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A model of the within-population variability of budburst in forest trees

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Table S1. Observation interval in % and in days for three species.

Species	Observation interval in %	Observation interval in days
Carpinus betulus	23	3.90
Castanea sativa	20	3.61
Quercus petraea	20	3.12

Table S2. Initial parameter values used during the WPV model calibration procedure. μ (°C-days) and σ (°C-days) are the mean and standard deviation of the distribution of F*, respectively (Eqn. 1). T_b and T_c (°C) are the threshold temperatures for the accumulation of forcing and chilling temperatures, respectively (Eqns. 5 and 9). g ($^oC^{-1}$) and h (dimensionless) are the parameters determining the interactive effect of the state of rest break and the prevailing air temperature on the ontogenetic competence (Eqn. 6). Ccri (number of days) is the chilling requirement of rest completion.

Variables	Initial parameter
μ	100, 200
σ	10, 30
T_b	3, 6, 9
T_c	5, 10
g	0, 0.01, 0.03, 0.05
h	0.5, 0, -0.5, -1
Ccri	100, 150

Table S3. The difference of budburst (BP50, the date at which 50% trees have burst buds) between the Orsay and Barbeau sites, for hornbeam and oak over 2004-2022 and 2003-2022, respectively. Positive (negative) value mean budburst in Barbeau (Orsay) is earlier.

Species	Averaged difference of budburst between Orsay and Barbeau/days	Minimum difference of budburst between Orsay and Barbeau/days	Maximum difference of budburst between Orsay and Barbeau/days
Carpinus	-2	-12	+2
Quercus	-1	-4	+1

Table S4. The sensitivity to preseason temperature (4 months preceding budburst, calculated using the WPV model) for the start and end of budburst for three tree species during the period 1961-2022, respectively. P value and adjusted coefficient of determination (R^2adj) are shown.

Species	Temperature sensitivity of start of budburst BP20 (in Days/^{o}C)	R^2_{adj}	P	Temperature sensitivity of end of budburst BP80 (in Days/^{o}C)	R^2_{adj}	P
Carpinus betulus	-5.25	0.33	<0.001	-4.65	0.29	<0.001
Castanea sativa	-2.9	0.1	0.02	-2.82	0.05	0.04
Quercus petraea	-4.4	0.24	<0.001	-4.14	0.19	<0.01

Table S5. Sensitivity of budburst to mean spring temperature (from January to May) for 50% of budburst (BP50) in three tree populations during the periods 1976-1984 and 1992-2006. Validation values are taken from Vitasse et al. (2009, their Table 4) (*: P<0.05, **:P<0.01, ***: P<0.001).

	Simulations from WPV model				Values from Vitasse et al.		
	Orsay		Orsay		Fontainebleau		Pyrénées
Species	Sensitivity of BP50 to decade (days per decade)	R^2	Sensitivity of BP50 to temperature (days per °C)	R^2	Sensitivity of BP50 to decade (days per decade)	Sensitivity of BP50 to temperature (days per °C)	Sensitivity of BP50 to temperature (days per °C)
Carpinus	-2.6	0.03	-8.8***	0.56	-1.80	-4.58*	
Quercus	-4.4*	0.21	-8.6***	0.64	-4.20*	-7.26**	-7.48***
Castanea	-5.0**	0.27	-6.9***	0.38			

Fig. S1. The flow diagram of the within-population variability (WPV) model for budburst. In short, the model represents the release of endodormancy through the accumulation of chilling temperatures and simulates the ontogenetic growth of the buds through the accumulation of forcing temperatures. One particularity of the model is that ontogenetic growth is regulated by the state of dormancy release and prevailing temperatures (Lundell et al. 2020). In the WPV model, we assumed that F* follows a normal distribution at the level of the tree population. At a given date, the proportion of trees that fulfilled a level of the forcing requirement are regarded as the percentage of trees to have burst buds in the population.

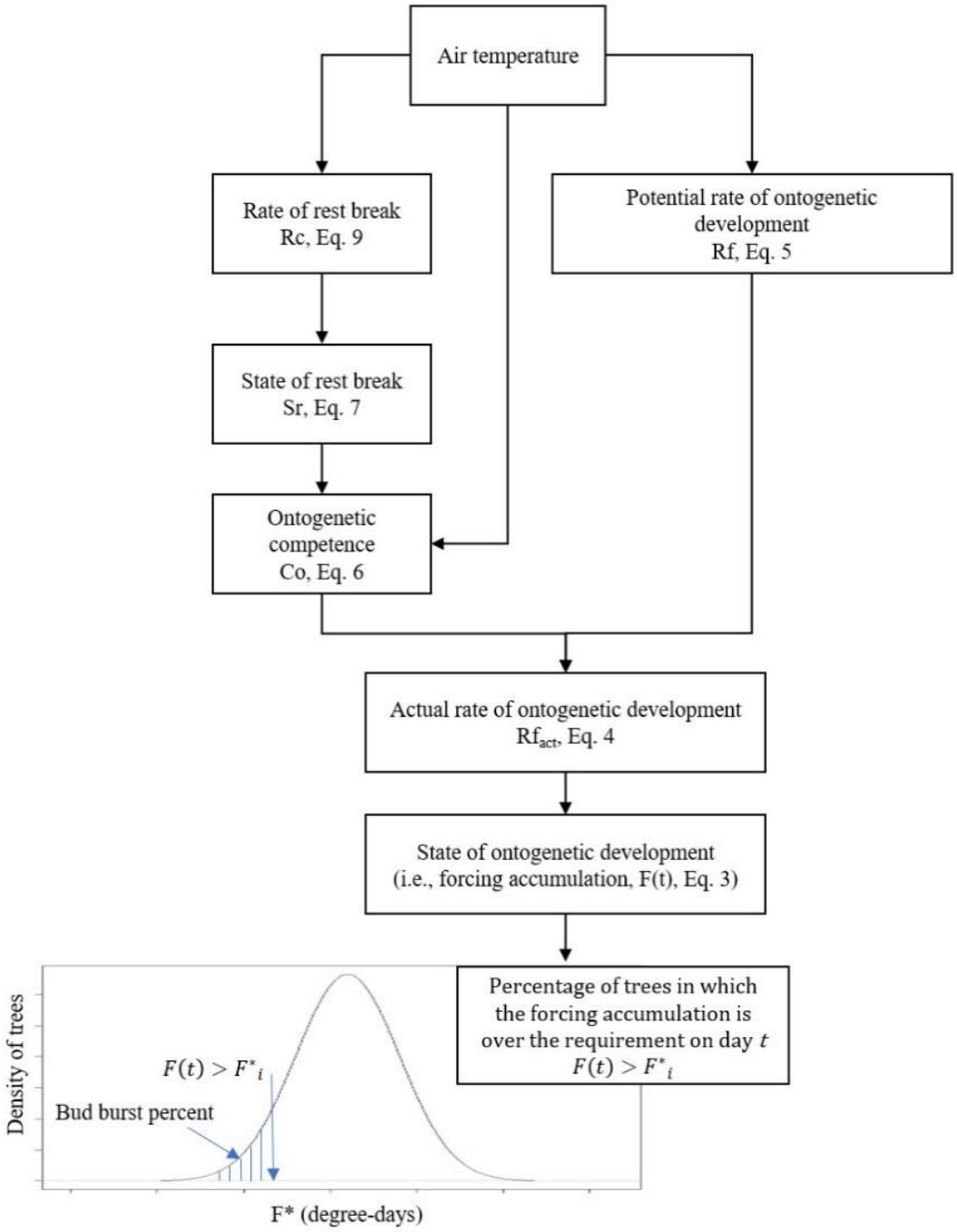


Fig. S2. Response of (a) the rate of chilling accumulation, (b) the rate of forcing accumulation to temperature, and (c,d,e) the response of ontogenetic growth (Co) to state of rest break (Sr) for the eight tree populations in the WPV model. Different colors represent the different species. Because of the same threshold of chilling accumulation (T_c) for hornbeam and oak, we changed here T_c slightly for hornbeam (from 10.5°C to 10.4°C) for sake of figure clarity. To illustrate the response of Co to the interaction between Sr and prevailing temperatures, we set a gradient of the prevailing temperatures (0°C, 10°C, and 20°C in subplots c to e).

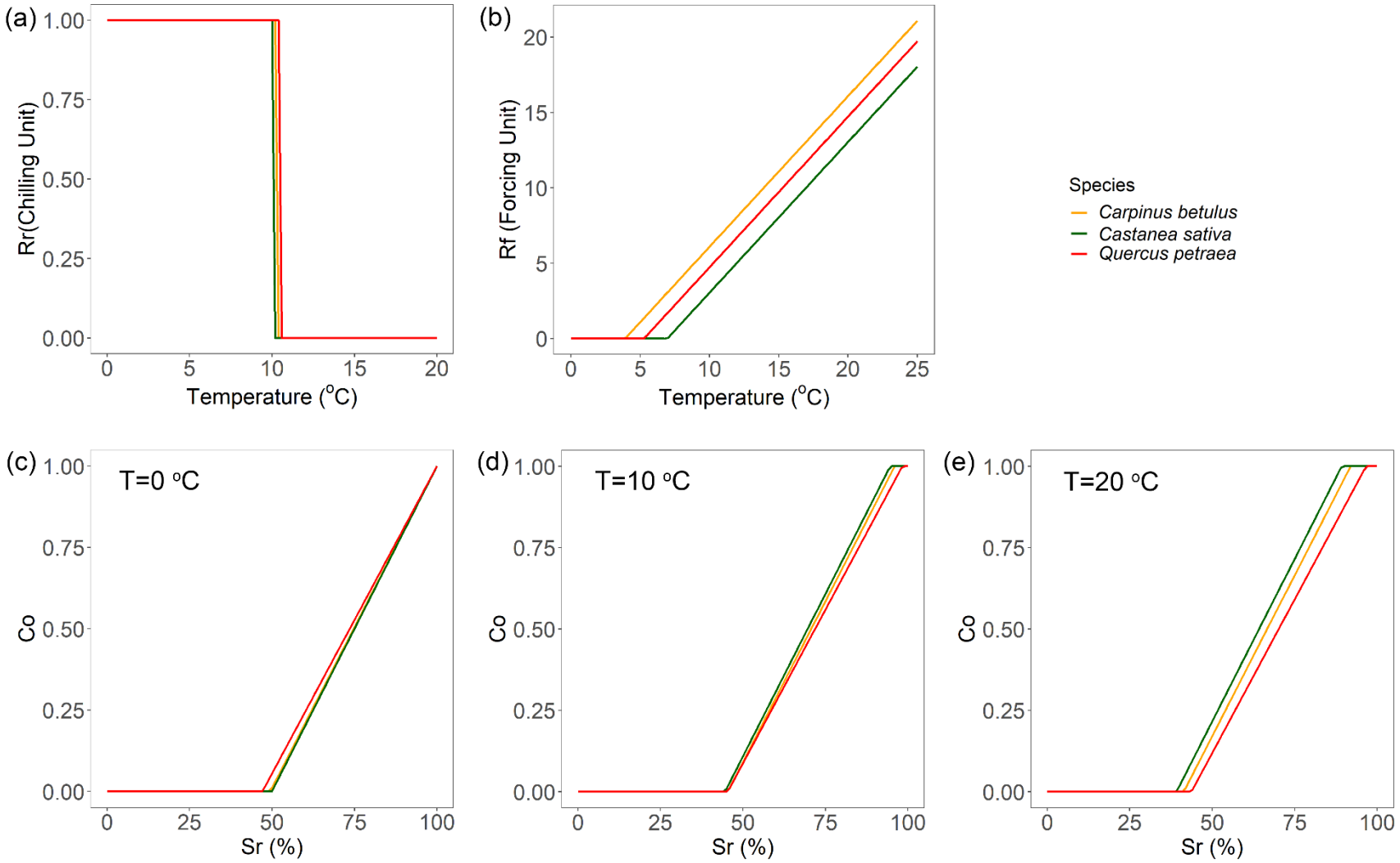


Fig. S3. Calculation of the root mean square error (RMSE) illustrated over two dimensions. $RMSE_{BP}$ is calculated over the percentage of budburst (BP) in the tree population (i.e., comparing the difference, in percent, between the observation and prediction of the budburst percent on the same day of the year, DoY). $RMSE_{DoY}$ is calculated over dates (i.e., comparing the difference, in number of days, between the observation and prediction for the same percentage of budburst).

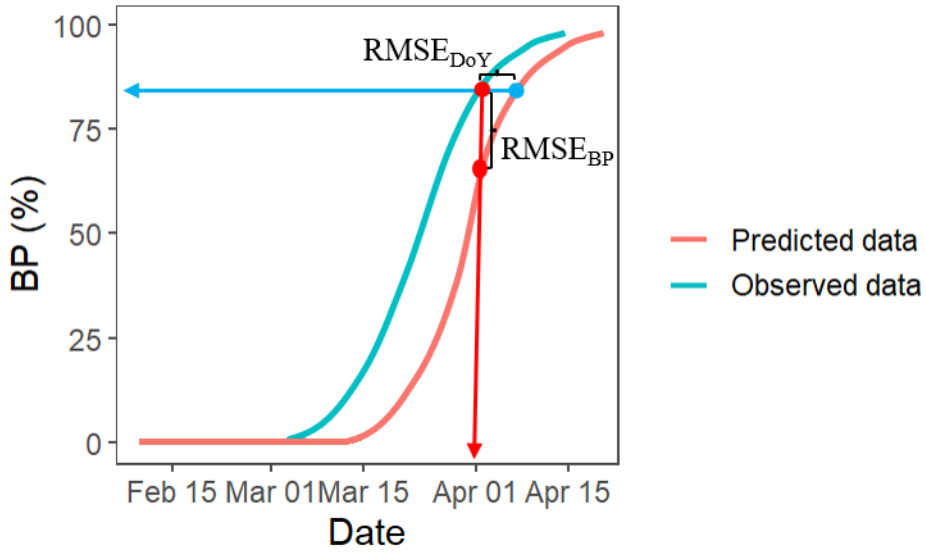


Fig. S4. The relation between root mean square error of the multi-objective aggregated cost function ($RMSE_{tot}$) and its components $RMSE_{BP}/INT_{BP}$, subplots (a, c, e) and $RMSE_{DoY}/INT_{DOY}$, subplots (b, d, f).. Each point represents the RMSE obtained for one iteration of the model calibration procedure, using the optim function (there are 150 points per figure, corresponding to 150 runs with low $RMSE_{BP}/INT_{BP}$ or $RMSE_{DoY}/INT_{DoY}$ among 768 runs of the option function starting from a particular, random location in the parameter space, see main text). The blue point identifies the minimum values obtained over $RMSE_{BP}/INT_{BP}$ or $RMSE_{DoY}/INT_{DoY}$ (i.e., minimum over the x-axis). The red point identifies the minimum obtained over $RMSE_{tot}$ (i.e., minimum over the y-axis). Red point is hidden by blue point in subplot (b) because the minima of $RMSE_{BP}/INT_{BP}$ or $RMSE_{DoY}/INT_{DoY}$ and $RMSE_{tot}$ are equal.

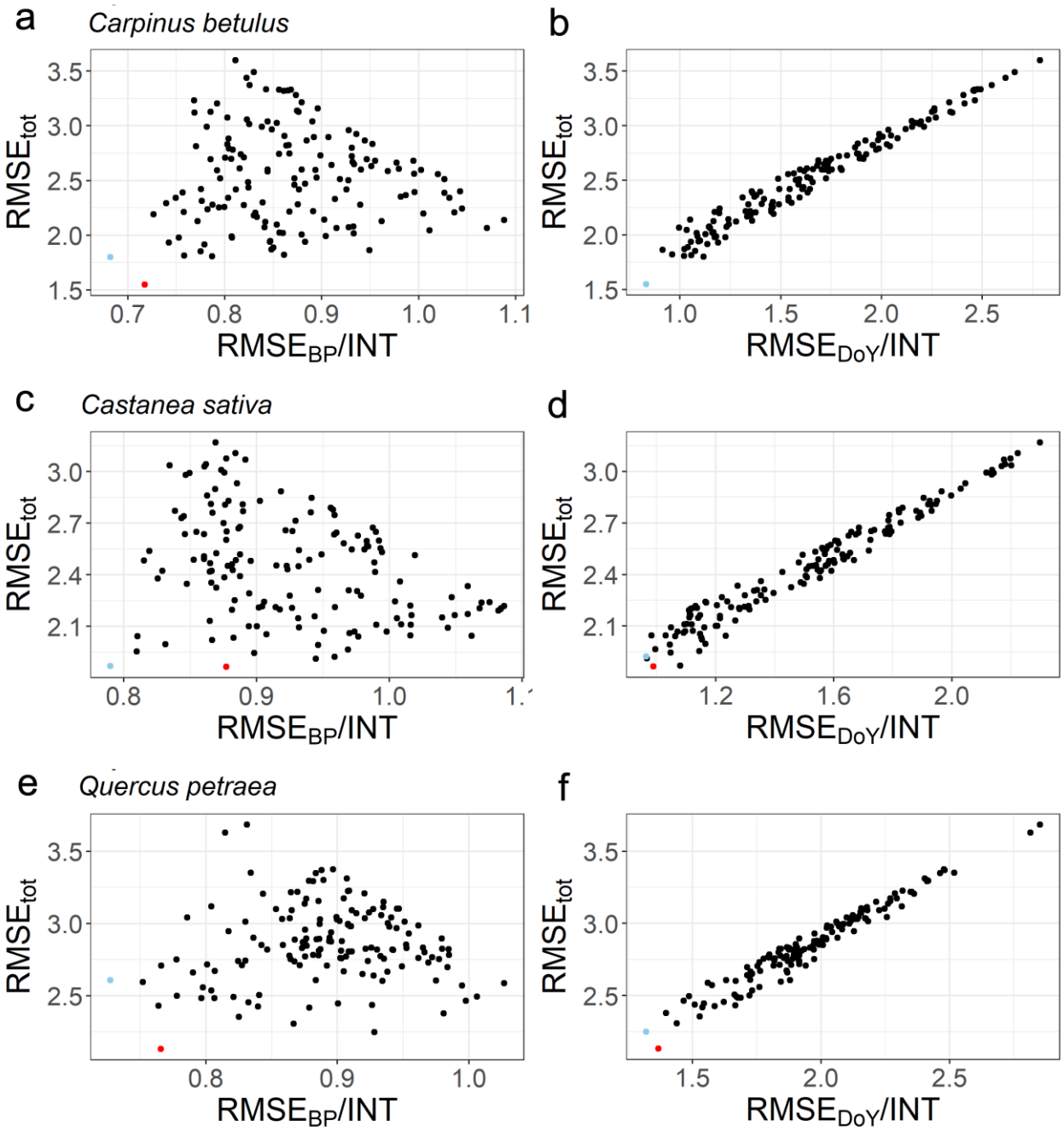
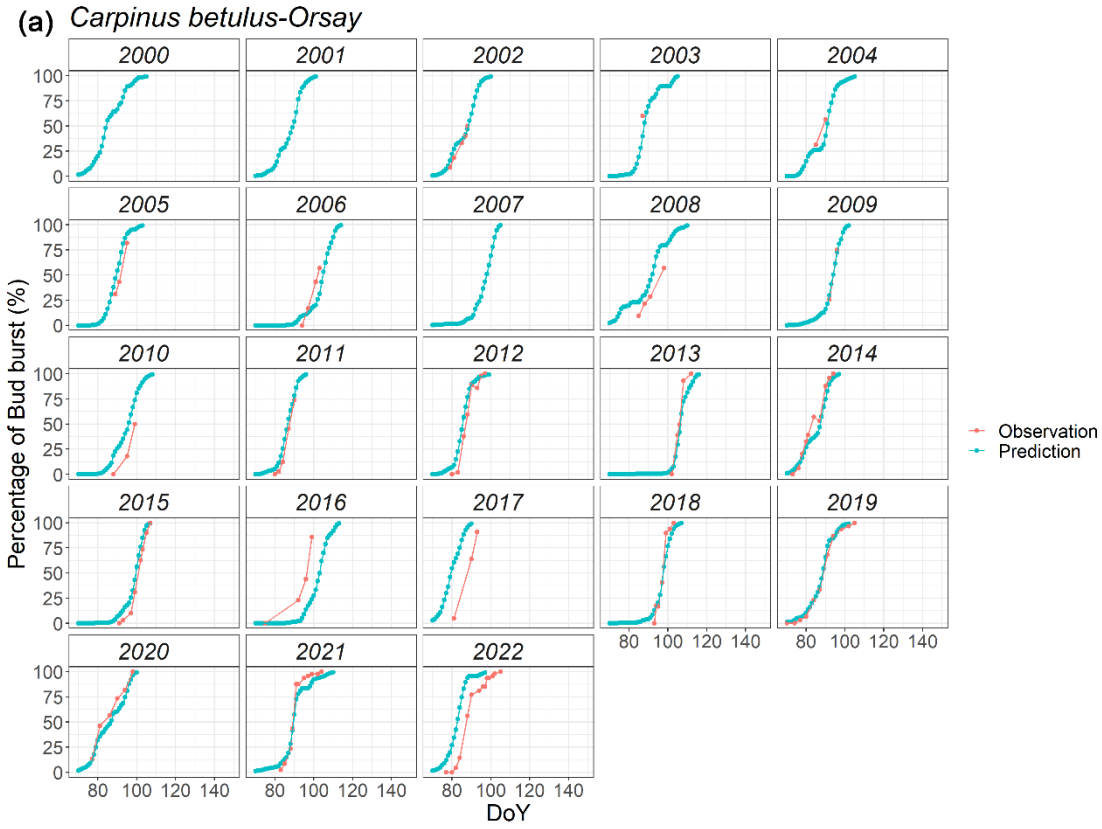
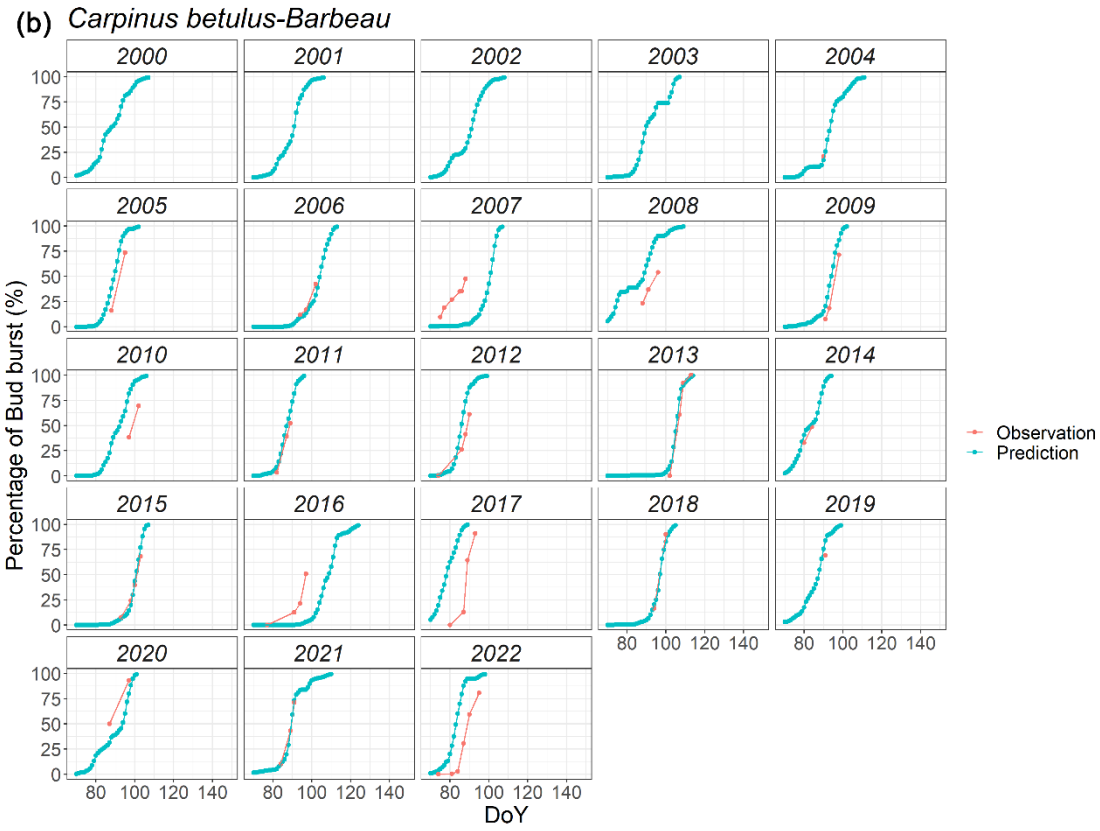
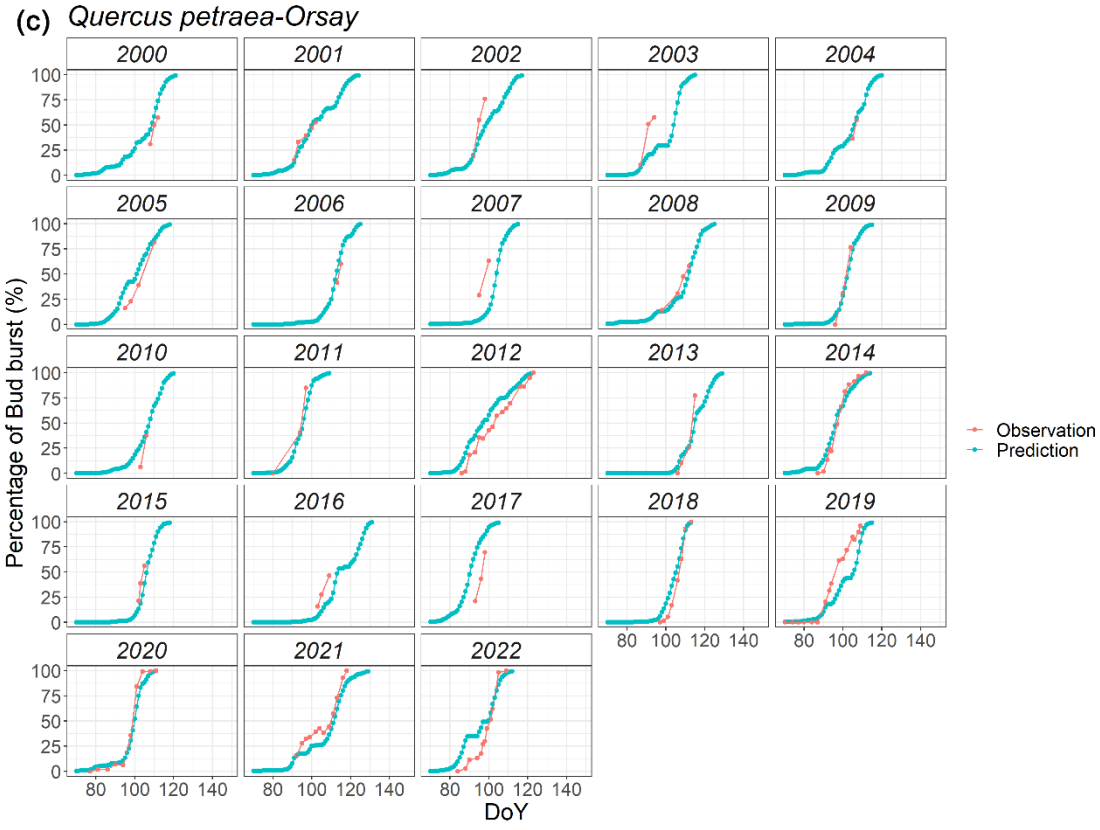


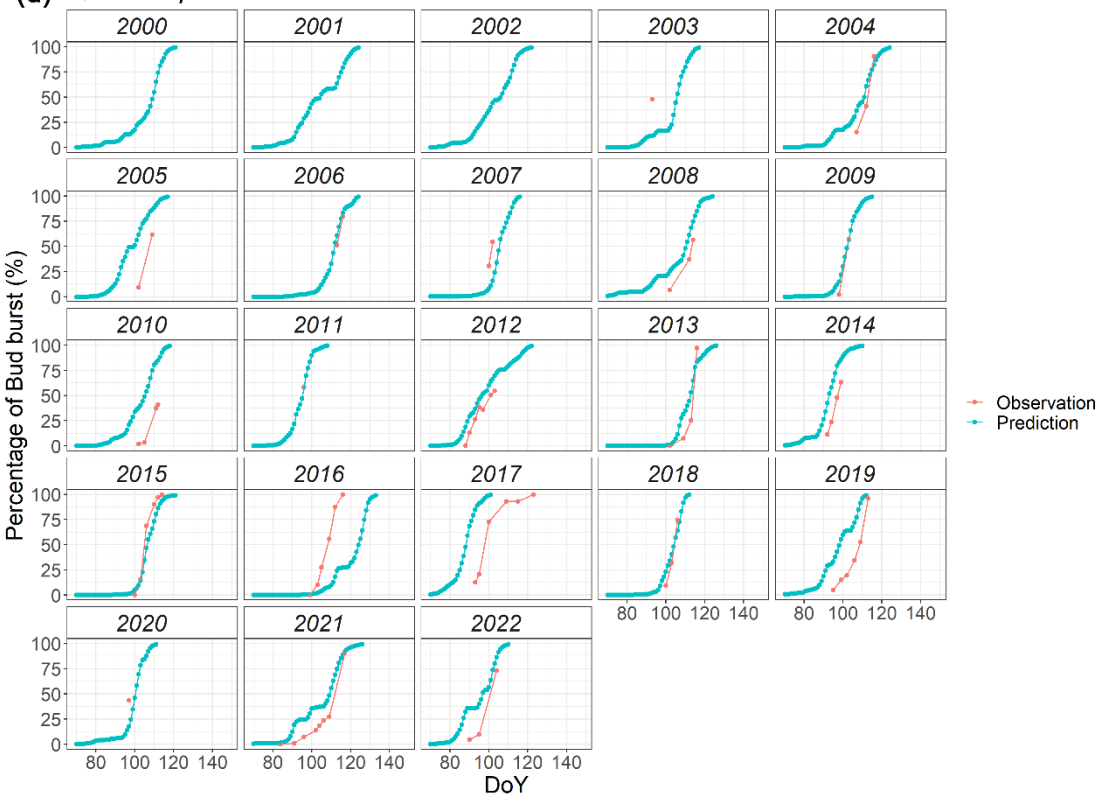
Fig. S5. Dynamics of budburst percent (BP) in five tree populations during the period 2000-2022. The blue points and blue lines are simulated by WPV model. The red points and red lines are observation data.




(b) Carpinus betulus-Barbeau
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
Percentage of Bud burst (%)
0
25
50
75
100
80
100
120
140
DoY
Observation
Prediction


(c) Quercus petraea-Orsay
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
Percentage of Bud burst (%)
0
25
50
75
100
80
100
120
140
DoY
Observation
Prediction

(d) *Quercus petraea-Barbeau*



(e) *Castanea sativa-Orsay*

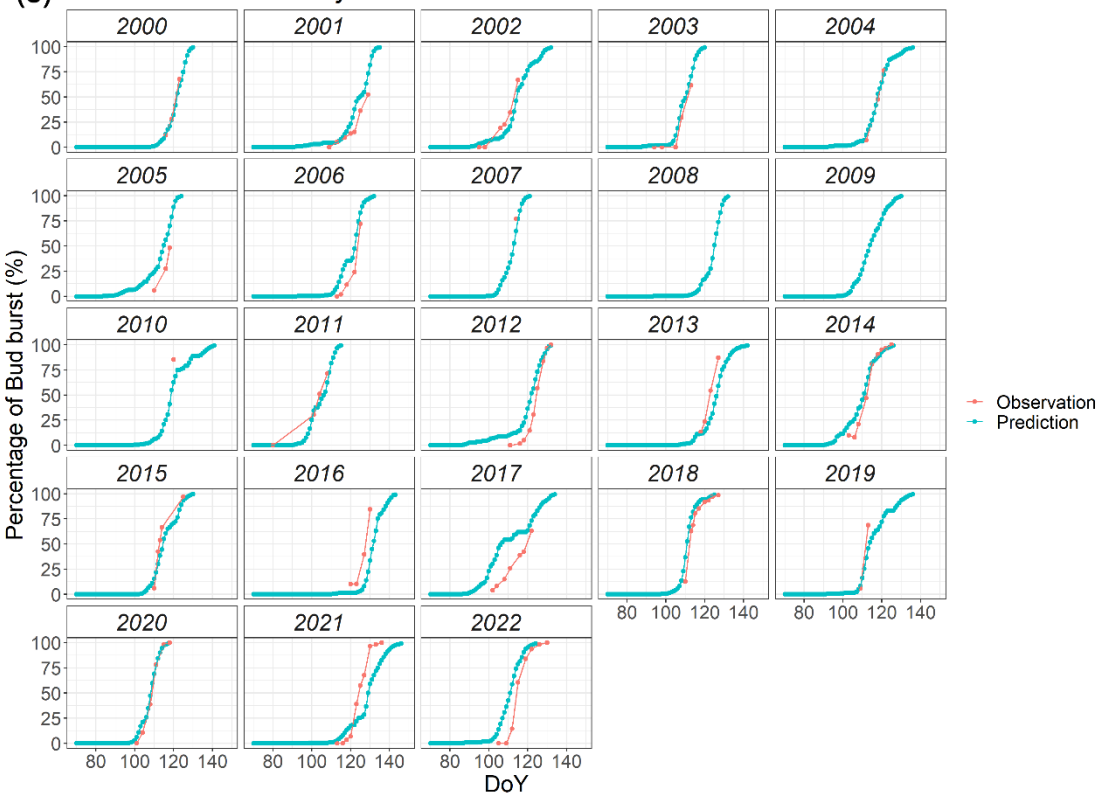


Fig. S6. Mean spring (January to May) air temperature in Barbeau and Orsay during the period 1961-2022.

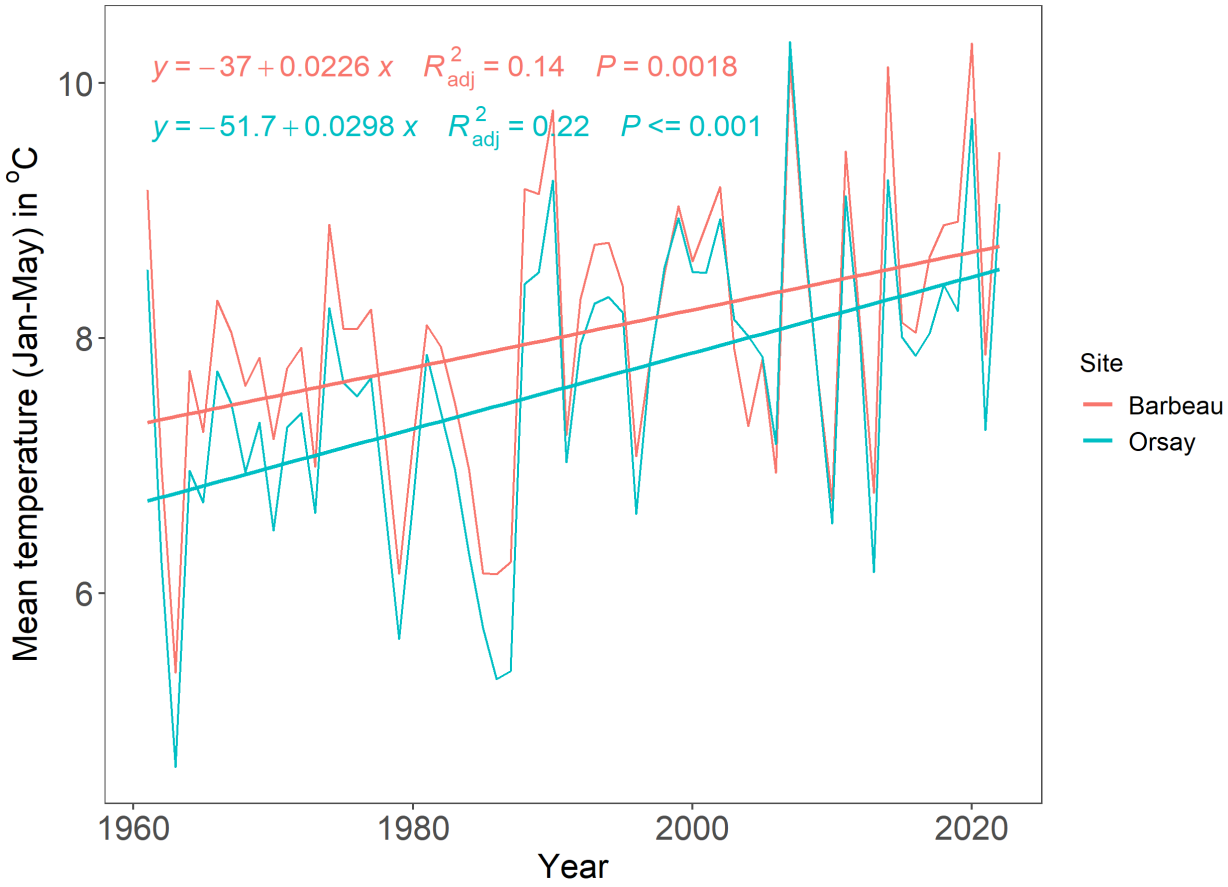
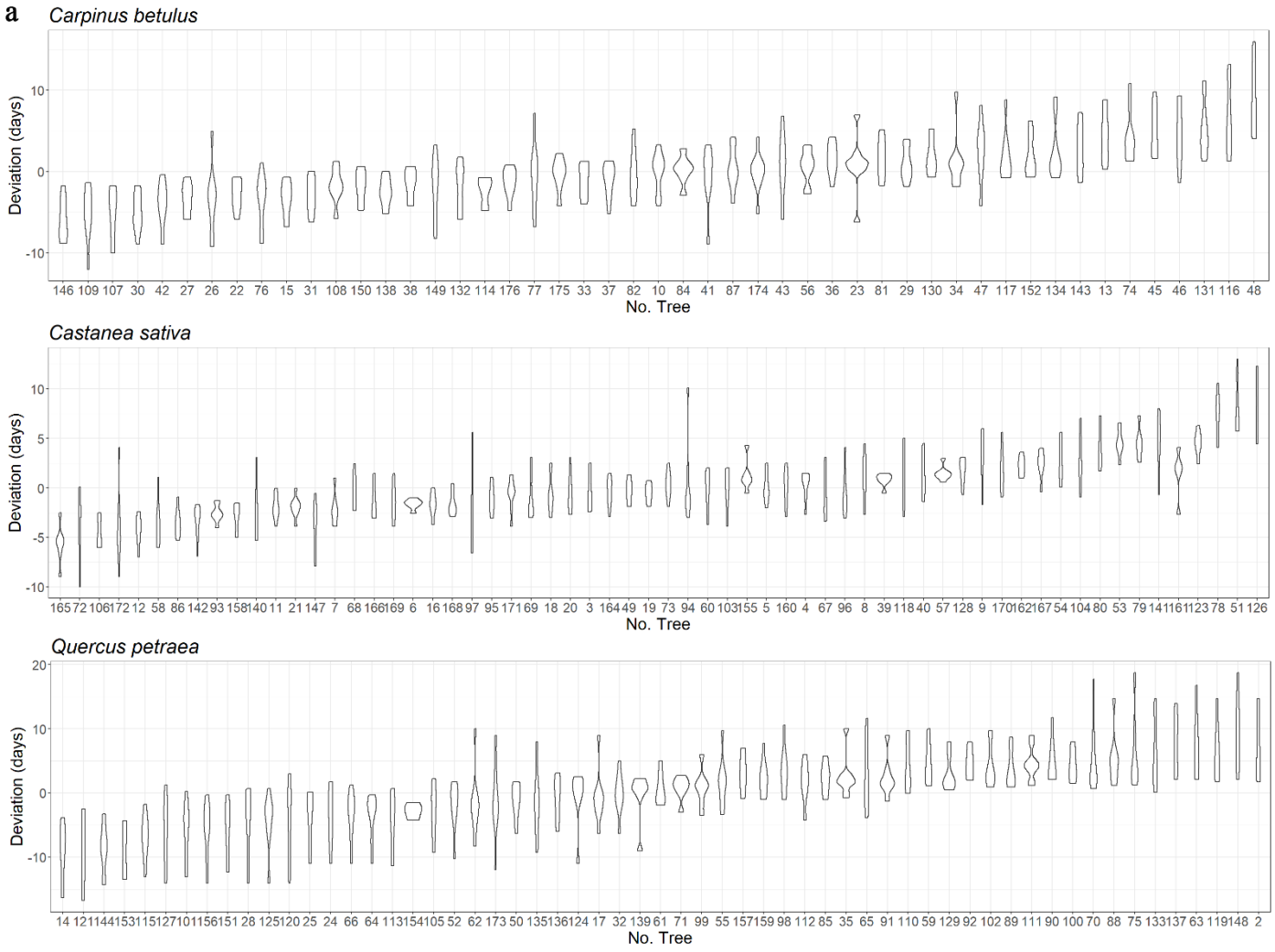


Fig. S7. Tree individual deviations of budburst (a) and tree individual forcing accumulation (b) for three tree species in Orsay in 2012-2022. Deviations were calculated annually for each tree, as the individual deviation of phenological event with respect to the within-population annual average. Forcing accumulation was calculated based on WPV model.



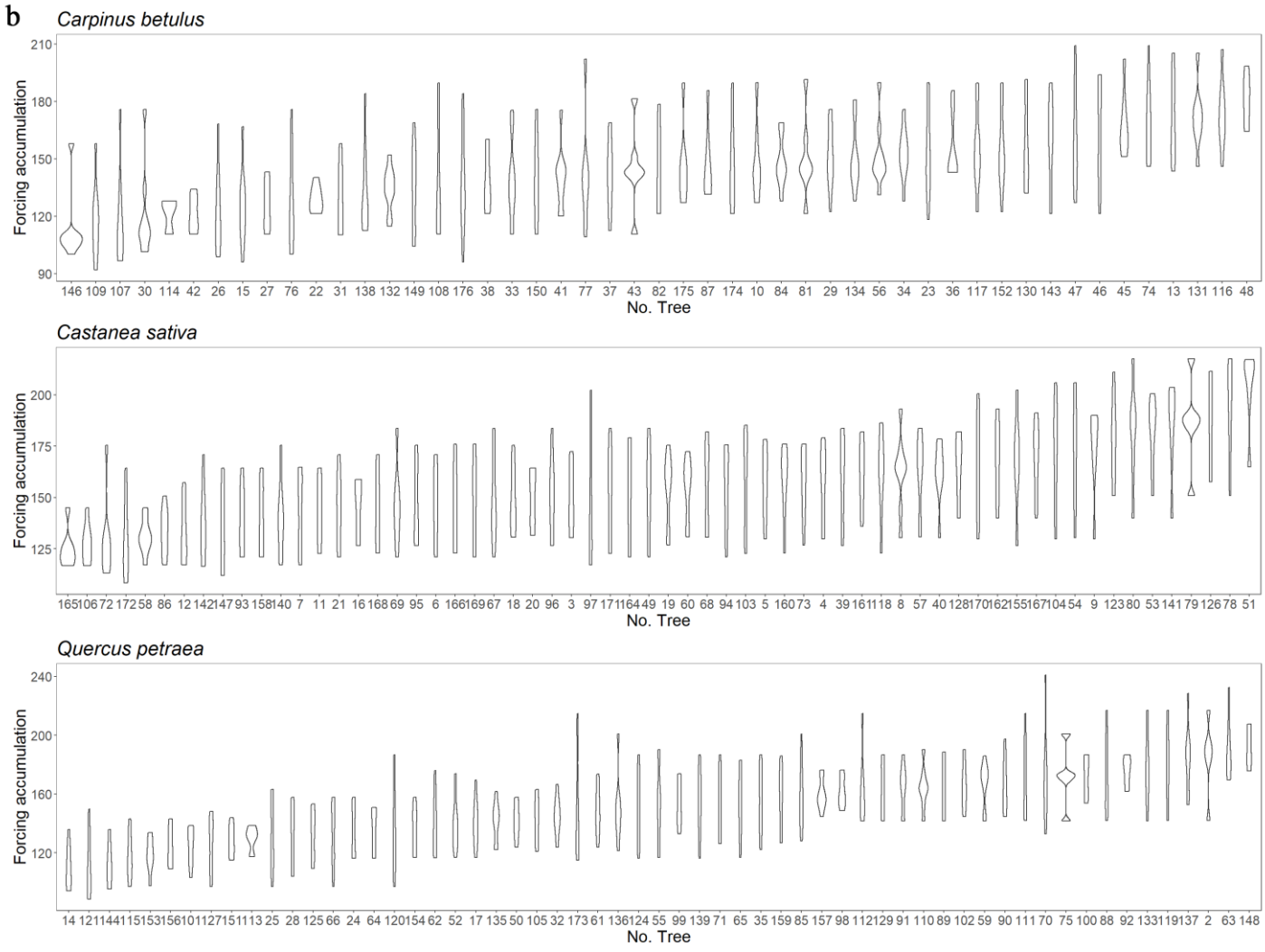

b
Carpinus betulus
Forcing accumulation
210
180
150
120
90
146 109 107 30 114 42 26 15 27 76 22 31 138 132 149 108 176 38 33 150 41 77 37 43 82 175 87 174 10 84 81 29 134 56 34 23 36 117 152 130 143 47 46 45 74 13 131 116 48
No. Tree
Castanea sativa
Forcing accumulation
200
175
150
125
165 106 72 172 58 86 12 142 147 93 158 140 7 11 21 16 168 69 95 6 166 169 67 18 20 96 3 97 171 164 49 19 60 68 94 103 5 160 73 4 39 161 118 8 57 40 128 170 162 155 167 104 54 9 123 80 53 141 79 126 78 51
No. Tree
Quercus petraea
Forcing accumulation
240
200
160
120
14 121 144 115 153 156 101 127 151 113 25 28 125 66 24 64 120 154 62 52 17 135 50 105 32 173 61 136 124 55 99 139 71 65 35 159 85 157 98 112 129 91 110 89 102 59 90 111 70 75 100 88 92 133 119 137 2 63 148
No. Tree

Fig. S8. Evaluation of the within-population variability (WPV) model, assuming that the WPV of budburst stems from the threshold of the forcing temperature (T_b) following a normal distribution. Validation data are in blue, and calibration data are in red. A point represents observed data on one day for the population in a given year. The one-to-one relation is shown as the black line. RMSE is root mean square error for the budburst percentage.

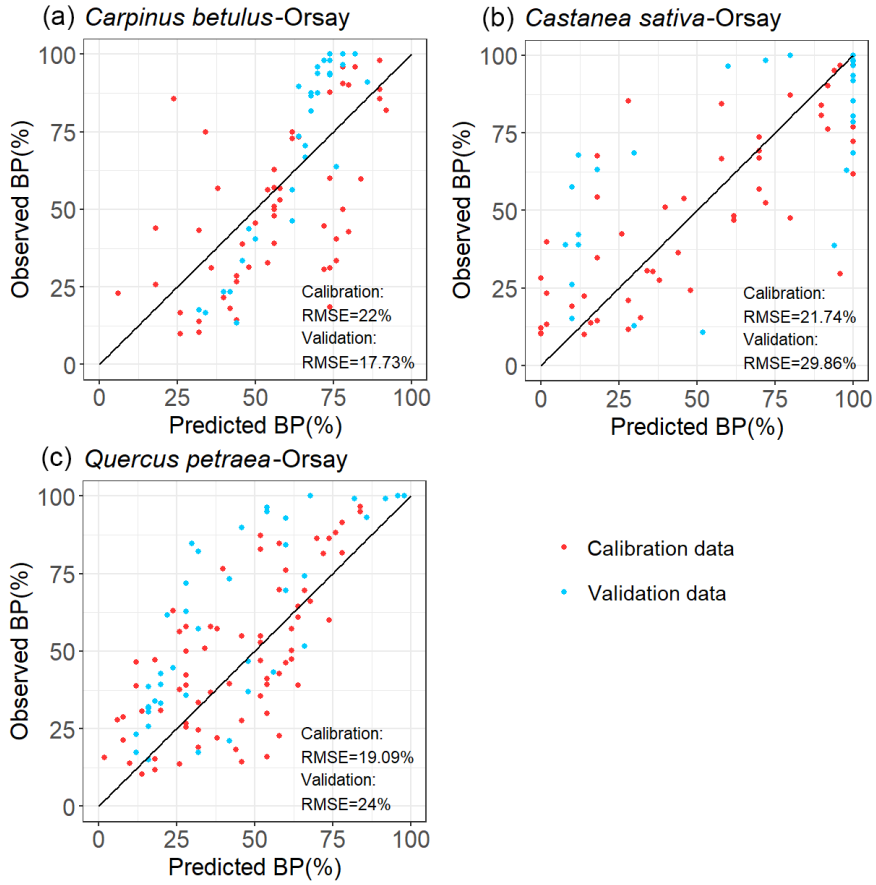


Fig. S9. Evaluation of the within-population variability (WPV) model, assuming that the WPV of budburst stems from the threshold of the forcing temperature (T_b) following a normal distribution. Validation data are in blue, and calibration data are in red. A point represents observed data on one day for the population in a given year. The one-to-one relation is shown as the black line. RMSE is root mean square error for the day of budburst (in days).

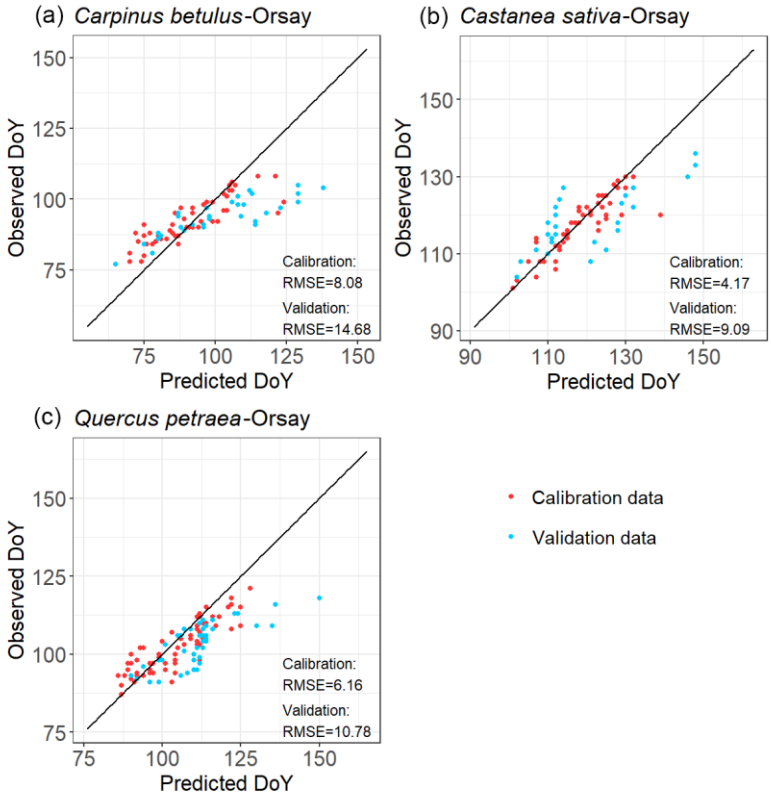


Fig.S10. Mean air temperature during budburst period (BP20 to BP80) in Orsay during the periods 1961-2022. Remember that the time period from BP20 to BP80 changes from year to year, as simulated by the WPV model (see Fig. 5).