Table S1. Plant species investigated in this study, and the abbreviation, number of observation sites and number of phenological records on the leaf unfolding day (LUD) for each species.

Plant species	Abbreviation	Number of observation sites	Number of LUD records
Aesculus hippocastanum	*Ah*	1156	53309
Alnus glutinosa	*Ag*	409	17542
Betula pendula	*Bp*	1132	51250
Fagus sylvatica	*Fs*	2886	184759
Fraxinus excelsior	*Fe*	488	21756
Quercus robur	*Qr*	816	36675
Total		6887	365291

Table S2. Optimized parameters of the unified phenology model and the setting of prior value and range of each parameter when conducting the parameter optimization.

Parameter	Definition	Prior value	range
d_{c0}	Start day of chilling accumulation	0	-120 – 60
CHA_0	Critical chilling requirement for releasing bud dormancy	20	0 – 50
T_{op}	Optimal chilling temperature	0	-5 – 15
c_1	Coefficient in Eq.1	0.01	0 – 1
c_2	Coefficient in Eq.1	0.01	0 – 50
c_3	Coefficient in Eq.2	-1	-10 – 0
c_4	Coefficient in Eq.2	10	-5 – 20
c_5	Coefficient in Eq.3	10	0 – 150
c_6	Coefficient in Eq.3	-0.01	-0.1 – 0

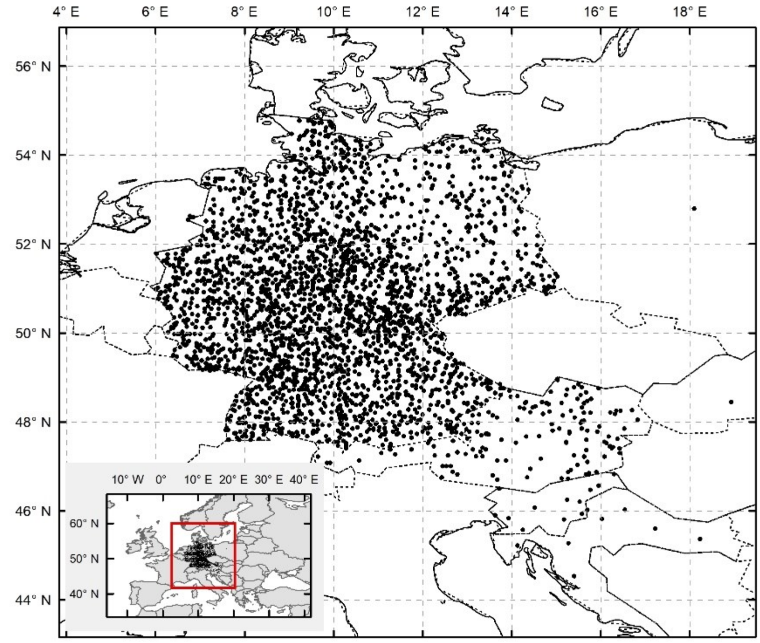

Figure S1 | Geographical locations of the 2898 phenological observation sites included in this study.

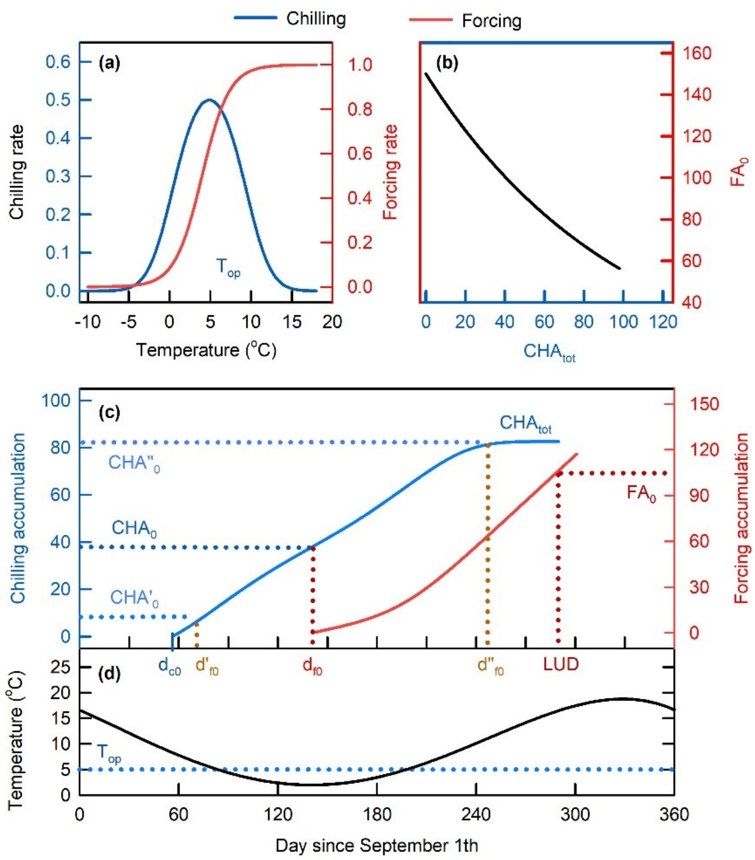

Figure S2 | Schematic plot of the unified phenological model. T_{op} is the optimal chilling temperature (°C). CHA_0, CHA'_0 and CHA''_0 are the critical chilling requirements for releasing dormancy. CHA_{tot} is the total chilling accumulation in the during the whole pre-growing season. FA_0 is the critical forcing requirements for leaf. d_{c0} is the start day of chilling accumulation. d_{f0}, d'_{f0} and d''_{f0} are the start day of forcing accumulation (time when dormancy is released) when chilling requirement equals to CHA_0, CHA'_0 and CHA''_0, respectively. LUD is the leaf unfolding day.

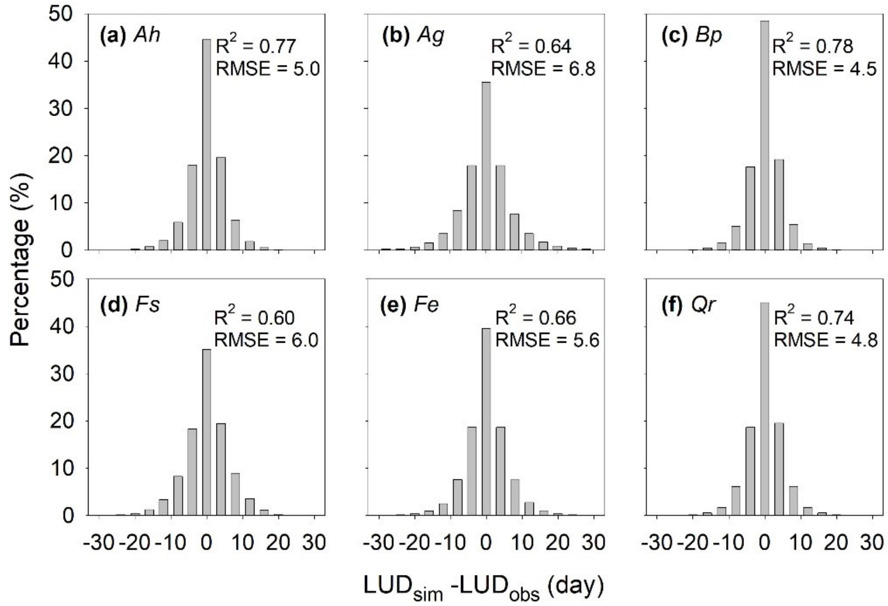

Figure S3 | Histogram of the errors in the LUD simulated by the unified phenological model. LUD_{sim} and LUD_{obs} are the simulated and observed LUD, respectively. R^2 for each species is the determining coefficient of the linear regression function between observed and simulated LUD. RMSE is the root mean square error of all simulated LUD for each species.

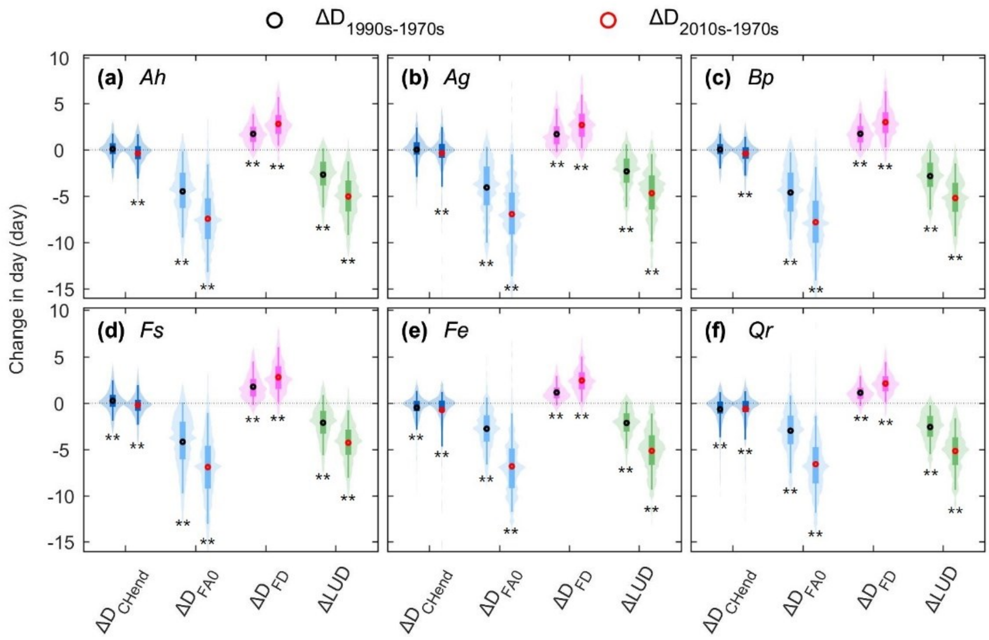

Figure S4 | Changes in the leaf unfolding days (ΔLUD) of six plant species in Europe from 1951 to 2014 and the potential contributions of changes in winter chilling and spring forcing to the ΔLUD. ΔD_{CHend} is the changes in date when dormancy is released. ΔD_{FD} is the potential changes in the duration (day) of forcing stage caused by changes in spring forcing temperatures. ΔD_{FA0} is the potential changes in the duration (in day) of forcing accumulation stage caused by rising forcing requirement due to chilling deficiency. Violins with the black and red dots show the changes of each variable from 1951-1980 to 1981-2000 (black, $\Delta D_{1990s\text{-}1970s}$), and to 2001-2014 (red, $\Delta D_{2010s\text{-}1970s}$), respectively. In each violin plot, balloon representing the probability density distribution of each value. Whiskers indicate the interquartile (thick) and 95 % confidence intervals (thin). The asterisks (**) indicate changes which are significantly different from zero. *AH* denotes *Aesculus hippocastanum*; *AG* denotes *Alnus glutinosa*; *BP* is *Betula pendula*; *FS* is *Fagus sylvatica*; *FE* is *Fraxinus excelsior*; *QR* is *Quercus robur*. The asterisks (**) indicate the changes in LUD are significantly different from zero ($p<0.01$).

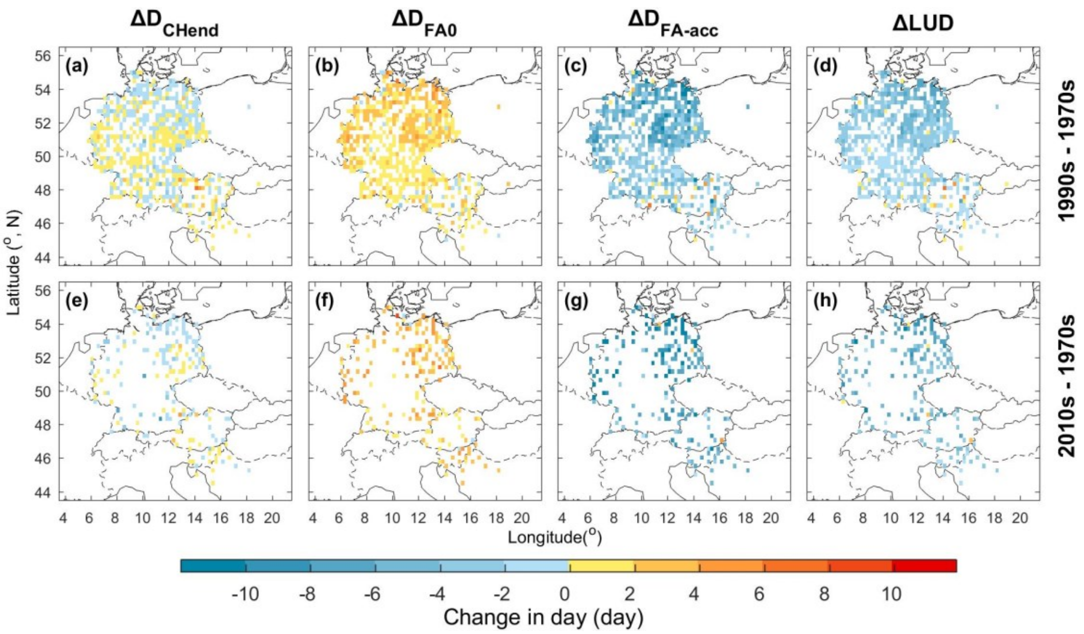

Figure S5 | Changes in the leaf unfolding days (ΔLUD) of six plant species in Europe from period 1951-1980 to 1981-2000 (1990s-1970s) and to 2001-2014 (2010s-1970s) and the potential contributions of changes in winter chilling and spring forcing to the ΔLUD. ΔD_{CHend} is the changes in date when dormancy is released. ΔD_{FD} is the potential changes in the duration (day) of forcing stage caused by changes in spring forcing temperatures. ΔD_{FA0} is the potential changes in the duration (in day) of forcing accumulation stage caused by rising forcing requirement due to chilling deficiency. As there may be phenological observations for multiple species at one sites, and locations of many sites can be very close to each other, here we only show the average change of each metrics for all samples within each 0.25°×0.25° grid cell.

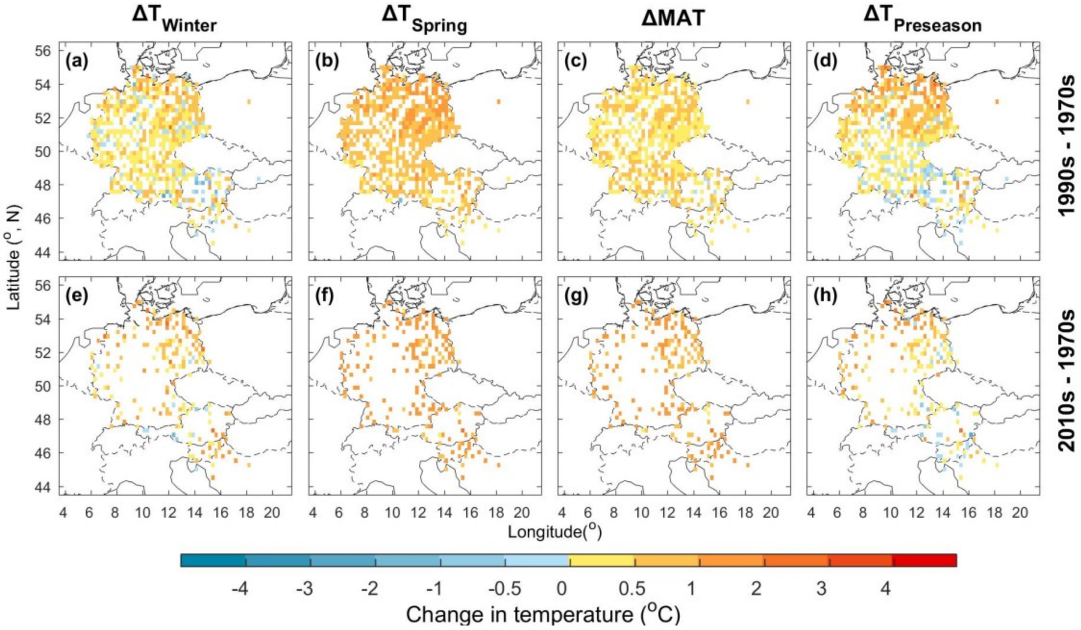

Figure S6 | Changes in mean winter temperature (ΔT_{winter}, °C), mean spring temperature (ΔT_{spring}, °C), mean annual temperature (ΔMAT, °C) and mean optimal preseason temperature ($\Delta T_{preseason}$, °C) in central Europe from period 1951-1980 to 1981-2000 (1990s-1970s) and to 2001-2014 (2010s-1970s). Here the winter season is defined as December-February, and spring is defined as March-May. The optimal preseason for each species at each site was defined as the period before the mean LUD for which the correlation coefficient between LUD and air temperature was highest during 1951-2014 (see Methods for the method to determine the optimal preseason for each species at each site). As there may be phenological observations for multiple species at one sites, and locations of many sites can be very close to each other, here we only show the average change of each metrics for all samples within each 0.25°×0.25° grid cell.

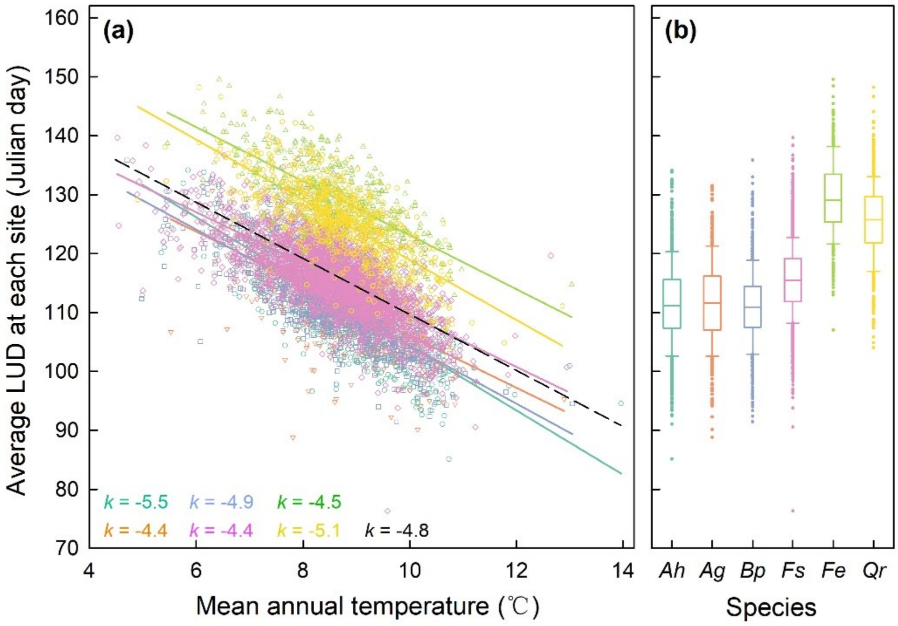

Figure S7 | Relationships between average leaf unfolding day (LUD) and the long-term (1951-2014) averaged mean annual temperature for six dominant tree species in Europe (a) and the comparison of the LUD of different tree species (b). In plot (a), the colorful lines are the linear regression lines between LUD and mean annual temperatures for different species, and the black dashed line is the regression line for all species together. *k* is the slope of the regression line. Trees species represented by each color can be found in plot (b), where *AH* denotes *Aesculus hippocastanum*; *AG* denotes *Alnus glutinosa*; *BP* is *Betula pendula*; *FS* is *Fagus sylvatica*; *FE* is *Fraxinus excelsior*; *QR* is *Quercus robur*.

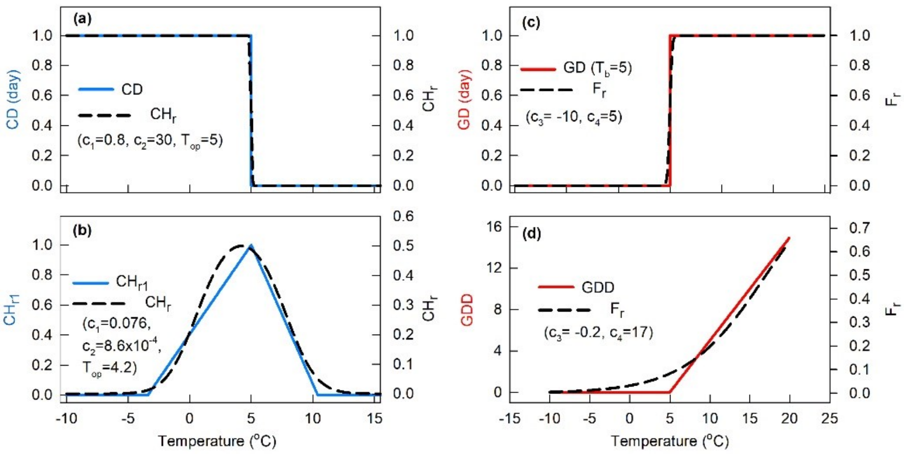

Figure S8 | Relationships between daily chilling rate (a, b) or daily forcing rate and the daily average temperature based on different chilling and forcing indexes. CD the widely used index-chilling day. CD equals to 1 when daily temperature (T_i, °C) is below a base temperature (T_b, e.g. 5 °C) or within a temperature range (e.g. 0-5 °C), otherwise, CD equals to 0. CH_r is the chilling rate calculated using the sigmoid function of the unified model (Eq. 1). c_1 and c_2 are the coefficients in Eq. 1, and T_{op} is the optimal chilling temperature. CH_{r1} is the daily chilling rate calculated using a triangular function[ref], in which $CH_{r1}=(T_i + 3.4)/(T_{op}+3.4)$, if $-3.4<T_i<T_{op}$; $CH_{r1}=(T_i - 10.4)/(T_{op}-10.4)$, if $T_{op}<Ti<10.4$; $CH_{r1}=0$, if $T_i \leqslant -3.4$ or $T_i \geqslant 10.4$. GD is the growing day. GD equals to 1 when daily temperature is higher than a T_b (e.g. 5 °C), otherwise, GD equals to 0. GDD is the growing degree-days. GDD equals to T_i-T_b when T_i is higher than T_b, otherwise, GDD equals to 0. F_r is the daily forcing rate calculated using the function in the unified model (Eq.2). c_3 and c_4 are the coefficients in Eq. 2.

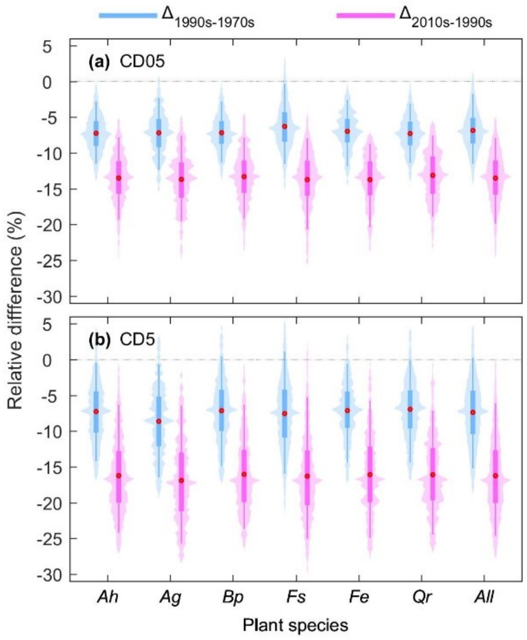

Figure S9 | The relative changes in annual total chilling days (CD05 (a) and CD5 (b)) from 1951-1980 to 1981-2000 ($\Delta D_{1990s\text{-}1970s}$) and to 2001-2014 ($\Delta D_{1990s\text{-}1970s}$), respectively. CD05 was calculated as the total chilling days when daily temperature was between 0 ^{o}C and 5 ^{o}C from 1 November to the average leaf unfolding day, and CD5 was calculated as the total chilling days when daily temperature was below 5 ^{o}C from 1 November to the average leaf unfolding day. In each violin plot, red dot is the mean value and balloon representing the probability density distribution of each value. Whiskers indicate the interquartile (thick) and 95 % confidence intervals (thin). *AH* denotes *Aesculus hippocastanum*; *AG* denotes *Alnus glutinosa*; *BP* is *Betula pendula*; *FS* is *Fagus sylvatica*; *FE* is *Fraxinus excelsior*; *QR* is *Quercus robur*; *All* denotes the average values for all of the six species.

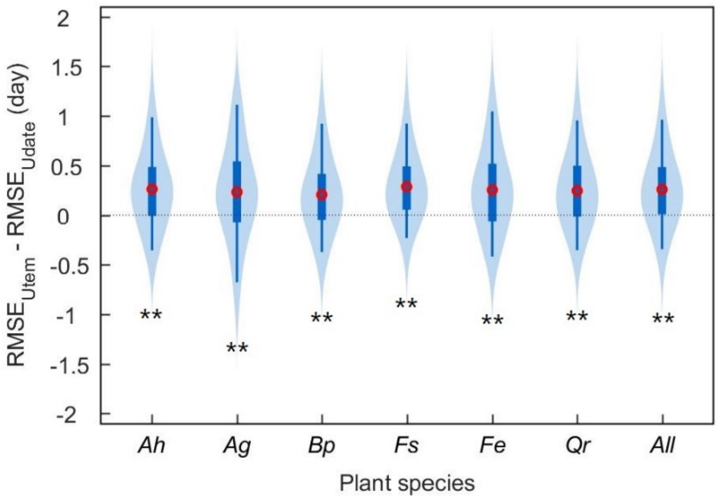

Figure S10 | Comparison of the root mean square error of leaf unfolding days simulated by the unified model in which the chilling accumulation is assumed to start from a specific date ($RMSE_{Udate}$) and by the unified model in which the chilling accumulation is assumed to start when daily mean temperature decrease to a threshold ($RMSE_{Utem}$). The asterisks (**) indicate differences in RMSEs are significantly different from zero. In U_{date} model, the start date of chilling accumulation is optimized for each tree species at each site. In U_{tem} model, the temperature threshold for determining the start time of chilling accumulation is also optimized for each tree species at each site.

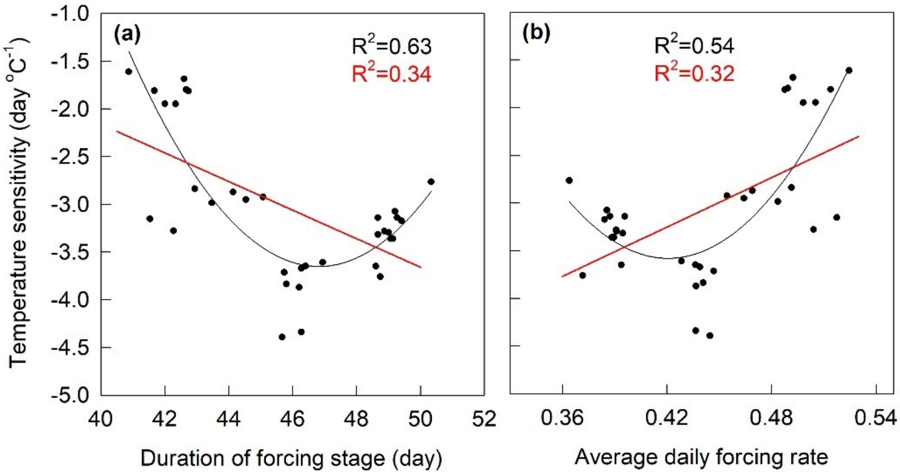

Figure S11 | Relationships between temperature sensitivities of leaf unfolding day and (a) the duration of forcing stage and (b) the average daily forcing rate during the forcing stage for *Aesculus hippocastanum* at an observation site in northwest Germany (7.82° E, 53.63 ° N). In each plot, the red and black lines are the linear and quadratic regression lines, respectively, and the R^2 in red and black color are the determining coefficients of the linear and quadratic regression functions, respectively. The temperature sensitivities were calculated based on a 15-year moving window from 1959 to 2013. Duration of forcing stage or average daily forcing rate represented by each dot is the mean value in each 15-year moving window.