

Changes in flowering phenology of woody plants from 1963 to 2014 in North China

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Abstract Existing evidence demonstrates that the first flowering date (FFD) of most plant species became earlier in response to temperature increase over the past several decades. However, the studies on changes in flowering duration (FD) were limited. By using the non-parametric Theil–Sen estimator, this study investigated the temporal trends in 127 time series of FFD, end of flowering date (EFD), and FD of 97 woody plants from 1963 to 2014 at three sites (Harbin, Beijing, and Xi'an) in North China. The relationship between flowering phenophases and temperature was analyzed using two phenological models. The results showed that most of FFD and EFD time series exhibited an apparent advancing trend. Among them, trends of 52.0% (40.9%) of FFD (EFD) time series were significant ($P < 0.05$). FFD and EFD time series (95.3 and 89.8%, respectively) responded negatively and significantly to pre-season temperature ($P < 0.05$). The direction of FD changes varied among sites and species. On average, a shortening trend of FD was observed at Harbin (-0.51 days decade⁻¹), with 7.5% of species significantly. However, FD on average extended by 0.42 and 0.93 days decade⁻¹ at Beijing (24.5% significantly) and Xi'an (28.9% significantly), respectively. The regression models could simulate the interannual changes in FFD and EFD with the mean

goodness of fit (R^2) ranging from 0.37 to 0.67, but fail to simulate the changes in FD accurately (R^2 ranging from 0.09 to 0.18). The growing degree day model could improve the R^2 for simulating FFD and EFD except for FD. Therefore, more phenological models need to be tested, and more drivers of FD need to be further investigated.

Keywords Climate change · Flowering duration · First flowering date · Phenological model · Phenology · China

Introduction

Phenology, as the study of recurring plant and animal life cycle stages and their timing and relationships with weather and climate, attracted considerable attention under the background of climate change (Schwartz 2013a). Plant phenophases such as leaf unfolding time and flowering time were commonly used as the indicators to track the impact of climate change on biological systems (Menzel et al. 2006; Rosenzweig et al. 2007; Ge et al. 2015), although biotic factors also exert important influence on plant phenophases, especially during periods of climatic stability (Wolkovich et al. 2014).

Flowering phenophases such as the beginning of flowering, end of flowering, and flowering duration were a group of the main events in the life cycle of plants. First, flowering phenophases and insect activity can both be impacted by climate variability (Memmott et al. 2007). Therefore, climate change may affect the insect–plant relationship and further impact reproductive success of plants (Hegland et al. 2008). If mismatches between the time of flowering and insect activity persist, then the population of specific plants may decline, and ecosystem structure may be disrupted (Burke et al. 2013). Second, many plants have important esthetic and cultural value. For example, cherry blossom festivals attract thousands of people to view in Japan,

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China, and the USA (Chung et al. 2011; Sakurai et al. 2011). Local economies can rely on blossom festivals. Third, since flowering phenology is directly related to the pollen season of plants, changes in flowering time of particular plants may affect the threat level of allergenic pollen (Reid and Gamble 2009; Ziello et al. 2012). Therefore, the changes in flowering phenology have serious ecological and social impacts.

To date, many studies have investigated the changes in first flowering date (FFD) of plants in response to temperature rise. Over the past several decades, many studies demonstrated that FFD of most plants became earlier across the globe (Menzel et al. 2006; Chambers et al. 2013; Ge et al. 2013; Schwartz et al. 2013b). However, fewer studies have examined changes in flowering duration (FD). Several previous results about the impacts of temperature increase on FD were controversial (Table 1). Warmer temperature would shorten the FD for specific species and regions (Arroyo et al. 1981; Crepinsek et al. 2012; Bock et al. 2014), but reverse conclusions also existed (Dunne et al. 2003; Miller-Rushing et al. 2007; Ziello et al. 2012). Also, FD also exhibited no significant changes in warmer climate (Bock et al. 2011) or did not respond to temperature change (Zhao et al. 2013) in certain cases. Therefore, we need to examine the changes in FD of more plant species in more regions.

In this study, using the flowering phenological data from 1963 to 2014 at three sites in North China, we examined the trends of FFD, end of flowering date (EFD), and FD of woody plants over time. Furthermore, we evaluated the effects of temperature change on FFD, EFD, and FD. At last, the accuracy of phenological models in simulating flowering phenology was assessed.

Materials and methods

Phenological data

Flowering phenology at Harbin, Beijing, and Xi'an in North China (Fig. S1) was investigated. These sites had a typical continental monsoon climate with a mean annual precipitation between 500 and 600 mm (1981–2010). Mean annual temperature was 4.9, 12.9, and 14.2 °C for Harbin, Beijing, and Xi'an, respectively (Fig. 1). The coldest month was January, while the warmest month was July.

Flowering data at these sites (Table 2) from 1963 to 2014 were acquired from China Phenology Observation Network (CPON). For each site, FFD and EFD were observed every 2 or 3 days for each plant species. According to observation criteria of CPON (Wan and Liu 1979), FFD was defined as the date when at least one fresh flower opening at any cluster for the whole plant. EFD was defined as the date when a majority of petals have fallen. The length of time between these two phenophases was FD. In order to detect long-term trends in flowering phenology, we only analyzed the phenological time series simultaneously meeting two criteria: (1) at least 15-year

records between 1963 and 2014 and (2) at least 5-year records before and after 2000. As a result, there were 38 to 49 perennial woody plants analyzed at each site (Table S1). The observation was interrupted during several periods. Therefore, the number of years with observation data was 30 to 46 (Table 2) and the number of species observed changed over time (Fig. 2).

Climate data

Climate data for each phenological site were obtained from the nearest climate station (the distance less than 30 km) in the national climate observation network. All data were downloaded from the National Meteorological Information Center of China (<http://data.cma.cn/>). The data consisted of daily mean temperature during the period 1963–2014.

Statistical analyses

First, for each species at each site, non-parametric Theil–Sen estimator was applied to estimating the linear trend of monthly temperature, FFD, EFD, and FD over time. The significance of the trends was tested by using Mann–Kendall trend test. Subsequently, we compared the phenological trends among different plant groups. For each site, we grouped the woody species by flowering time (early and late flowering species) and length of flowering duration (short duration and long duration species) separately. Early flowering was defined as FFD being earlier than or equals to the median FFD of all species, while late flowering was defined as the FFD being later than the median FFD of all species. Short duration was defined as the FD being shorter than or equal to the median FD of all species, while longer duration was defined as the FD being longer than the median FD of all species.

Second, we analyzed the temperature effects on flowering phenology. Because the change in FD was co-determined by changes in FFD and EFD, we studied the temperature effect on FFD and EFD separately. The pre-season impacting the phenophases most markedly was usually several months before the phenological events (Menzel 2003; Bolmgren et al. 2013; Dai et al. 2013), but this period differed among species and locations. Here, the optimal pre-season of FFD was defined as the period (with 15-day steps) before the mean FFD for which the Spearman's rank correlation coefficient (R) between FFD and mean temperature was highest during 1963–2014. This approach was adopted by previous studies (Matsumoto et al. 2003; Chen and Xu 2012; Dai et al. 2014; Fu et al. 2015), but the only difference was that they used Pearson's R rather than Spearman's rank R . In terms of EFD, the start date of optimal pre-season was same as that of FFD, but the end date was determined as the mean date of EFD. The relationship between flowering phenology and temperature can be expressed by temperature sensitivity, which was computed as Theil–Sen's slope

Table 1 Previously reported changes in flowering duration (FD)

Location	Vegetation	Climate	Phenological observation	Period	Reference
FD shortened in warmer temperature Central Chile	97 species in scrub and cushion plant communities	Mediterranean climate	Observed once per 2 weeks	FD along the altitude (spring 1978 to winter 1979)	Arroyo et al. (1981)
Northeastern Slovenia	Five cultivars of hazel (<i>Corylus avellana</i>)	Temperate continental climate	Estimated FD as the time between date when 5% of flowers open and last flowers open	FD during two periods (1969–1979 and 1994–2007)	Crepinsek et al. (2012)
Island of Guernsey, UK FD extended in warmer temperature Colorado, USA	232 herbaceous and woody species	Temperate marine climate	Observed once per week	FD during 1985–2011	Bock et al. (2014)
Mt. Takao, in Tokyo, Japan	11 subalpine meadow plant species	Highland climate	Observed once per week, defined FD as the time from buds to enlarged fruits	FD in experimental warming (1995–1998)	Dunne et al. (2003)
13 countries in Europe	17 species and hybrids of cherry (<i>Cerasus</i> sp.)	Subtropical monsoon climate	Defined FD as the time between FFD and peak flowering date (~80% of the flowers had opened)	FD from 1981 to 2005	Miller-Rushing et al. (2007)
FD showed no significant changes in warmer temperature or could not be related to temperature Bürgerspital, Germany Xishuangbanna, southwestern China	29 woody and herbaceous plants	Temperate climate	Defined FD as the time between the first flower opening and the full flowering (50% of flowers open)	FD from 1971 to 2000	Ziello et al. (2012)
	Grape cultivar (Silvaner) 21 deciduous tree species	Temperate climate Tropical monsoon climate	Observed FFD and EFD following BBCH code Defined FD as days from the onset of flowering to all flowers shed in a year	FD from 1950 to 2010 FD from 1973 to 1999	Bock et al. (2011) Zhao et al. (2013)

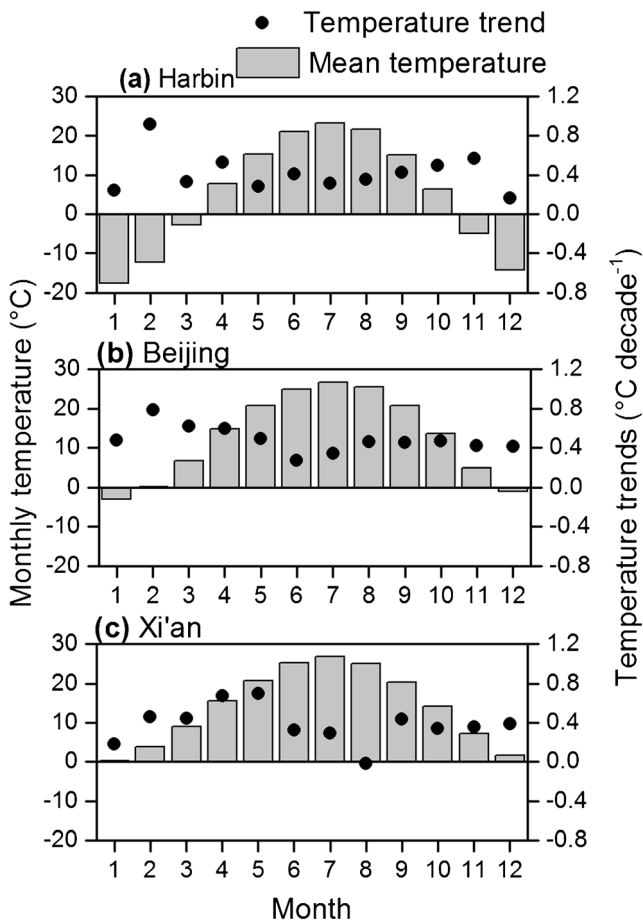


Fig. 1 Monthly mean temperature and trends of temperature from 1963 to 2014. Monthly temperature is calculated as the mean of 1981–2000. The years with no phenological data (see Fig. 2) are ignored when calculating the temperature trends. Positive trend values indicate warming. **a** Harbin. **b** Beijing. **c** Xi'an

between FFD (or EFD) and mean temperature of the optimal pre-season.

At last, we tested whether the phenological models could simulate the flowering phenophases accurately. Two types of model were adopted. The first was linear regression model

$$t_F = a_1 x_{fpre} + b_1 \quad (1)$$

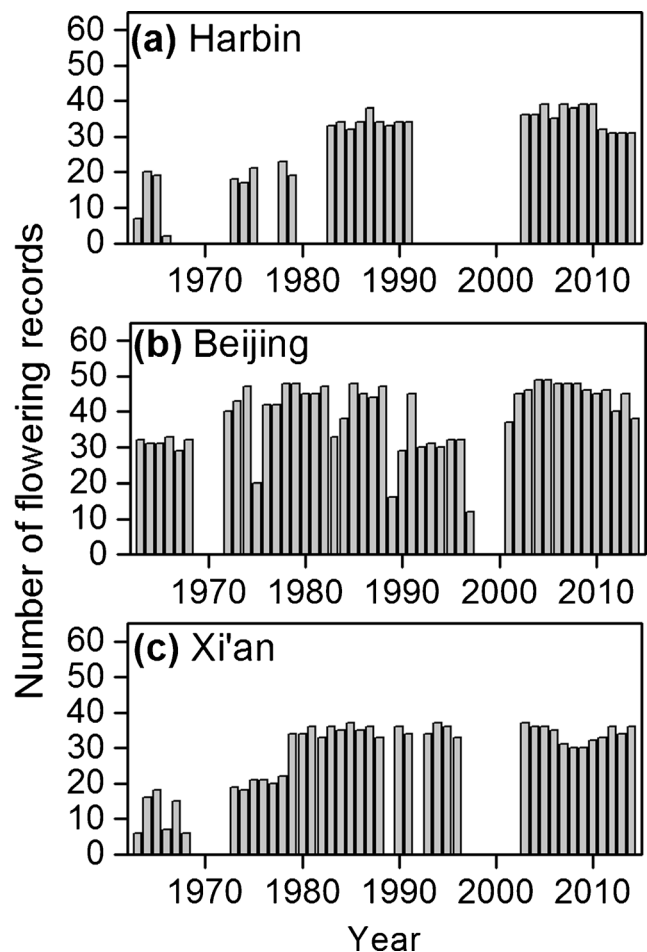


Fig. 2 The number of flowering records for each year at each site. **a** Harbin. **b** Beijing. **c** Xi'an

where t_F is the simulated FFD. x_{fpre} is the mean temperature during the optimal pre-season of FFD. a_1 and b_1 are regression slope and intercept, respectively.

$$t_E = a_2 x_{epre} + b_2 \quad (2)$$

where t_E is the simulated EFD. x_{epre} is the mean temperature during the optimal pre-season of EFD. a_2 and b_2 are regression slope and intercept, respectively.

Table 2 Summary of location, observation period, and the number of species for each site

Site	D_P (km)	D_C (km)	D_{CP} (km)	Latitude (N)	Longitude (E)	Elevation (m)	Period	Number of years	Number of species
Harbin	4.0	9.0	11.5	45° 42' 26"	126° 38' 36"	143	1963–2014	30	40
Beijing	14.5	14.0	27.0	39° 59' 56"	116° 16' 20"	75	1963–2014	46	49
Xi'an	6.5	5.0	11.0	34° 12' 31"	108° 57' 17"	431	1963–2014	40	38

D_P distance between phenological site and city center, D_C distance between climate station and city center, D_{CP} distance between climate station and phenological stations

The second model we chose was growing degree day (GDD) model. The equations for this model are as follows

$$\sum_{t=t_0}^{t_F} R(x_t) = \text{GDD}_{\text{FFD}} \quad (3)$$

$$\sum_{t=t_0}^{t_E} R(x_t) = \text{GDD}_{\text{EFD}} \quad (4)$$

$$R(x_t) = \begin{cases} 0 & \text{if } x_t \leq T_b \\ x_t - T_b & \text{if } x_t > T_b \end{cases} \quad (5)$$

where x_t is the daily mean temperature at the day of year t , and GDDs are measured as the sum of $R(x_t)$ (daily mean temperature above a base temperature T_b ; Eq. 5), starting at the day of year t_0 . The GDDs achieve the critical degree day threshold (GDD_{FFD}) at time t_F , which indicates the onset of FFD (Eq. 3). Similarly, the GDDs achieve GDD_{EFD} at time t_E , which indicates the onset of EFD (Eq. 4). In this model, four parameters (t_0 , T_b , GDD_{FFD} , GDD_{EFD}) were unknown and needed to be fitted.

At each site, the above two models were both fitted for individual species using daily mean temperature and FFD or EFD time series through the least square method. For each type of model, the simulation of FD was through calculating the difference between the simulated EFD and FFD. The goodness of the model in simulating FFD, EFD, and FD was measured by the percentage variance explained by the model (R^2) and $RMSE$ between the observed and the simulated time series.

Results

Changes in temperature

During the study period, the slopes of monthly temperatures on year calculated through Theil–Sen estimator were positive and statistically significant (Mann–Kendall test; $P < 0.05$) except for only several months (January, March, May, December of Harbin; January and August of Xi'an). This suggested that all sites experienced significant warming from 1963 to 2014 (Fig. 1). The degree of warming was stronger in winter and spring compared to summer and autumn.

Changes in first flowering date

At Harbin, the earliest mean FFD was April 16 (*Ulmus pumila*), the latest was July 10 (*Sorbaria kirilowii*). May was the month with the maximum number of species in FFD (Fig. 3a). Compared to Harbin, the overall flowering phenology in Beijing was earlier. At Beijing, the mean FFD ranged from March 16 (*U. pumila*) to July 14 (*Sophora japonica*). April was the month with the maximum number of species in

FFD (Fig. 3b). At Xi'an, the number of species in FFD showed a similar pattern with Beijing (Fig. 3c).

Overall, temporal trends of FFD were negative (Table 3, Fig. 4). The average trends of all FFD time series were -1.43 , -1.67 , and -2.68 days decade $^{-1}$ at Harbin, Beijing, and Xi'an, respectively. Similar to the mean trends, the median trends of all FFD time series were -1.16 , -1.74 , and -2.59 days decade $^{-1}$ at Harbin, Beijing, and Xi'an, respectively. At Harbin, 22.5% of the species advanced their FFD significantly ($P < 0.05$). The percentage of significantly advancing trends at Beijing (63.3%) and Xi'an (68.4%) was obviously larger than Harbin (Fig. 4b, c). No species delayed their FFD significantly at all sites. In addition, all plant groups showed advancing trends in FFD (Table 3). The difference of trends in FFD between short duration and long duration species was not significantly different from zero (two-sample t test) at all sites. The early flowering and late flowering species showed a significant difference of trends in FFD at Xi'an ($P < 0.05$).

The time series of median FFD anomaly showed that most anomalies of FFD were positive before 2000 at all the three sites (Fig. 5). After 2000, most anomalies of FFD became negative (Beijing and Xi'an) or fluctuated around the multi-year mean (Harbin).

Changes in end of flowering date

At Harbin, the earliest mean EFD was April 25 (*U. pumila*), the latest was August 23 (*Lespedeza bicolor*). June was the month with the maximum number of species end of flowering (Fig. 3a). At Beijing, the mean EFD ranged from March 24 (*U. pumila*) to September 25 (*Lagerstroemia indica*), and it ranged between March 10 (*Corylus heterophylla*) and September 22 (*Koeleria bipinnata* var. *integrifoliola*) at Xi'an (Fig. 3b, c). The largest number of species ended their flowering in April for Beijing and Xi'an.

Similar to FFD, temporal trends of EFD were negative (Table 3, Fig. 4). At Harbin, 32.5% of the species significantly ended their flowering time earlier. At Beijing and Xi'an, EFD also became remarkably earlier (44.9% significantly for Beijing; 44.7% significantly for Xi'an). The trends of EFD averaged from all species were -1.97 , -1.28 , and -1.79 days decade $^{-1}$ at Harbin, Beijing, and Xi'an, respectively (Table 3). Such advancing trends were robust when calculating the medians (-1.60 , -1.48 , and -2.03 days decade $^{-1}$ at three sites, respectively). Furthermore, all plant groups consistently showed advancing trends in EFD (Table 3). At Xi'an, the advance of EFD for late flowering species was significantly stronger than that for early flowering species ($P < 0.05$). At Beijing, the advance of EFD for short duration species was significantly stronger than that for long duration species ($P < 0.05$).

Fig. 3 Percentage of species in first flowering, end of flowering by month (*left column*), and frequency distribution of flowering duration (*right column*). **a** Harbin. **b** Beijing. **c** Xi'an

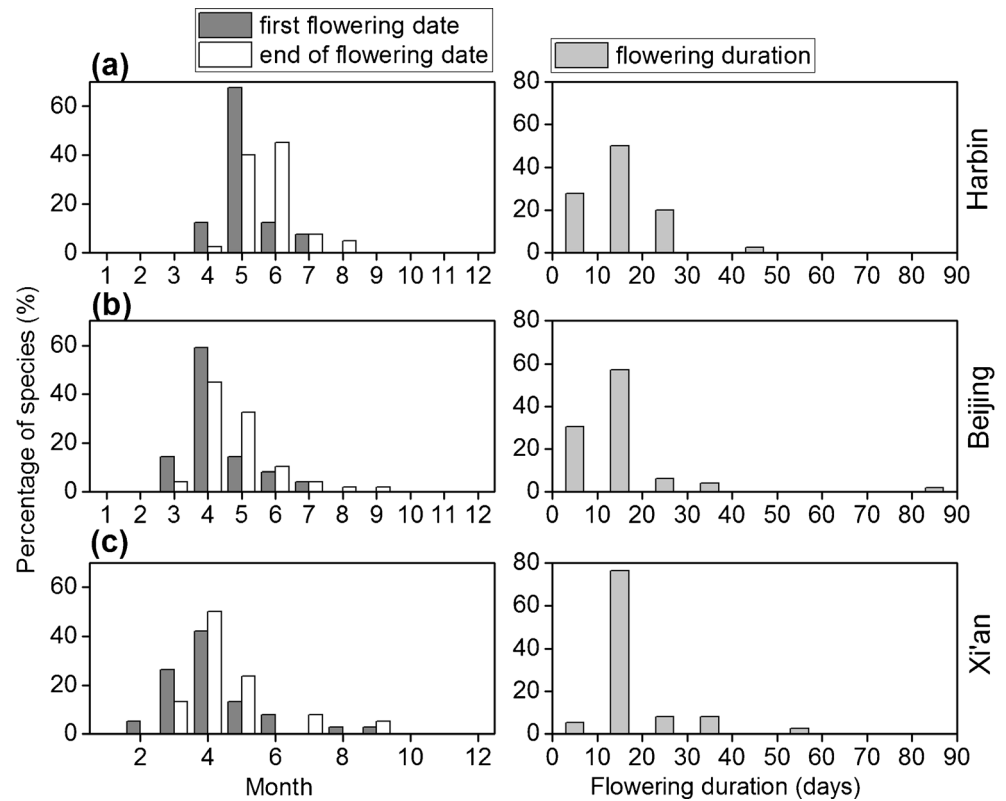


Table 3 The trends in first flowering date (FFD), end of flowering date (EFD), and flowering duration (FD) during 1963–2014 for different plant groups and sites

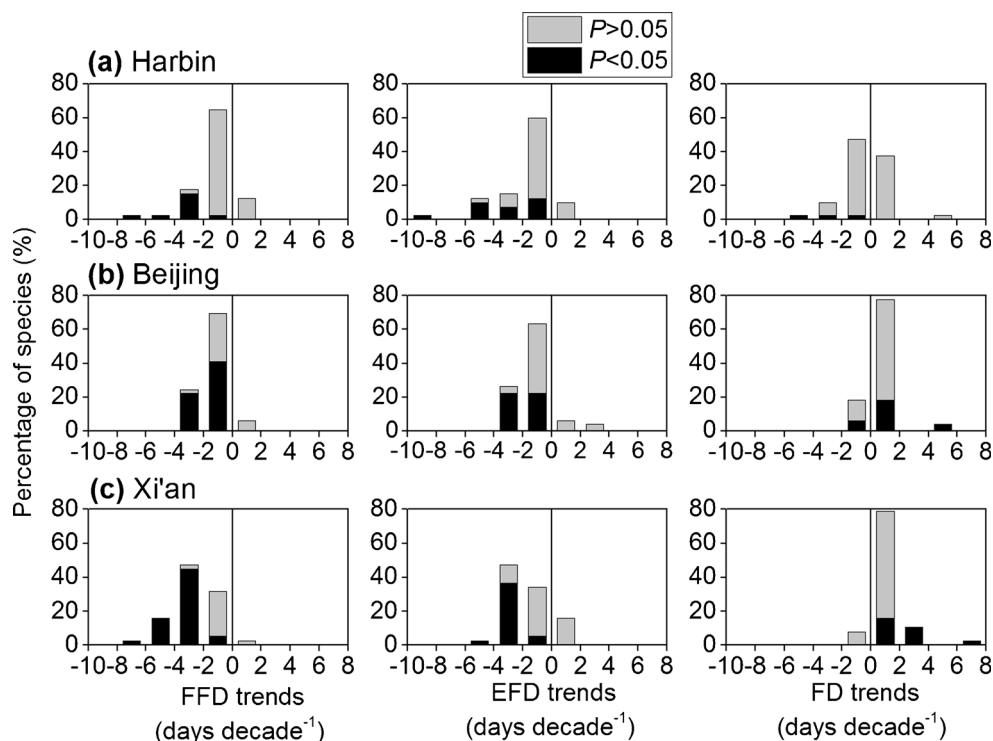
Site	Group	Number of plant species	FFD				EFD				FD			
			P_{mean}	S_{mean}	S_{SD}	S_{median}	P_{mean}	S_{mean}	S_{SD}	S_{median}	P_{mean}	S_{mean}	S_{SD}	S_{median}
Harbin	All	40 (878)	142	-1.43	1.42	-1.16	158	-1.97	2.00	-1.60	15.0	-0.51	1.45	-0.45
Beijing	All	49 (1797)	114	-1.67	0.72	-1.74	130	-1.28	1.22	-1.48	15.9	0.42	1.12	0.30
Xi'an	All	38 (1154)	109	-2.68	1.50	-2.59	127	-1.79	1.36	-2.03	17.8	0.93	1.26	0.75
Harbin	Early FFD	20 (467)	128*	-1.11	0.88	-1.24	140*	-1.48	1.08	-1.42	12.7	-0.30	0.58	-0.27
	Late FFD	20 (411)	157*	-1.76	1.77	-1.13	175*	-2.46	2.56	-1.85	17.3	-0.72	1.96	-0.72
Beijing	Early FFD	25 (950)	95*	-1.75	0.66	-1.67	109*	-1.47	1.00	-1.29	13.9	0.32	0.70	0.22
	Late FFD	24 (847)	135*	-1.57	0.78	-1.74	153*	-1.09	1.41	-1.51	17.9	0.53	1.44	0.32
Xi'an	Early FFD	19 (623)	81.2*	-1.94*	1.12	-2.00	98.6*	-1.14*	1.04	-1.29	17.4	0.85	1.06	0.71
	Late FFD	19 (531)	136.7*	-3.42*	1.48	-3.42	155.0*	-2.44*	1.35	-3.00	18.3	1.01	1.47	0.77
Harbin	Short FD	20 (443)	135*	-1.31	1.58	-1.05	116*	-1.70	2.17	-1.35	9.5*	-0.35	0.90	-0.05
	Long FD	20 (435)	150*	-1.55	1.27	-1.29	145*	-2.24	1.83	-1.87	20.5*	-0.67	1.85	-0.67
Beijing	Short FD	25 (955)	106*	-1.68	0.69	-1.74	116*	-1.86*	0.77	-1.97	9.7*	-0.06*	0.47	0.00
	Long FD	24 (842)	123*	-1.65	0.76	-1.67	145*	-0.69*	1.72	-0.79	22.3*	0.93*	1.36	0.63
Xi'an	Short FD	19 (583)	107.2	-2.51	1.75	-2.22	120	-1.93	1.4	-2.07	12.8*	0.56	0.91	0.61
	Long FD	19 (571)	110.8	-2.86	1.23	-2.8	134	-1.65	1.34	-2.00	22.9*	1.30	1.47	1.00

The trends are calculated through Theil–Sen estimator. The number of records (each species/year represent one record) is shown in brackets. Unit of FFD and EFD: day of the year. Unit of FD: days

P_{mean} the mean phenophase, S_{mean} mean of trends (unit: days decade⁻¹), S_{SD} standard deviation of trends (unit: days decade⁻¹), S_{median} median of trends (unit: days decade⁻¹)

*after italic entries: mean values are significantly different between groups (two-sample *t* test; $P < 0.05$)

Fig. 4 Frequency distributions of trends in phenophases from 1963 to 2014. *Black shadings* represent species for which the trends are statistically significant (Mann–Kendall test; $P < 0.05$). **a** Harbin. **b** Beijing. **c** Xi'an. *Left column*: first flowering date (FFD); *middle column*: end of flowering date (EFD); *right column*: flowering duration (FD)



The interannual changes of EFD were consistent with that of FFD (Fig. 5). In the recent decade, most EFD anomalies shifted from positive one to negative one, resulting in negative trends of EFD for all the three sites.

Changes in flowering duration

Mean FD ranged from 6.4 days (*Crataegus pinnatifida* var. *major*) to 48.3 days (*L. bicolor*) at Harbin (Fig. 3). At Beijing,

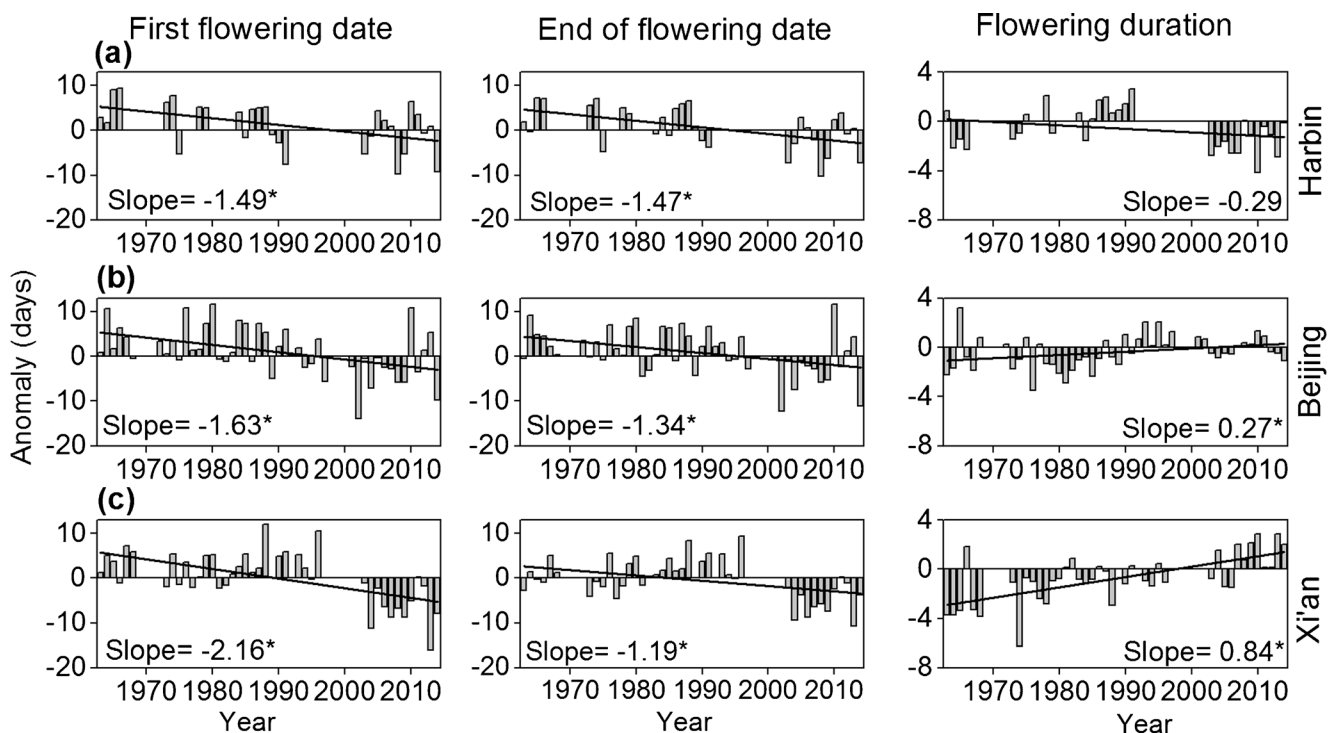


Fig. 5 Time series of first flowering date, end of the flowering date, and flowering duration calculated from the median anomaly of all species. The regression lines and slopes are shown. $*P < 0.05$. **a** Harbin. **b** Beijing. **c** Xi'an

the shortest and longest FD were 5.7 days (*Populus simonii*) and 82.7 days (*L. indica*), respectively. At Xi'an, mean FD ranged between 7.8 days (*Ginkgo biloba*) and 50.4 days (*Albizia julibrissin*). For all the sites, most species had an FD between 10 and 20 days (Fig. 3).

Temporal trends of FD were different among sites (Fig. 4). At Harbin, 7.5% of the species shortened FD significantly ($P < 0.05$). The changes in FD at Beijing were inconsistent with that at Harbin: 4.1% of the species shortened their FD significantly, while 24.5% of the species lengthened their FD significantly. At Xi'an, 28.9% of the species lengthened FD significantly. When examining the mean or median value of all species, a shortening of FD was observed at Harbin, but the extending FD was found at Beijing and Xi'an (Table 3). There were no significant differences in trends of FD between plants groups. The only exception was that the long duration species showed a strong extending trend in FD ($0.93 \text{ days decade}^{-1}$), while the short duration species showed very weak changes in FD ($-0.06 \text{ days decade}^{-1}$) at Beijing.

On the interannual scale, the changes in FD were not consistent among sites (Fig. 5). At Harbin, FD anomalies were around zero before 2000, but almost all anomalies became negative after 2000, causing an overall shortened trend in FD. At Beijing, most FD anomalies were negative before 1992 and then became relatively stable around zero, so the trend in FD anomaly was positive. At Xi'an, a clear shift towards longer FD occurred around 1996.

Relationship between flowering phenology and temperature

In most cases, the optimal length of the preseason ranged between 30 and 75 days (Fig. S2). The average length of the preseason was 53 to 62 days for FFD and 71 to 77 days for EFD among the three sites.

In almost all cases, the temperature sensitivities of FFD had a negative sign with warmer temperatures resulting in earlier FFD (Fig. 6). At Harbin, 95.0% of species showed negative and significant temperature sensitivities ($P < 0.05$). Among them, temperature sensitivities ranged from $-7.5 \text{ days } ^\circ\text{C}^{-1}$ (*Sorbaria sorbifolia*) to $-1.7 \text{ days } ^\circ\text{C}^{-1}$ (*Spiraea trichocarpa*). At Beijing, 98.0% of the species showed negative and significant temperature sensitivities, ranging from $-6.1 \text{ days } ^\circ\text{C}^{-1}$ (*Platycladus orientalis*) to $-1.7 \text{ days } ^\circ\text{C}^{-1}$ (*Ailanthus altissima*). Similarly, at Xi'an, significantly negative temperature sensitivities varied from $-6.4 \text{ days } ^\circ\text{C}^{-1}$ (*A. julibrissin*) to $-2.6 \text{ days } ^\circ\text{C}^{-1}$ (*Pinus tabulaeformis*) among 97.4% of the species. For all the sites, most temperature sensitivities of FFD ranged from -5 to $-2 \text{ days } ^\circ\text{C}^{-1}$.

Similar to FFD, the temperature sensitivity of EFD had a negative sign in almost all cases (Fig. 6). At Harbin, 82.5% of the species showed significant and negative temperature sensitivities ($P < 0.05$). At Beijing, significantly negative

temperature sensitivities were found in 91.8% of species, while only one species showed significantly positive temperature sensitivity. At Xi'an, the temperature sensitivities of EFD were negative and significant for 92.1% of species. Most temperature sensitivities of EFD ranged from -4 to $-2 \text{ days } ^\circ\text{C}^{-1}$.

Phenological models and uncertainties

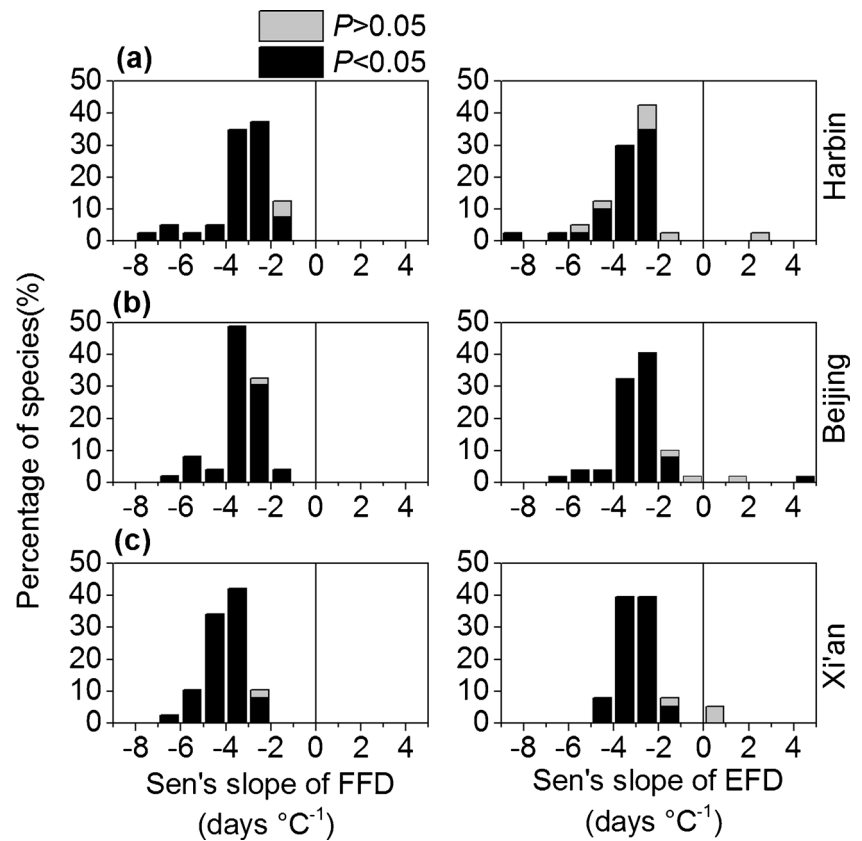
The regression models could simulate the interannual changes in FFD accurately. Mean goodness of fit (R^2) ranged from 0.50 to 0.67, and the percentage of species with significant R^2 ($P < 0.05$) reached 87.5 to 100% at three sites (Table 4, Fig. S3). The mean RMSE for simulating FFD ranged between 3.9 and 4.4 days. Regarding EFD, the R^2 ranged between 0.37 and 0.48 on average (Table 4). The mean RMSE of EFD simulation (5.1 to 6.1 days) was slightly larger than that of FFD. However, the regression models failed to simulate interannual changes in FD accurately (Fig. S5). Mean R^2 ranged from 0.09 to 0.18, and only 22.5 to 57.9% of R^2 values were statistically significant (Table 4). Nevertheless, the mean RMSE of regression models for FD (4.8 to 5.9 days) were close to that for FFD and EFD. Regarding plant groups, the FFD, EFD, and FD of early flowering species can be simulated more accurately than those of late flowering species except for FFD of Xi'an (Table 4). The FFD, EFD, and FD of short duration species can be simulated more accurately than those of long duration species except for the FFD and FD of Xi'an (Table 4).

From the parameter fitting results of GDD models, we found that the plants at Harbin need more GDDs for FFD and EFD (Table 5). The mean R^2 of GDD models was improved at all sites (Table 5, Figs. S3 and S4), but the RMSE was still very close to that of regression models. For the FD, the mean RMSE (4.8–5.8 days) of GDD models approximated those of regression models, and the R^2 even slightly declined at Xi'an. The FFD, EFD, and FD of early flowering species had a higher mean R^2 , higher percentage of significant R^2 , and lower RMSE compared to the late flowering species, suggesting that the flowering phenophases of early flowering species can be easier simulated. Besides, the short duration species showed lower RMSE when simulating EFD and FD compared to the long duration species.

Discussion

Our results showed that three sites are undergoing rapid warming (Fig. 1). Since the climate and phenological stations are located in urbanized area, urbanization is expected to contribute to the warming trends. The best way to quantitatively measure the contribution of urban heat island (UHI) effect to warming is to compare the temperature trends at urbanized stations with that at surrounding suburban or rural stations.

Fig. 6 Frequency distributions of slopes of FFD and EFD on preseason temperature calculated from Theil–Sen estimator for each site. *Solid shading* of columns represents species for which the slopes are significant (Mann–Kendall test; $P < 0.05$). *Left column*: first flowering date (FFD); *right column*: end of flowering date (EFD). **a** Harbin. **b** Beijing. **c** Xi'an



At Harbin, the warming trend of annual mean temperature (1953–2004) at one urbanized station (same with this study) was $0.487^{\circ}\text{C decade}^{-1}$, which is stronger than warming trends ($0.361^{\circ}\text{C decade}^{-1}$) of two rural stations (Liu and Wang

2010). Wang et al. (2013) analyzed a homogenized dataset of daily mean, maximum, and minimum temperature observations at 20 stations in Greater Beijing from 1978 to 2008. They classified observing stations into four categories

Table 4 Validity of regression model for different plant groups and sites

Station	Group	FFD			EFD			FD		
		R^2	Sig (%)	RMSE	R^2	Sig (%)	RMSE	R^2	Sig (%)	RMSE
Harbin	All	0.50	87.5	4.4	0.37	80.0	6.1	0.11	22.5	5.9
Beijing	All	0.63	100.0	3.9	0.47	91.8	5.2	0.09	36.7	4.8
Xi'an	All	0.67	97.4	4.3	0.48	89.5	5.1	0.18	57.9	4.9
Harbin	Early FFD	0.61	95.0	3.9	0.44	100.0	5.2	0.13	25.0	5.1
	Late FFD	0.39	80.0	5.0	0.30	60.0	7.0	0.09	20.0	6.7
Beijing	Early FFD	0.69	100.0	3.8	0.54	100.0	4.7	0.09	40.0	4.2
	Late FFD	0.57	100.0	4.0	0.39	83.3	5.8	0.09	33.3	5.6
Xi'an	Early FFD	0.64	100.0	4.5	0.49	100.0	4.7	0.21	78.9	4.6
	Late FFD	0.70	94.7	4.1	0.47	78.9	5.6	0.16	36.8	5.3
Harbin	Short FD	0.52	85.0	4.4	0.47	90.0	4.6	0.10	25.0	4.0
	Long FD	0.49	90.0	4.4	0.27	70.0	7.7	0.11	20.0	7.9
Beijing	Short FD	0.64	100.0	3.9	0.55	100.0	4.9	0.08	32.0	3.9
	Long FD	0.62	100.0	3.9	0.38	83.3	5.6	0.10	41.7	5.8
Xi'an	Short FD	0.66	94.7	4.4	0.52	94.7	4.8	0.15	42.1	4.3
	Long FD	0.69	100.0	4.2	0.43	84.2	5.4	0.21	73.7	5.6

R^2 mean goodness of fit for all models, Sig percentage of species with significant R^2 ($P < 0.05$), RMSE mean root-mean-square error (days) for all models

Table 5 The parameters and validity of GDD models for different plant groups and sites

Station	Group	t_0	T_b	FFD				EFD				FD		
				GDD_{FFD}	R^2	Sig (%)	$RMSE$	GDD_{EFD}	R^2	Sig (%)	$RMSE$	R^2	Sig (%)	$RMSE$
Harbin	All	1	2.25	400.1	0.55	92.5	4.4	628.4	0.44	87.5	6.1	0.12	22.5	5.8
Beijing	All	43	0.50	367.4	0.66	100.0	3.9	609.1	0.52	89.8	5.5	0.08	28.6	4.8
Xi'an	All	52	1.00	335.8	0.72	97.4	4.1	584.1	0.51	89.5	5.8	0.13	44.7	5.1
Harbin	Early FFD	1	1.75	252.1	0.66	95.0	3.8	411.9	0.50	95.0	5.2	0.15	40.0	4.8
	Late FFD	1	2.50	603.7	0.44	90.0	5.0	760.1	0.39	80.0	7.0	0.09	5.0	6.8
Beijing	Early FFD	40	0.50	227.7	0.73	100.0	3.7	375.1	0.61	100.0	4.6	0.09	32.0	3.8
	Late FFD	52	0.50	626.8	0.58	100.0	4.2	824.3	0.42	79.2	6.4	0.07	25.0	5.8
Xi'an	Early FFD	40	0.50	212.2	0.73	100.0	4.0	370.6	0.53	100.0	4.9	0.17	63.2	4.5
	Late FFD	55	2.50	535.5	0.72	94.7	4.2	769.3	0.49	78.9	6.7	0.09	26.3	5.7
Harbin	Short FD	1	1.00	305.7	0.56	90.0	4.4	436.5	0.54	100.0	4.5	0.12	25.0	3.7
	Long FD	1	2.50	445.2	0.54	95.0	4.4	708.3	0.34	75.0	7.8	0.11	20.0	8.0
Beijing	Short FD	49	0.50	274.3	0.66	100.0	4.0	430.9	0.59	100.0	4.8	0.06	24.0	3.7
	Long FD	41.5	0.25	404.1	0.65	100.0	3.9	660.9	0.44	79.2	6.2	0.10	33.3	5.9
Xi'an	Short FD	52	0.50	467.5	0.69	94.7	4.3	640.9	0.55	94.7	5.3	0.09	36.8	4.3
	Long FD	52	1.50	262.3	0.76	100.0	3.9	572.3	0.48	84.2	6.3	0.17	52.6	6.0

The model parameters shown here are medians of all models

t_0 the start day of the year to accumulate GDD, T_b base temperature, GDD_{FFD} GDD required for FFD, GDD_{EFD} GDD required for EFD, R^2 mean goodness of fit for all models, *Sig* percentage of species with significant R^2 ($P < 0.05$), $RMSE$ mean root-mean-square error (days) for all models

(urbanized, suburban, rural, and mountain) and found that the warming trends of urbanized stations ($0.603^\circ\text{C decade}^{-1}$) are 15.5% stronger than the warming trends of suburban, rural, and mountain stations ($0.522^\circ\text{C decade}^{-1}$) (Wang et al. 2013). The UHI effect on the trends of annual mean temperature at Xi'an was $0.20^\circ\text{C decade}^{-1}$ ($0.31^\circ\text{C decade}^{-1}$ at urbanized station vs. $0.11^\circ\text{C decade}^{-1}$ at rural stations) from 1951 to 2006 (Gao et al. 2009). From above results, we can conclude that UHI effects contributed to 25.9, 13.4, and 64.5% of temperature increase at Harbin, Beijing, and Xi'an, respectively. Therefore, the observed flowering phenological changes in this study are the results of both UHI effect and underlying climate change.

This study found a clear pattern of advancing FFD from 1963 to 2014 in North China. The magnitude of advance was $1.9\text{ days decade}^{-1}$ averaged from all species at all sites. Such changes in FFD were consistent with other parts of the world, such as south-central England (Fitter and Fitter 2002), Hungary (Szabó et al. 2016), Northeast Spain (Penuelas et al. 2002), Southern Sweden (Bolmgren et al. 2013), Canada (Gonsamo et al. 2013), and Northeastern USA (Wolfe et al. 2005). Many studies found that earlier season plants exhibit a faster rate of changes in FFD (Abu-Asab et al. 2001; Menzel 2003; Ho et al. 2006), which was in agreement with our results at Beijing (Table 3). However, one study found that late flowering plants changed their flowering time to a greater extent than early flowering plants (Hoye et al. 2013), which were corresponded to our results at Harbin and

Xi'an. Thus, there were no consistent relationships between changes in FFD and onset date of flowering.

Compared to the changes in FFD, the changes in EFD have rarely been investigated in the past. This was likely due to that EFD observation was a difficult and time-consuming process. Observers needed to continuously monitor the number of petals remained in the plants, and document the date when almost all petals have fallen. Therefore, the dataset used in this study was unique regarding its long-term observation in EFD. The results showed that the changes in EFD were very similar to that of FFD. EFD time series (40.9%) became significantly earlier during 1963–2014 across three sites.

In North China with a temperate climate, FFD and EFD were significantly influenced by preseason temperature (Fig. 6). The Sen's slope of FFD against preseason temperature was significantly negative in 95.3% of time series. This result was in agreement with earlier results (Fitter and Fitter 2002; Bolmgren et al. 2013; Gonsamo et al. 2013; Szabó et al. 2016). Regarding EFD, a significant EFD–temperature relationship was found in 89.8% of time series. Therefore, the temperature was an important driving factor of FFD and EFD. The advancing FFD and EFD from 1963 to 2014 could be attributed to temperature increase at these sites.

The overall trends in FD varied among sites. The mean trend in FD was negative at Harbin, while it was positive at Beijing and Xi'an. At the species level, the proportion of significant trends of FD was smaller than those of FFD and EFD (Fig. 4). In order to compare our results with previous studies,

we summarized the earlier studies about the changes in FD (Table 1). All these studies in Table 1 focused on various climate and vegetation types and had different definitions of FD. In addition, data collection methods were also different. These differences may cause inconsistency in the response of FD to warming.

The diverse responses of FD to temperature increase suggested that plants may have different responsive mechanisms to climate. If temperatures become higher, the rate of floral development might be faster, in which case, buds would require less time to mature and then flowers would open for shorter periods, and maintenance costs of flowers reduced (Arroyo et al. 1981). Alternatively, plants may extend FD in a favorable environment so as to increase the chance of reproductive success (Vega and Marques 2015). Thus, we suppose that the trade-off between these two mechanisms may cause diverse responses of FD.

As mentioned above, for the species we investigated, both FFD and EFD were mainly affected by preseason temperature. Therefore, accurate simulation of flowering phenology would be expected. However, only the interannual changes in FFD and EFD could be simulated well. Both the regression and GDD models failed to simulate the interannual changes in FD accurately (R^2 was 0.08 to 0.18) with the *RMSE* of about 4 to 6 days. Considering that the FD of most species was between 10 and 20 days, the uncertainties of 4–6 days was a large relative error. Phenological models we adopted could only simulate the length of FD roughly, but could not reflect its interannual changes exactly. Thus, other phenological models need to be further tested for simulating FD. Specifically, the somewhat arbitrary thresholds (e.g., base temperature in GDD models) derived from model optimization routines need thorough experimental testing for individual species (Primack et al. 2015).

Other environmental factors may impact FD, such as sunshine duration (Zhao et al. 2013), precipitation, and humidity (Vega and Marques 2015). The evolution of flowering phenology is the result of a trade-off that balances many factors, including growth, reproductive capacity, and temporal overlap with pollinators (Hafidahl and Craig 2014). Thus, biotic factors (e.g., competition between species for soil resources, light or pollinators) could not be neglected, especially during periods of low climatic variability (Wolkovich et al. 2014). Further effort was needed to disentangle all these potential biotic and abiotic factors impacting FD.

In addition, this study used FFD as the indicator of the beginning of flowering. The data were not optimal as a single flower may open well in advance than the bulk of the tree. Thus, in some cases, the phenological records can be outliers compared with the majority of the tree, and the date of 10% flowering may be more appropriate than FFD. However, the data of 10% flowering were not available now and needed to be added to our observation in future.

Conclusions

At three sites in North China, the FFD and EFD of woody plants advanced notably from 1963 to 2014 as a result of the increase in temperature. The conventional phenological models using temperature as independent variable could explain most parts of interannual variance in FFD and EFD.

However, the changes in FD of woody plants were complex. FD was overall getting shorter at Harbin, but getting longer at Beijing and Xi'an, although the percentage of species with significant trends was small. Combined with other long-term studies, we can conclude that the direction of FD change varied among locations and species. Meanwhile, no consistent link was found between warming and FD change. The regression and GDD models could not explain large parts of interannual variance in FD, suggesting that more phenological models with better fitting should be tested and more abiotic and biotic drivers of FD (e.g., sun exposure, pollinators) need to be considered in future.

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Supplementary material

(Table S1, Figure S1-S5)

Table S1 Summary of plant species investigated in this study.

Sites	No.	Species	Genus	Family	FFD
Harbin	1	<i>Ulmus pumila</i>	<i>Ulmus</i>	Ulmaceae	108
	2	<i>Syringa oblata</i>	<i>Syringa</i>	Oleaceae	131
	3	<i>Sorbaria kirilowii</i>	<i>Sorbaria</i>	Rosaceae	192
	4	<i>Juglans mandshurica</i>	<i>Juglans</i>	Juglandaceae	140
	5	<i>Lonicera maackii</i>	<i>Lonicera</i>	Caprifoliaceae	147
	6	<i>Amygdalus triloba</i>	<i>Amygdalus</i>	Rosaceae	125
	7	<i>Armeniaca sibirica</i>	<i>Armeniaca</i>	Rosaceae	124
	8	<i>Syringa reticulata</i> var. <i>amurensis</i>	<i>Syringa</i>	Oleaceae	161
	9	<i>Forsythia mandschurica</i>	<i>Forsythia</i>	Oleaceae	111
	10	<i>Philadelphus schrenkii</i>	<i>Philadelphus</i>	Saxifragaceae	151
	11	<i>Phellodendron amurense</i>	<i>Phellodendron</i>	Rutaceae	158
	12	<i>Viburnum opulus</i>	<i>Viburnum</i>	Caprifoliaceae	148
	13	<i>Fraxinus mandschurica</i>	<i>Fraxinus</i>	Oleaceae	126
	14	<i>Syringa oblata</i> var. <i>alba</i>	<i>Syringa</i>	Oleaceae	130
	15	<i>Salix matsudana</i>	<i>Salix</i>	Salicaceae	122
	16	<i>Sambucus williamsii</i>	<i>Sambucus</i>	Caprifoliaceae	137
	17	<i>Viburnum burejaeticum</i>	<i>Viburnum</i>	Caprifoliaceae	139
	18	<i>Morus alba</i>	<i>Morus</i>	Moraceae	142
	19	<i>Catalpa ovata</i>	<i>Catalpa</i>	Bignoniaceae	182
	20	<i>Sorbus pohuashanensis</i>	<i>Sorbus</i>	Rosaceae	140
	21	<i>Weigela florida</i>	<i>Weigela</i>	Caprifoliaceae	141
	22	<i>Malus baccata</i>	<i>Malus</i>	Rosaceae	132
	23	<i>Caragana arborescens</i>	<i>Caragana</i>	Leguminosae	139
	24	<i>Xanthoceras sorbifolia</i>	<i>Xanthoceras</i>	Sapindaceae	141
	25	<i>Acer ginnala</i>	<i>Acer</i>	Aceraceae	146
	26	<i>Flueggea suffruticosa</i>	<i>Flueggea</i>	Euphorbiaceae	173
	27	<i>Lonicera tatarinowii</i> Maxim.	<i>Lonicera</i>	Caprifoliaceae	150
	28	<i>Lеспедеза bicolor</i>	<i>Lеспедеза</i>	Leguminosae	188
	29	<i>Spiraea trichocarpa</i>	<i>Spiraea</i>	Rosaceae	156
	30	<i>Rhododendron dauricum</i>	<i>Rhododendron</i>	Ericaceae	115
	31	<i>Acer saccharum</i>	<i>Acer</i>	Aceraceae	116
	32	<i>Crataegus pinnatifida</i> var. <i>major</i>	<i>Crataegus</i>	Rosaceae	145
	33	<i>Prinsepia sinensis</i>	<i>Prinsepia</i>	Rosaceae	126
	34	<i>Ligustrum obtusifolium</i>	<i>Ligustrum</i>	Oleaceae	169
	35	<i>Vitis amurensis</i>	<i>Vitis</i>	Vitaceae	149
	36	<i>Spiraea pubescens</i>	<i>Spiraea</i>	Rosaceae	142
	37	<i>Ribes odoratum</i> Wendl.	<i>Ribes</i>	Saxifragaceae	133

	38	<i>Syringa villosa</i>	<i>Syringa</i>	Oleaceae	151
	39	<i>Salix matsudana f. tortuosa</i>	<i>Salix</i>	Salicaceae	120
	40	<i>Lonicera ferdinandii</i>	<i>Lonicera</i>	Caprifoliaceae	150
Beijing	1	<i>Amygdalus davidiana</i>	<i>Amygdalus</i>	Rosaceae	84
	2	<i>Castanea mollissima</i>	<i>Castanea</i>	Fagaceae	153
	3	<i>Salix matsudana</i>	<i>Salix</i>	Salicaceae	94
	4	<i>Albizia julibrissin</i>	<i>Albizia</i>	Leguminosae	162
	5	<i>Populus canadensis</i>	<i>Populus</i>	Salicaceae	88
	6	<i>Paeonia suffruticosa</i>	<i>Paeonia</i>	Paeoniaceae	113
	7	<i>Morus alba</i>	<i>Morus</i>	Moraceae	114
	8	<i>Salix matsudana var. pendula</i>	<i>Salix</i>	Salicaceae	97
	9	<i>Malus micromalus</i>	<i>Malus</i>	Rosaceae	106
	10	<i>Syringa oblata</i>	<i>Syringa</i>	Oleaceae	99
	11	<i>Armeniaca vulgaris</i>	<i>Armeniaca</i>	Rosaceae	95
	12	<i>Pinus tabulaeformis</i>	<i>Pinus</i>	Pinaceae	121
	13	<i>Ulmus pumila</i>	<i>Ulmus</i>	Ulmaceae	77
	14	<i>Magnolia denudata</i>	<i>Magnolia</i>	Magnoliaceae	91
	15	<i>Robinia pseudoacacia</i>	<i>Robinia</i>	Leguminosae	124
	16	<i>Sabina chinensis</i>	<i>Sabina</i>	Cupressaceae	92
	17	<i>Sophora japonica</i>	<i>Sophora</i>	Leguminosae	196
	18	<i>Cerasus yedoensis</i>	<i>Cerasus</i>	Rosaceae	106
	19	<i>Acer mono</i>	<i>Acer</i>	Aceraceae	104
	20	<i>Fraxinus chinensis</i>	<i>Fraxinus</i>	Oleaceae	111
	21	<i>Platycladus orientalis</i>	<i>Platycladus</i>	Cupressaceae	89
	22	<i>Syringa reticulata var. amurensis</i>	<i>Syringa</i>	Oleaceae	139
	23	<i>Diospyros lotus</i>	<i>Diospyros</i>	Ebenaceae	139
	24	<i>Diospyros kaki</i>	<i>Diospyros</i>	Ebenaceae	136
	25	<i>Firmiana simples</i>	<i>Firmiana</i>	Sterculiaceae	173
	26	<i>Syringa oblata</i>	<i>Syringa</i>	Oleaceae	102
	27	<i>Cercis chinensis</i>	<i>Cercis</i>	Leguminosae	106
	28	<i>Wisteria sinensis</i>	<i>Wisteria</i>	Leguminosae	114
	29	<i>Lagerstroemia indica</i>	<i>Lagerstroem</i>	Lythraceae	191
	30	<i>Ailanthus altissima</i>	<i>Ailanthus</i>	Simaroubaceae	146
	31	<i>Populus tomentosa</i>	<i>Populus</i>	Salicaceae	78
	32	<i>Amygdalus triloba</i>	<i>Amygdalus</i>	Rosaceae	99
	33	<i>Juglans regia</i>	<i>Juglans</i>	Juglandaceae	115
	34	<i>Koelreuteria paniculata</i>	<i>Koelreuteria</i>	Sapindaceae	155
	35	<i>Catalpa bungei</i>	<i>Catalpa</i>	Bignoniaceae	120
	36	<i>Amygdalus persica var. persica f. duplex</i>	<i>Amygdalus</i>	Rosaceae	100
	37	<i>Forsythia suspensa</i>	<i>Forsythia</i>	Oleaceae	90
	38	<i>Pyrus betulifolia</i>	<i>Pyrus</i>	Rosaceae	107
	39	<i>Punica granatum</i>	<i>Punica</i>	Punicaceae	143
	40	<i>Syringa oblata var. alba</i>	<i>Syringa</i>	Oleaceae	104

	41	<i>Cerasus serrulata</i> var. <i>lannesiana</i>	<i>Cerasus</i>	Rosaceae	103
	42	<i>Paulownia fortunei</i>	<i>Paulownia</i>	Scrophulariaceae	113
	43	<i>Cotinus coggygria</i>	<i>Cotinus</i>	Anacardiaceae	114
	44	<i>Rosa xanthina</i>	<i>Rosa</i>	Rosaceae	115
	45	<i>Rhodotypos scandens</i>	<i>Rhodotypos</i>	Rosaceae	110
	46	<i>Jasminum floridum</i>	<i>Jasminum</i>	Oleaceae	93
	47	<i>Fructus Crataegi</i>	<i>Fructus</i>	Rosaceae	122
	48	<i>Populus simonii</i>	<i>Populus</i>	Salicaceae	93
	49	<i>Jasminum nudiflorum</i>	<i>Jasminum</i>	Oleaceae	78
Xi'an	1	<i>Ulmus pumila</i>	<i>Ulmus</i>	Ulmaceae	108
	2	<i>Cercis chinensis</i>	<i>Cercis</i>	Leguminosae	131
	3	<i>Magnolia denudata</i>	<i>Magnolia</i>	Magnoliaceae	192
	4	<i>Ailanthus altissima</i>	<i>Ailanthus</i>	Simaroubaceae	140
	5	<i>Robinia pseudoacacia</i>	<i>Robinia</i>	Leguminosae	147
	6	<i>Populus tomentosa</i>	<i>Populus</i>	Salicaceae	125
	7	<i>Paeonia suffruticosa</i>	<i>Paeonia</i>	Paeoniaceae	124
	8	<i>Amygdalus davidiana</i>	<i>Amygdalus</i>	Rosaceae	161
	9	<i>Salix babylonica</i>	<i>Salix</i>	Salicaceae	111
	10	<i>Acer mono</i>	<i>Acer</i>	Aceraceae	151
	11	<i>Phellodendron amurense</i>	<i>Phellodendron</i>	Rutaceae	158
	12	<i>Viburnum opulus</i>	<i>Viburnum</i>	Caprifoliaceae	148
	13	<i>Albizia julibrissin</i>	<i>Albizia</i>	Leguminosae	126
	14	<i>Koelreuteria paniculata</i>	<i>Koelreuteria</i>	Sapindaceae	130
	15	<i>Cerasus yedoensis</i>	<i>Cerasus</i>	Rosaceae	106
	16	<i>Diospyros kaki</i>	<i>Diospyros</i>	Ebenaceae	137
	17	<i>Wisteria sinensis</i>	<i>Wisteria</i>	Leguminosae	139
	18	<i>Juglans regia</i>	<i>Juglans</i>	Juglandaceae	142
	19	<i>Catalpa ovata</i>	<i>Catalpa</i>	Bignoniaceae	182
	20	<i>Melia azedarach</i>	<i>Melia</i>	Meliaceae	140
	21	<i>Ulmus pumila</i>	<i>Ulmus</i>	Ulmaceae	141
	22	<i>Malus baccata</i>	<i>Malus</i>	Rosaceae	132
	23	<i>Chaenomeles sinensis</i>	<i>Chaenomeles</i>	Rosaceae	139
	24	<i>Bothrocaryum controversum</i>	<i>Bothrocaryum</i>	Cornaceae	141
	25	<i>Pyrus betulifolia</i>	<i>Pyrus</i>	Rosaceae	146
	26	<i>Pterocarya stenoptera</i>	<i>Pterocarya</i>	Juglandaceae	173
	27	<i>Lonicera tatarinowii</i> Maxim.	<i>Lonicera</i>	Caprifoliaceae	150
	28	<i>Diospyros lotus</i>	<i>Diospyros</i>	Ebenaceae	188
	29	<i>Forsythia suspensa</i>	<i>Forsythia</i>	Oleaceae	156
	30	<i>Cerasus tomentosa</i>	<i>Cerasus</i>	Rosaceae	115
	31	<i>Xanthoceras sorbifolia</i>	<i>Xanthoceras</i>	Sapindaceae	116
	32	<i>Sapium sebiferum</i>	<i>Sapium</i>	Euphorbiaceae	145
	33	<i>Ginkgo biloba</i>	<i>Ginkgo</i>	Ginkgoaceae	126
	34	<i>Corylus heterophylla</i>	<i>Corylus</i>	Betulaceae	169
	35	<i>Koelreuteria bipinnata</i> Franch.	<i>Koelreuteria</i>	Sapindaceae	149

	<i>var. integrifoliola</i>			
36	<i>Forsythia viridissima</i>	<i>Forsythia</i>	Oleaceae	142
37	<i>Amorpha fruticosa</i>	<i>Amorpha</i>	Leguminosae	133
38	<i>Fructus Crataegi</i>	<i>Fructus</i>	Rosaceae	151

Note: FFD (in day of the year) was calculated as mean first flowering date from 1963 to 2014.

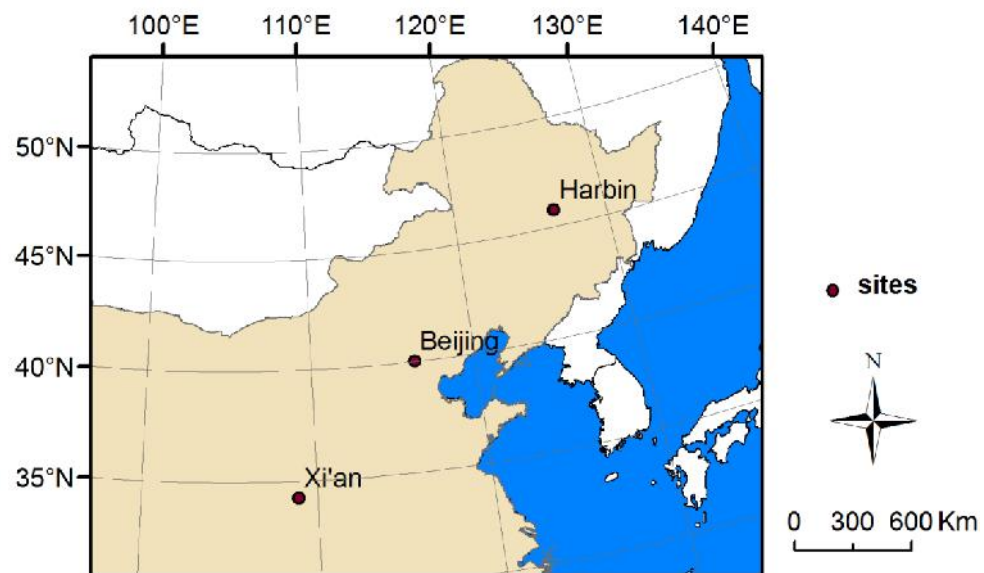


Fig. S1 Geographical locations of three sites investigated in this study

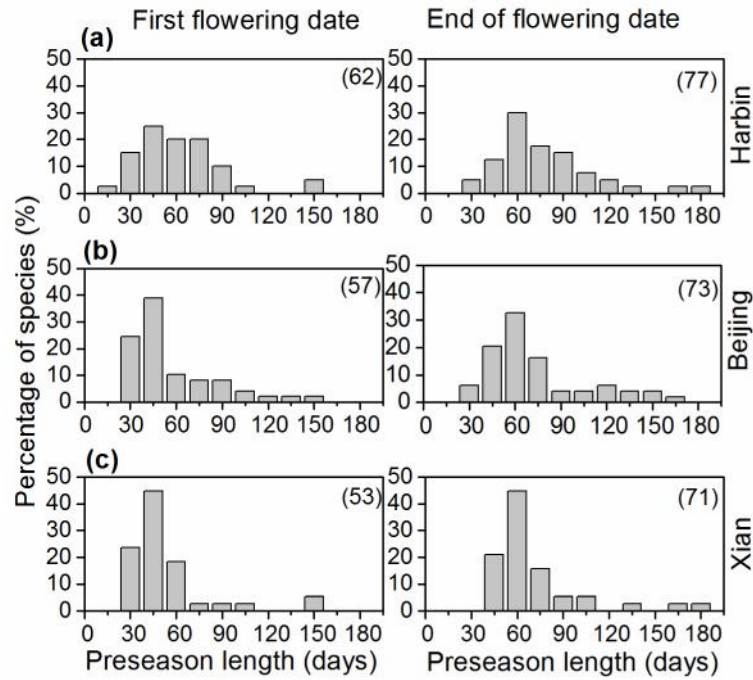


Fig. S2 The distribution of preseason length for plant species at each site. The optimal preseason was defined as the period before phenophase (first flowering date or end of flowering date) for which the Spearman's rank correlation coefficient between phenophase and mean temperature was highest. The numbers in the brackets are the mean values. (a) Harbin; (b) Beijing; (c) Xi'an

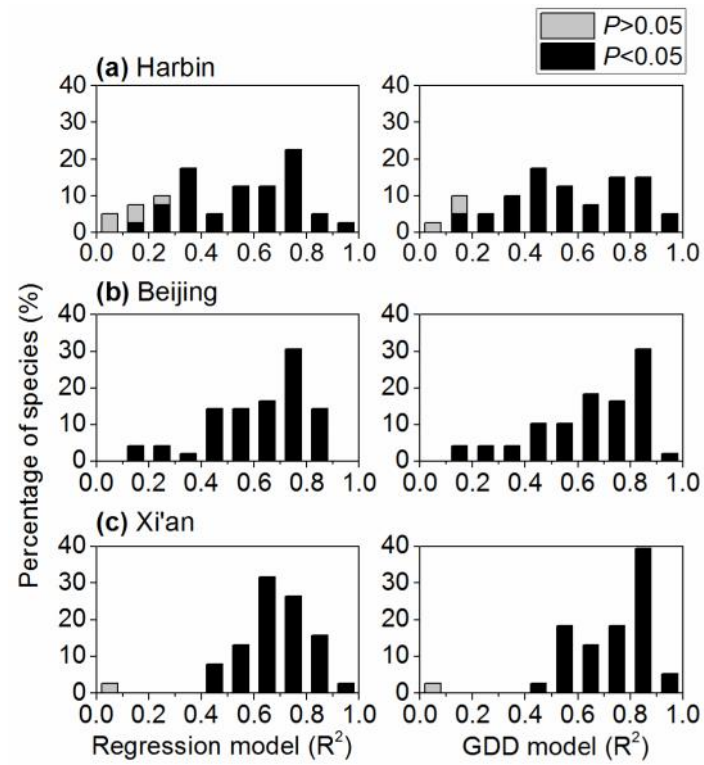


Fig. S3 The frequency distribution of goodness of fit (R^2) for two types of models when simulating first flowering date of plants species at each site. Two types of models include regression model and growing degree day (GDD) model.

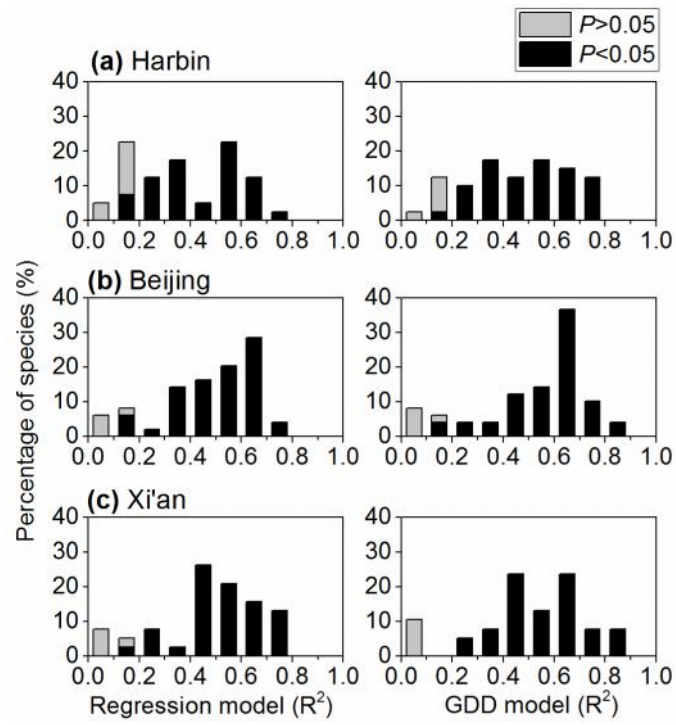


Fig.S4 The frequency distribution of goodness of fit (R^2) for two types of models when simulating the end of flowering date of plants species at each site. Two types of models include regression model and growing degree day (GDD) model.

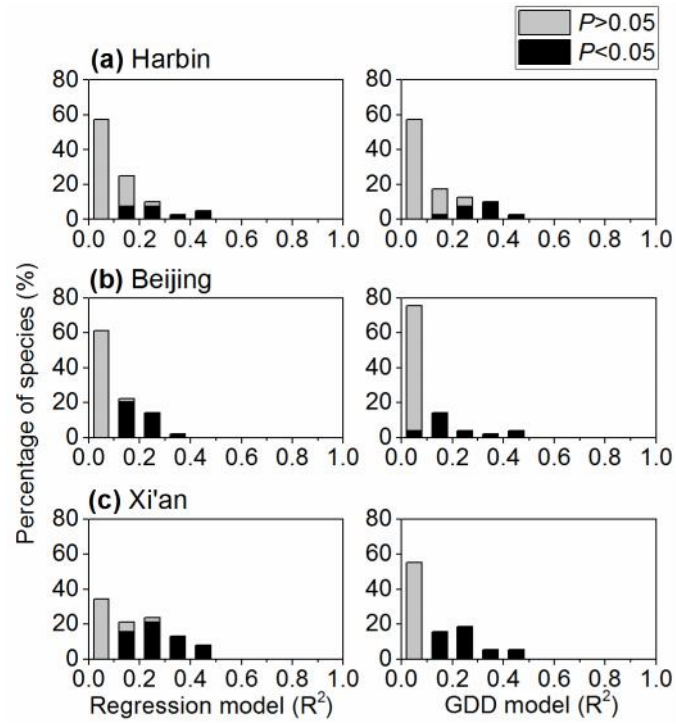


Fig. S5 The frequency distribution of goodness of fit (R^2) for two types of models when simulating flowering duration of plants species at each site. Two types of models include regression model and growing degree day (GDD) model.