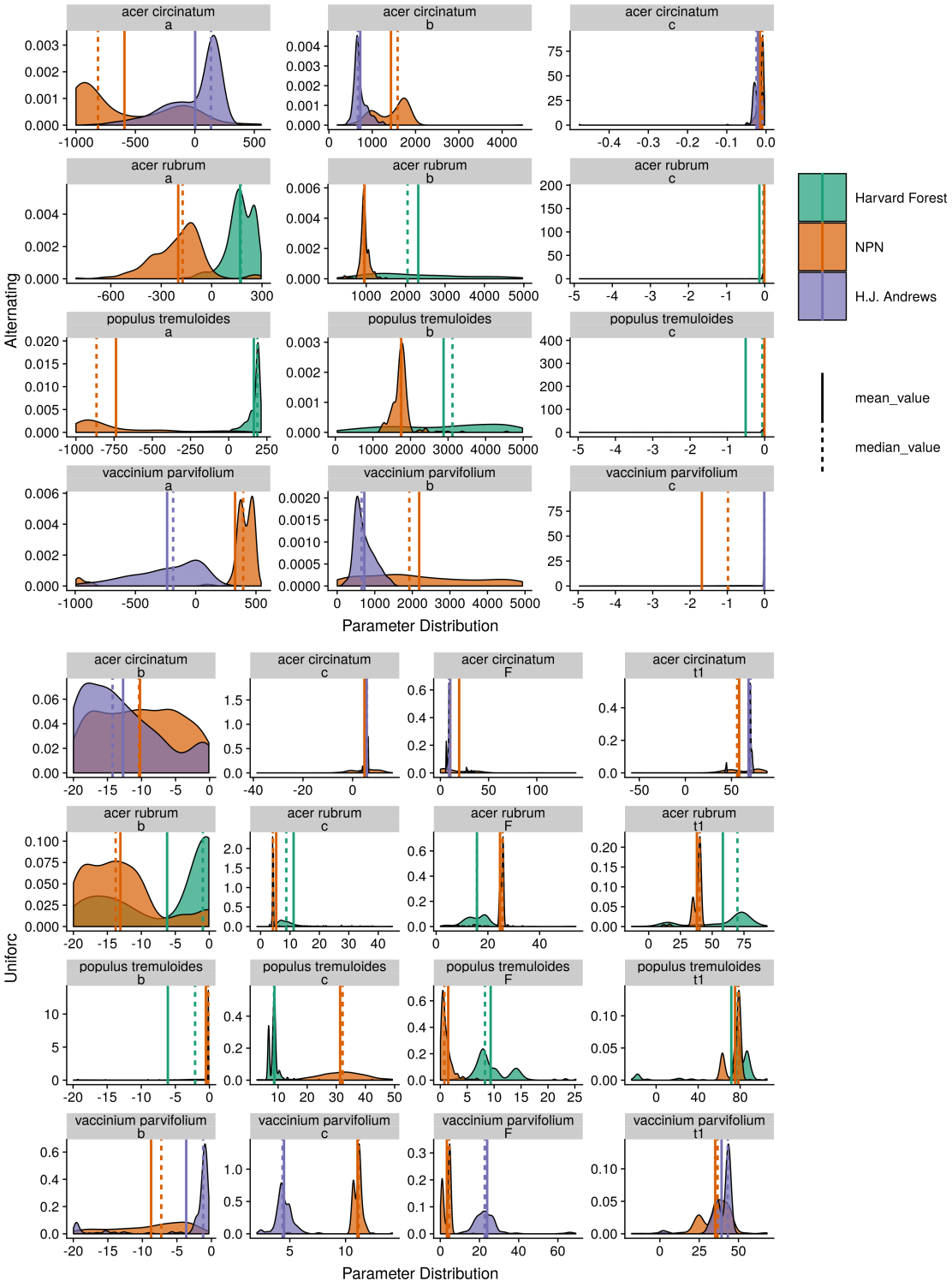
acer circinatum
a
b
c
acer rubrum
a
b
c
populus tremuloides
a
b
c
vaccinium parvifolium
a
b
c
Alternating
Parameter Distribution
Harvard Forest
NPN
H.J. Andrews
mean_value
median_value
acer circinatum
b
c
F
t1
acer rubrum
b
c
F
t1
populus tremuloides
b
c
F
t1
vaccinium parvifolium
b
c
F
t1
Uniforc
Parameter Distribution

Figure S11

Table S1: Species used in the analysis along with the sample size from each dataset. The numbers indicate the sample size of the training data and the size of the testing data in parenthesis.

species	phenophase	phenophase_type	harvard	hjandrews	hubbard	jornada	npn
acer circinatum	371	Budburst	-	266 (66)	-	-	39 (10)
acer circinatum	501	Flowers	-	116 (29)	-	-	33 (8)
acer pensylvanicum	371	Budburst	80 (20)	-	-	-	34 (9)
acer rubrum	371	Budburst	100 (25)	-	-	-	957 (239)
acer rubrum	501	Flowers	96 (24)	-	-	-	668 (167)
acer saccharum	371	Budburst	60 (15)	-	164 (41)	-	365 (91)
betula alleghaniensis	371	Budburst	60 (15)	-	178 (44)	-	133 (33)
betula alleghaniensis	501	Flowers	26 (7)	-	-	-	64 (16)
betula lenta	371	Budburst	58 (14)	-	-	-	96 (24)
betula papyrifera	371	Budburst	76 (19)	-	-	-	96 (26)
betula papyrifera	501	Flowers	18 (5)	-	-	-	36 (9)
fagus grandifolia	371	Budburst	76 (19)	-	177 (44)	-	259 (65)
fraxinus americana	371	Budburst	84 (21)	-	-	-	90 (23)
fraxinus americana	501	Flowers	22 (6)	-	-	-	52 (13)
ilex verticillata	371	Budburst	35 (9)	-	-	-	26 (6)
larrea tridentata	501	Flowers	-	-	-	27 (7)	118 (30)
nyssa sylvatica	371	Budburst	27 (7)	-	-	-	63 (16)
pinus strobus	496	Budburst	38 (10)	-	-	-	77 (19)
populus tremuloides	371	Budburst	38 (10)	-	-	-	208 (51)
populus tremuloides	501	Flowers	17 (4)	-	-	-	79 (22)
prosopis glandulosa	501	Flowers	-	-	-	49 (12)	78 (20)
prunus serotina	371	Budburst	58 (14)	-	-	-	228 (57)
pseudotsuga menziesii	480	Budburst	-	182 (46)	-	-	38 (10)
quercus alba	371	Budburst	62 (15)	-	-	-	174 (43)
quercus rubra	371	Budburst	80 (20)	-	-	-	242 (60)
quercus rubra	501	Flowers	56 (14)	-	-	-	127 (32)
quercus velutina	371	Budburst	77 (19)	-	-	-	72 (18)
rhododendron macrophyllum	371	Budburst	-	84 (21)	-	-	48 (12)
rhododendron macrophyllum	501	Flowers	-	27 (7)	-	-	50 (12)
trillium ovatum	488	Budburst	-	222 (55)	-	-	68 (17)
trillium ovatum	501	Flowers	-	169 (42)	-	-	60 (15)
vaccinium corymbosum	371	Budburst	38 (10)	-	-	-	60 (15)
vaccinium corymbosum	501	Flowers	38 (10)	-	-	-	65 (16)
vaccinium parvifolium	371	Budburst	-	149 (37)	-	-	25 (6)
vaccinium parvifolium	501	Flowers	-	162 (41)	-	-	25 (6)

Table S1

Table S2: Overall best models when doing cross dataset comparisons. Observations for all species and phenophases were aggregated together to calculate RMSE and Pearsons coefficient for each combination of Parameter source (either USA-NPN or LTER), observation source (either USA-NPN or LTER), and model (6 possible phenology models). Bold indicates the best performing model for a specific parameter and observation combination, with some combinations having ties among multiple models.

Table S2

Parameter Source	Held Out Observation Source	Alternating		Fixed GDD		GDD		Linear		M1		MSB		Naive		Uniforc	
		p	RMSE	p	RMSE	p	RMSE	p	RMSE	p	RMSE	p	RMSE	p	RMSE	p	RMSE
LTER	LTER	0.87	8.73	0.84	10.14	**0.90**	7.89	0.81	10.27	**0.90**	7.89	0.87	8.73	0.72	12.35	**0.90**	**7.86**
LTER	USA-NPN	0.44	26.07	**0.72**	22.70	0.68	20.52	0.65	22.94	0.68	20.52	0.44	26.07	0.34	31.25	0.70	**19.69**
USA-NPN	LTER	0.63	16.17	0.69	16.15	0.70	13.73	0.68	16.59	0.71	13.79	0.66	15.79	0.61	27.08	**0.72**	**13.48**
USA-NPN	USA-NPN	0.80	15.27	0.76	20.18	**0.82**	14.67	0.77	16.19	**0.82**	14.71	0.80	15.20	0.53	21.57	**0.82**	**14.37**