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Shifts in spring phenophases, frost events and frost risk for woody plants in temperate China

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ABSTRACT: In light of recent warming trends around the world, a growing concern is that the timing of spring phenophases in plants will occur earlier and that plants will therefore suffer from spring last-frost events more often. The changes in frost risks could have significant implications for agricultural and forestry systems. In this study, we investigated whether plant phenophases changed at a higher or lower rate compared to potentially damaging spring frost events in the temperate monsoon area of China. Based on phenological data derived from the Chinese phenological observation network and meteorological data from 15 study sites, changes in first-leaf dates and first-flowering dates for 12 deciduous woody plants were analyzed in comparison to last-frost dates. The results show that plant phenophases in spring advanced by a mean trend of -0.17 d yr^{-1} from 1963 to 2011. Over the same period, last-frost dates advanced at a rate of -0.23 d yr^{-1} (-0.51 to 0.10 d yr^{-1}). Because the spring frost risk is decided by the relationship between last-frost date and plant phenophases in spring, the frost index, defined as the difference in days between the onset of spring phenophases and the last-frost date, was used to assess the frost risk. The significantly increased frost index (0.087 d yr^{-1}, $p < 0.01$) suggests that the frost risk of plant phenophases in the study area declined over the nearly half-century study period. These findings provide the basis for tackling frost risk in the region.

KEY WORDS: Climate change · Spring phenology · Frost risk · Last-frost dates

1. INTRODUCTION

Recent phenological changes in response to climate change in the Northern Hemisphere have been detected using data of ground-based observational networks (Parmesan & Yohe 2003, Root et al. 2003, Menzel et al. 2006, Rutishauser et al. 2007, Ge et al. 2011) and remote sensing (White et al. 2009, Jeong et al. 2011, Piao et al. 2011, Wu & Liu 2013). Most studies have found advanced spring events and delayed autumn events, which indicate an extension of the length of the growing season of deciduous plants (Linderholm 2006, Donnelly et al. 2012). The lengthening of the growing season over the past several decades has mainly been due to a pronounced advance of spring events, while the delay of autumn events has generally been less pronounced (Menzel et al. 2006). This shift in plant phenology has important effects on the carbon balance of forest ecosystems (Picard et al. 2005, Richardson et al. 2010, Schwartz et al. 2013), the distribution of plant species (Chuine 2010), ecosystem structure and function (Devaux & Lande 2010) and frost risk (Bennie et al. 2010). Moreover, the phenological response to climate warming varied between different functional groups, leading to a mismatch in timing between, for example, plants and pollinators (Visser et al. 1998) and host plants and herbivorous insects (DeLucia et al. 2012), further impacting the growth or reproduction of plants. Since aeroallergens are directly related to pollen amounts

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and seasons (Beggs 2004, Reid & Gamble 2009), changes in time and duration of the pollen season can affect human health as well.

The change in frost risk is one important aspect of the effects of phenological change. The frost risk of plants depends on both changes to plant phenophases and the timing of frost occurrences (Schwartz 1993, Scheifinger et al. 2003). Of interest here is whether plant phenophases (an observable stage or phase in the annual life cycle of a specific plant or animal) change at a higher or lower rate in terms of potentially damaging events, such as the timing of a last spring frost. For example, if the last-frost dates (LFD) advanced more quickly than changes in plant phenophases, frost risk should be reduced as the timing of the 2 events diverge. Therefore, the relationship between plant phenophases and frost events needs to be studied further.

The occurrence of plant phenophases and frost events are controlled by different mechanisms. A large body of evidence indicates that temperature, both alone and through interactions with other cues such as photoperiod, is the primary factor triggering plant phenophases in spring (Partanen et al. 1998, Chuine 2000). The timing of a last frost in spring, in contrast, is mainly dependent on temperature extremes. When assessing frost risk, therefore, plant phenophases and the timing of a final frost should be considered in tandem.

Studies on frost risk and phenophases have drawn different conclusions. Some studies in China looking at these factors separately have identified changes to spring phenophases (Ge et al. 2011, Wang et al. 2012) or the occurrence of frost or temperature extremes (Liu et al. 2008, Huang et al. 2010). A number of studies have examined frost risk and phenophase together, including studies in China (Schwartz & Chen 2002, Dai et al. 2013), and several modelling studies in Europe (Cannell & Smith 1986, Kramer 1994, Leinonen 1996, Hänninen 2006). Using a site-specific analysis, Dai et al. (2013) found that the percentage of species of woody plants exposed to frost during their flowering period has decreased in temperate China. However, whether the frost risk of vegetative phenophases (e.g. leaf timing) has consistently changed and whether differences in the frost resistance of phenophases and the changes in frost risk are correlated need to be further investigated.

The area experiencing temperate monsoons is an important agricultural region in China. Spring frosts often cause much damage to plants in this area (Fen et al. 1995). Climate averages in the area have become significantly warmer and drier over the past half century (Ding et al. 2007). These factors make this area suitable as an experimental region to investigate changes in plant phenophases and the timing of spring frost events. Specifically, our objectives were (1) to compare shifts in plant phenophases and the last-frost events damaging plants and to assess changes in the frost risk over the last half century in temperate China and (2) to identify the relationship between the frost resistance and the frost risk change of different phenophases.

2. MATERIALS AND METHODS

2.1. Phenological and meteorological data

All phenological data in this study were derived from the Chinese Phenological Observation Network (CPON), which began its observations in 1963 under the auspices of the Institute of Geographic Sciences and Natural Resources Research (IGSNRR) of the Chinese Academy of Sciences. For this study, 23 spring phenophases at 15 different CPON sites from 1963 to 2011 were available for analysis (Fig. 1). A total of 206 different cases were therefore available, with 1 case consisting of a single phenological event at a specific site. Twelve species of deciduous woody plants and 2 phases — first-flowering date and first-leaf date — were observed (Table 1). According to the uniform observation criteria and guidelines of CPON (Wan & Liu 1979), first-flowering date (FFD) and first-leaf date (FLD) are defined, respectively, as the date in spring when a fixed individual specimen formed its first full flower and first full leaf.

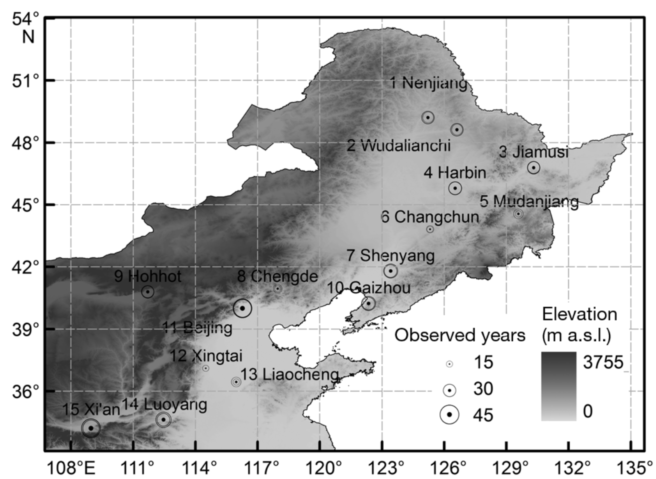

Fig. 1. Phenological stations used for the study. Center of circle: location; circle size: number of years observed at each site during the 1963–2011 study period; m.a.s.l: meters above sea level. Site numbers and names are shown

Table 1. Phenophases selected in the study. Site numbers correspond to sites shown in Fig. 1. FFD: first-flowering date; FLD: first-leaf date; T_c: the minimum temperature in the mean occurrence dates of each phenophase based on climate averages from 1963 to 2011 at each site

Pheno-phase no.	Species	Phase	Sites	Mean date	T_c (°C) (mean ± SD)
1	*Populus × canadensis*	FFD	7, 8, 9, 11, 12, 13, 14, 15	29 Mar	3.6 ± 1.4
2	*Ulmus pumila*	FFD	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	1 Apr	1.4 ± 1.0
3	*Salix babylonica*	FLD	1, 5, 7, 9, 10, 12, 13, 14, 15	3 Apr	3.1 ± 0.7
4	*Amygdalus davidiana*	FFD	6, 7, 8, 9, 11, 15	4 Apr	2.9 ± 1.1
5	*Salix babylonica*	FFD	1, 5, 7, 10, 12, 13, 14, 15	9 Apr	4.3 ± 1.4
6	*Armeniaca vulgaris*	FFD	3, 5, 8, 9, 10, 11, 12, 13, 15	11 Apr	4.6 ± 1.4
7	*Amygdalus davidiana*	FLD	6, 7, 8, 9, 11, 15	13 Apr	5.5 ± 1.3
8	*Sophora japonica*	FLD	8, 9, 12, 13, 14, 15	15 Apr	7.8 ± 1.0
9	*Salix matsudana*	FLD	1, 2, 4, 5, 7, 9, 10, 11, 12, 13	16 Apr	4.0 ± 1.4
10	*Populus × canadensis*	FLD	2, 7, 8, 9, 11, 12, 13, 14, 15	16 Apr	6.4 ± 1.5
11	*Salix matsudana*	FFD	1, 2, 4, 5, 7, 9, 10, 11, 12, 13	17 Apr	4.2 ± 1.7
12	*Armeniaca vulgaris*	FLD	3, 5, 10, 11, 12, 13, 15	18 Apr	7.5 ± 1.0
13	*Ailanthus altissima*	FLD	7, 10, 11, 12, 14, 15	19 Apr	9.4 ± 0.9
14	*Robinia pseudoacacia*	FLD	4, 7, 8, 9, 10, 11, 12, 13, 14, 15	19 Apr	7.8 ± 1.0
15	*Syringa oblata*	FLD	1, 2, 3, 4, 6, 7, 8, 9, 10, 11, 12, 14, 15	20 Apr	5.5 ± 1.4
16	*Ulmus pumila*	FLD	1, 2, 3, 4, 5, 6, 7, 9, 10, 11, 12, 13, 14, 15	21 Apr	5.6 ± 1.3
17	*Amygdalus triloba*	FFD	2, 3, 4, 6, 9, 10, 11, 12, 15	22 Apr	6.0 ± 1.4
18	*Syringa oblata*	FFD	1, 2, 3, 4, 6, 7, 8, 9, 10, 11, 12, 14, 15	23 Apr	6.7 ± 1.4
19	*Amygdalus triloba*	FLD	2, 3, 4, 6, 9, 10, 11, 12, 15	23 Apr	6.5 ± 1.1
20	*Morus alba*	FLD	1, 4, 9, 10, 11, 12, 15	30 Apr	8.8 ± 1.1
21	*Morus alba*	FFD	4, 9, 10, 11, 12, 15	1 May	9.9 ± 1.2
22	*Robinia pseudoacacia*	FFD	4, 7, 8, 9, 10, 11, 12, 13, 14, 15	6 May	11.1 ± 1.2
23	*Ailanthus altissima*	FFD	7, 10, 11, 12, 14, 15	24 May	15.6 ± 1.2

Among the 23 phenophases, the earlier phenophases are more at risk of suffering frost, but they also may be much more resistant to extreme temperature, e.g. the *Ulmus pumila* (Siberian elm) has long been shown to be able to endure temperature fluctuations at low temperature extremes (Dorsett 1916). We use the critical temperature (T_c) to describe the frost resistance of each phenophase (Table 1). T_c is defined as the minimum temperature in the mean dates of phenophases based on climate averages from 1963 to 2011. Phenophases with lower T_c values tend to have stronger frost resistance and be less sensitive to last-frost events. It is also noteworthy that during the 48 yr study period, no observations were carried out in certain periods at each of the observational sites. These gaps were due first to the social upheavals of the Cultural Revolution (1969–1972) and then to CPON funding shortages in the late 1990s (Fig. 1). Because the missing observation data affect the temporal consistency of observational results, we interpolated the missing data by applying the results of a phenological model. Although the interpolated phenological data may introduce considerable bias into the results, we were able to quantify these uncertainties in our analyses (see Section 2.2).

Meteorological data were derived from the Chinese Meteorological Administration (http://cdc.cma.gov.cn/, in Chinese) and included daily mean, maximum and minimum temperatures from 15 climate stations (Fig. 1). These climate stations were relatively close to the corresponding phenological sites (usually <5 km in distance), except Site 2 (Wudalianchi) and Site 10 (Gaizhou) for which the corresponding meteorological stations were about 30 km away.

According to Snyder & de Melo-Abreu (2005), a 'frost' occurs when the air temperature reaches 0°C or lower, measured at a height of between 1.25 and 2.0 m above soil level and inside an appropriate weather shelter. Based on this definition, if minimum temperatures are ≤0°C on any particular day in historical meteorological data, then a frost can be said to have occurred on that day. So LFDs can be defined as the last day in the spring on which the temperature (at 1.25 to 2 m) falls to 0°C or below.

2.2. Methods

2.2.1. Interpolation of missing data using a phenological model

Robust phenological models can be used to simulate past, present and future species phenology over wide areas when long-term, ground-based phenological observations are unavailable (Cleland et al. 2007). In this study, the simple spring warming (SW) model (also called the thermal time model) was used to interpolate missing observation data in the study area (Cannell & Smith 1983, Hunter & Lechowicz 1992). The equation for this model is:

$$\text{HDD} = \sum_{t=t_0}^{t_y} \max(0, x_t - T_b) = F \quad (1)$$

where x_t is the daily mean temperature and HDD (heating degree days) is measured as the sum of daily mean temperature above a base temperature T_b, starting at day-of-year (DOY) t_0 (Eq. 1). The HDD achieves the critical degree day threshold (F) at time t_y, which indicates that the specific phenophase has started (Eq. 1). The 3 unknown parameters (t_0, F, T_b) are fitted according to observation data.

We fitted the SW model by the least-squares method using odd years of each phenophase series at each site (Chuine et al. 1998). A simulated annealing method was used for seeking the optimal parameters (Chuine et al. 1998). Internal validity (goodness-of-fit) was evaluated by calculating the percentage of variance explained by the model (R^2) and the standard error (SE) between the observed dates and the simulated dates. External validity, measured by the R^2 and SE between remaining cases and simulated dates, was used to assess the predictive ability of the model for independent data. Finally, a continuous phenophase series was formed by interpolating the missing observed data through the simulated dates by using the models described above. The uncertainties for these interpolations were estimated using the SE of external validity of the models.

2.2.2. Change of phenology and frost risk

In order to assess the frost risk, Schwartz (1993) first used a new measure, the 'damage index' (lilac first-leaf date minus last-frost date) to assess the risk of frost damage to spring plant development in eastern North America. Subsequently, the same method was used to assess the frost risk in other parts of the world (Schwartz & Chen 2002, Scheifinger et al. 2003, Schwartz et al. 2006). In the present study, the 'damage index' was re-termed the 'frost index', because we expanded the original method by using different phenophases rather than only the first-leaf date of lilac for frost risk assessment. Here, the frost index, defined as the temporal difference between the spring phenophases of plants and last-frost dates, can indicate the relative internal timing of spring phenological events and the potential for plant frost damage in a given year. As the frost index becomes increasingly positive, the potential for frost damage in plants decreases.

Table 2. Internal and external validity of spring warming models for all 206 frost–phenophase cases. The average, maximum, and minimum values of percentage variance explained (R^2) and standard error (SE) on internal and external data are shown

Statistical effect	Internal validity	External validity
R^2 (mean ± SD)	0.61 ± 0.25	0.70 ± 0.22
R^2 (min.)	0.15	0.16
R^2 (max.)	0.98	0.99
SE (d, mean ± SD)	3.71 ± 1.55	3.45 ± 1.47
SE (d, min.)	1.00	1.47
SE (d, max.)	9.24	9.81

Subsequently, we performed a linear regression between plant phenophases, last-frost dates, the frost index and time (in years), respectively. The temporal trends in plant phenophases, last-frost dates and the frost index could then be represented by the slope of a linear regression. A 2-tailed t-test was used to test the significance of the regression slope.

3. RESULTS

3.1. Model validity

For internal validity, the explained variance (R^2) was from 0.15 to 0.98, with a mean of 0.61 for all cases (Table 2). Accordingly, the average SE of all models for internal validity was 3.71 d. Regarding external validity, R^2 and SE were 0.70 and 3.45 d, respectively (Table 2). Therefore, the SW model can be said to have simulated the FFD accurately, so the missing phenological data for each plant phenophase series could be validly interpolated through corresponding SW models. Uncertainties introduced by the interpolated data were estimated using the SE of external validity.

3.2. Trends in plant phenophases and last-frost dates

Except for *Ailanthus altissima* FFD (Phenophase No. 23), the interquartile range of last-frost dates overlaps, to a large extent, the interquartile range of plant phenophases from 1963 to 2011 (Fig. 2), indicating that there is a high probability that plants in the study region have suffered frost events. When com-

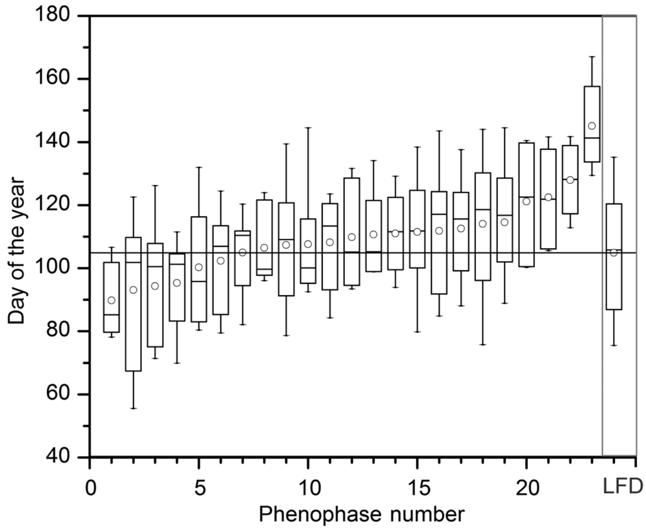

Fig. 2. Mean timings of each plant phenophase and last-frost dates at corresponding sites. Bottoms and tops of boxes: 25th and 75th percentiles; bands within boxes: medians; whiskers: minimum and maximum; circles: mean value over the entire distribution of sites; LFD (plot at far right): last-frost date. Horizontal black line: mean LFD. Phenophase numbers are defined in Table 1

paring means, however, only the first 6 phenophases occurred earlier than the LFD (Fig. 2); thus, these phenophases can probably endure lower temperatures. As Table 1 shows, the T_c for these 6 phenophases were between 1.4 and 4.6°C, which was lower than all other phenophases except *Salix matsudana* FLD (Phenophase No. 9). With a T_c of 1.4°C, *Ulmus pumila* FFD (Phenophase No. 2) is particularly hardy, able to endure temperatures ≥1.5°C lower than even the hardiest of the other species studied.

Fig. 3 shows the linear trends in plant phenophases and last-frost dates from 1963 to 2011. We found that distributions of these trend values for each plant phenophase and last-frost dates were inclined towards the negative (Fig. 3). For all plant phenophases, the trend averages from corresponding distribution sites were negative (Fig. 3). *Ailanthus altissima* FLD (Phenophase No. 13) advanced most quickly at a rate of −0.20 d yr^{-1}, while *Sophora japonica* FLD (Phenophase No. 8) advanced at a minimum rate of −0.13 d yr^{-1} (Fig. 3). With respect to LFD, 14 stations showed negative trends, and only 1 station showed a positive trend. Overall, trends in plant phenophases and last-frost dates from 1963 to 2011 averaged −0.17 ± 0.09 (mean ± SD) and −0.23 ± 0.15 d yr^{-1}, respectively. Of 206 cases of plant phenophases, 156 (75.7%) showed significantly negative trends ($p < 0.05$; Fig. 3). Similarly, 12 (80.0%) of 15 cases of last-frost dates showed significantly negative trends. These advanced spring events indicate a general warming in the study area of temperate China from 1963 to 2011.

3.3. Trends in the frost index

Trends in the frost index for the 23 selected phenophases at corresponding sites are summarized in Fig. 4. For each plant phenophase, distributions of trends in the frost index were inclined towards the positive. The mean and median values of the frost index showed increased trends for all plant phenophases (Fig. 4). There were 1 to 4 significantly positive trend values for each plant phenophase. In general, 143 (69.4%) of 206 cases were positive, with 53 (25.7%) cases being significant ($p < 0.05$; Fig. 4). The trend in the regional frost index from 1963 to 2011 was 0.087 d yr^{-1}, averaged from all 206 cases ($p < 0.01$; Fig. 5). From 1995 to 2005, the frost index showed high variation, and the years 1998 and 2000 were associated, respectively, with the lowest and highest frost index (Fig. 5). On the decadal scale, the frost index increased gradually over time, and the frost index in the last decade was maximal compared

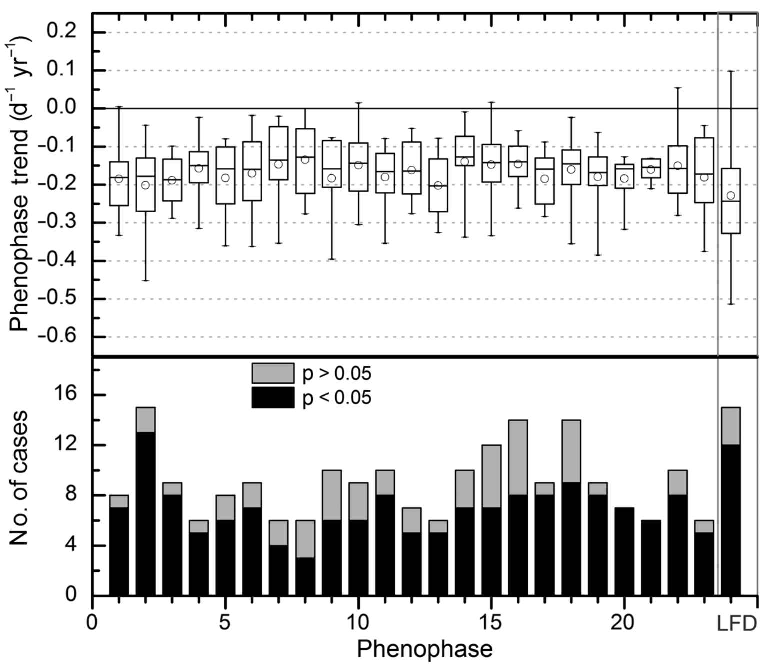

Fig. 3. Trends in each plant phenophase and last-frost dates at corresponding sites in temperate China from 1963 to 2011 (top) and the number of cases with significant trends (bottom). LFD (plot at far right): last-frost date. Phenophase numbers are defined in Table 1. See Fig. 2 for boxplot description

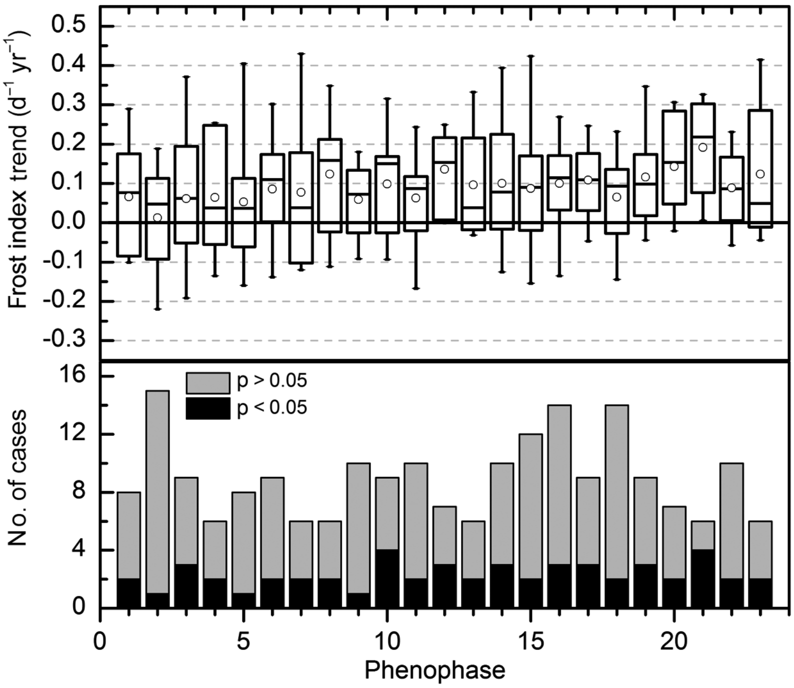

Fig. 4. Trends in the frost index according to the 23 selected phenophases at corresponding sites (top) and the number of cases with significant trends (bottom). Phenophase numbers are defined in Table 1. See Fig. 2 for boxplot description

to earlier decades (Fig. 5). This increase in the frost index indicates a declining frost risk in the study area over the past 48 yr.

For each phenophase at its corresponding site, the change in the frost index can be divided into 4 types (Fig. 6). If mean plant phenophases occur later than the mean LFD, and the trend of the LFD is more negative than the trend of the plant phenophase (TYPE I; Fig. 6a), the frost index would increase, indicating that plants are less likely to suffer spring frosts

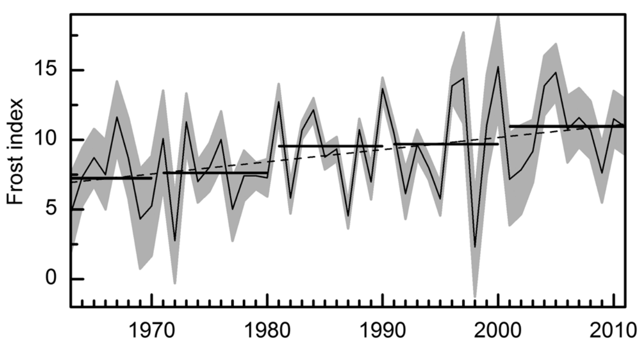

Fig. 5. Annual frost index averaged from all cases in the study region from 1963 to 2011 (thin black line). Gray area: uncertainty due to the interpolated data by models; dashed line: regression line ($y = 0.087x - 164.17$, $R^2 = 0.16$, $p < 0.01$); thick black lines: mean frost index for each of the periods 1963–1970, 1971–1980, 1981–1990, 1991–2000, and 2001–2011

(Fig. 6b). Likewise, if the mean plant phenophase is earlier than the mean LFD, and the LFD and plant phenophase converge (TYPE II; Fig. 6c), the frost index also increases (Fig. 6d). In contrast, if the mean plant phenophase occurs later than the mean LFD, and the LFD and the plant phenophase converge (TYPE III; Fig. 6e), the frost index will decrease (Fig. 6f). The last situation occurs when the mean plant phenophase comes earlier than the mean LFD, and the plant phenophase and LFD diverge (TYPE IV; Fig. 6g). TYPE IV also leads to a decreased frost index (Fig. 6h). Of the 206 cases, 38, 47 and 16 cases belonged to TYPE II, III and IV, respectively. A slight majority of cases belonged to TYPE I (105 of 206, 51.0%).

Furthermore, we examined the relationship between the mean trends in the frost index and frost resistance (represented by T_c) of each phenophase (Fig. 7). We found that T_c correlates significantly and positively with the trends in the frost index ($R^2 = 0.45$, $p < 0.001$), which means that the phenophases with lower frost resistances (higher T_c) tend to have stronger trends in the frost index time series (i.e. frost risk decreased more) than phenophases with higher frost resistance.

4. DISCUSSION

Our results confirm that the spring phenophase events of plants in the temperate monsoon area of China have occurred increasingly earlier over the past several decades, which is in accord with previous studies focused on other phenophases (Ge et al. 2011, Dai et al. 2012, 2013, Wang et al. 2012). The advanced trends of spring events in China are also consistent with phenological trends in other parts of the Northern Hemisphere (Matsumoto et al. 2003, Menzel et al. 2006, Schwartz et al. 2006). The phenological trends were, however, found to have varied between different species and phases. According to previous studies (Menzel et al. 2006, Bai et al. 2011, Doi 2012), earlier phenophases advanced a greater number of days than later ones under the same warming scenarios. This divergence explains why the frost risk decreased more (i.e. the frost index increased more) for the phenophases with lower frost resistance, since later phenophases are usually associated with lower frost resistance (as Table 1 indicates).

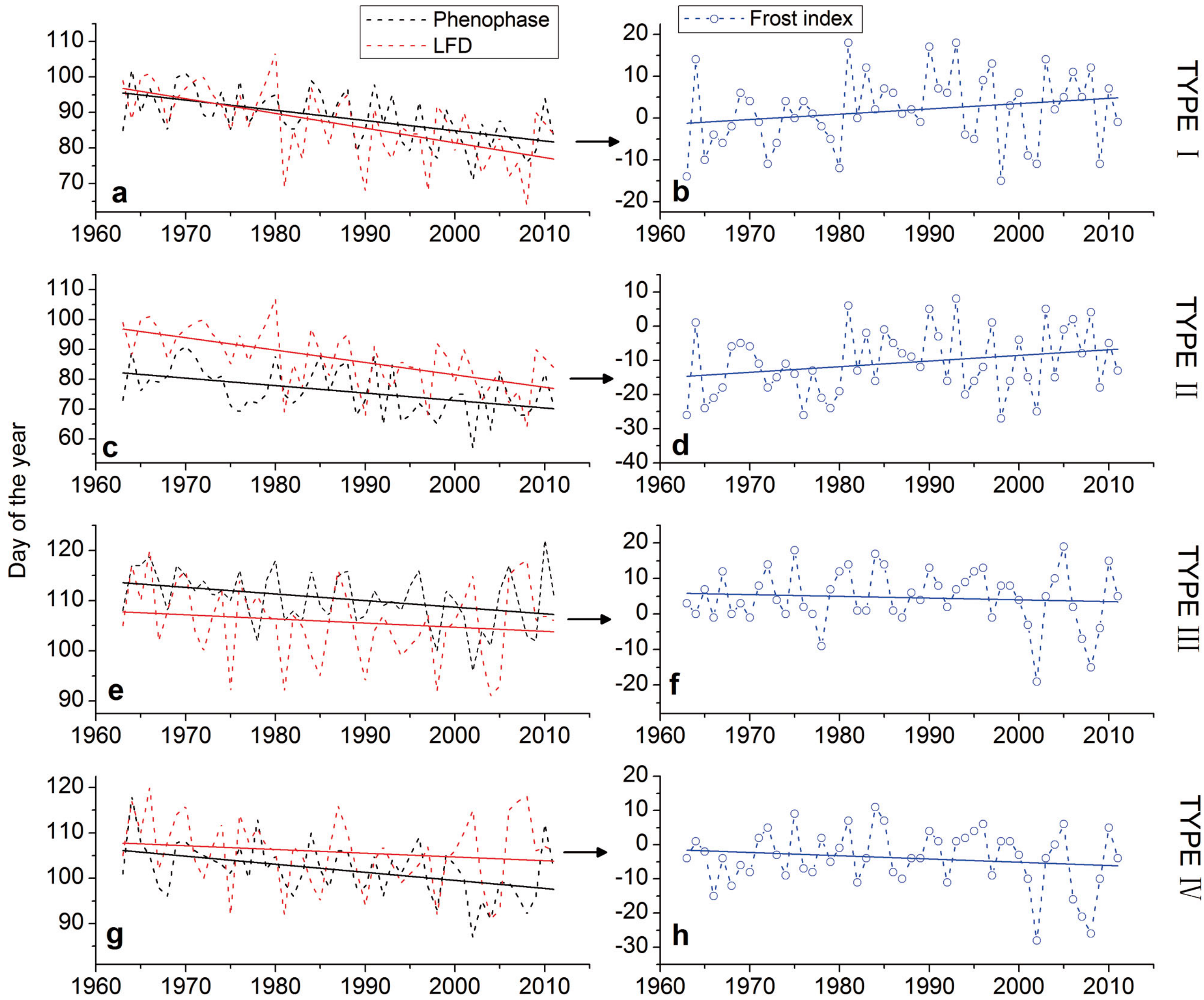

Fig. 6. Examples of 4 types of frost index change. (a) TYPE I (e.g. *Populus × canadensis* first-flowering date [FFD] at Beijing): mean plant phenophase > mean last-frost date [LFD], and plant phenophase and LFD diverge. (c) TYPE II (e.g. *Ulmus pumila* FFD at Beijing): mean plant phenophase < mean LFD, and plant phenophase and LFD converge. (e) TYPE III (e.g. *Salix babylonica* FFD at Shenyang): mean plant phenophase > mean LFD, and plant phenophase and LFD converge. (g) TYPE IV (e.g. *Ulmus pumila* FFD at Shenyang): mean plant phenophase < mean LFD, and plant phenophase and LFD diverge. (b,d) TYPES I and II both represent increased frost indexes. (f,h) TYPES III and IV both represent decreased frost indexes. The annual change (dashed lines) and regression lines (solid lines) are both shown

It is well known that spring plant phenophases in temperate areas are mainly determined by the mean temperature in spring, though other factors (e.g. winter chill, photoperiod, or precipitation) may also play a role in altering the timing of plant development, depending on species and location (Cleland et al. 2007). Considering that LFD is impacted by minimum temperature, the trends in plant phenophases relative to LFD are mainly determined by trends in mean temperature relative to minimum temperature. In most parts of the world, minimum temperatures have increased and diurnal temperature ranges (DTR) have decreased (Jones et al. 1999). In other words, increased trends in minimum temperatures have tended globally to be stronger than those in mean temperatures. Therefore, the results of this study that show that the last-frost dates have advanced more quickly than plant phenophases are consistent with the global trends in mean and minimum temperatures.

Our results are also consistent with the results of Schwartz & Chen (2002), who found that the frost risk of *Syringa oblata* (lilac) FLD in China decreased between 1959 and 1993. In Central Europe, the timing of last-frost dates in spring has also been shown to be accelerating faster than the changes of phenological phases (Menzel et al. 2003, Scheifinger et al. 2003).

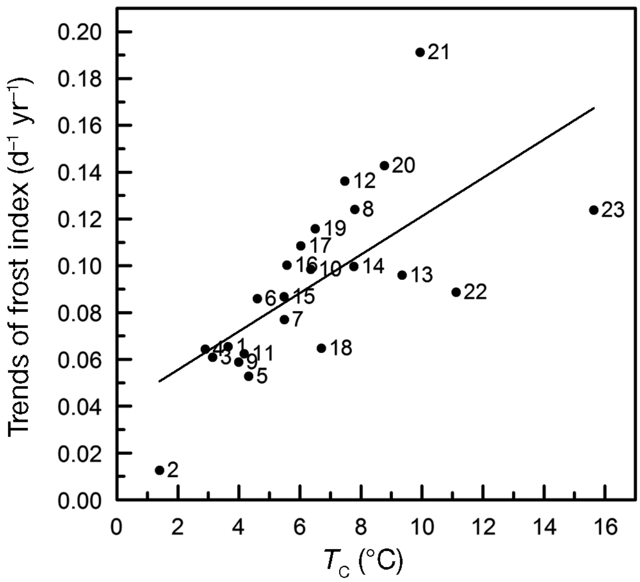

Fig. 7. Relationship between mean trends in the frost index for 23 phenophases and their critical temperatures (T_c). Phenophase numbers are defined in Table 1. The regression line is shown ($R^2 = 0.45$, $p < 0.001$)

These findings are in contrast with North America, where the frost risk has not changed significantly (Schwartz & Reiter 2000), a divergence that may be caused by differences in regional climate change. A notable exception in contrast to results from other parts of the world comes from Canada, where studies have shown decreased minimum temperatures in the east and increased DTR in the mid-regions (Easterling et al. 1997).

Though most phenological observations for the present study were conducted in rural areas, recent urban growth and changes in local land use may also affect the DTR (Karl et al. 1993), further influencing the relationship between plant phenophases and LFD. The earlier study (Easterling et al. 1997) showed that urban effects on globally and hemispherically averaged temperature time series tend to be negligible, but recent regional studies have found that the contribution of urban warming to total annual mean temperature change is 20 to 37.9% in China (Ren et al. 2008, Wang & Ge 2012). This urban effect results in increases in both minimum and mean temperatures, and thus causes the LFD and plant phenophases to advance simultaneously. When assessing trends in plant phenophases relative to LFD, the overall heat-island effect is <20%.

Over the past half century, not only has the last-frost date advanced significantly in China, as shown in the present study, but the first fall frost dates in China have also been delayed at a rate of 0.2 d yr^{-1}, from 1955 to 2000 (Liu et al. 2008). This trend suggests a lengthening of the frost-free period, which enhances the potential for multiple cropping and increased total yields of some crops (Schwartz & Chen 2002). Considering the annual variability in frost risk as deduced in this study (Fig. 5), however, careful frost protection schemes need to be devised if greater stability in agriculture yields and higher survival rates of transplanted trees are to be realized. Frost protection schemes can be divided into 2 types, passive and active (Snyder & de Melo-Abreu 2005). Selecting species or varieties with strong frost resistance (e.g. *Ulmus pumila*), creating physical barriers to control cold air drainage (e.g. walls and bushes) and covering row crops with plastic tunnels are all useful passive methods (Snyder & de Melo-Abreu 2005). Active methods are, however, also suitable for frost protection in the study area. For example, using the model developed in this study, the FFD of frost-sensitive fruit trees (e.g. apricot) can be more accurately predicted, thus enabling farmers and growers to more actively and effectively apply wind machines, heaters and sprinklers to protect flowers from frost damage.

5. CONCLUSIONS

Between 1963 and 2011, plant phenophases in spring advanced by a mean trend of −0.17 d yr^{-1} in temperate China. Among the 23 plant phenophases investigated, *Ailanthus altissima* FLD advanced most quickly at a rate of −0.20 d yr^{-1}, while *Sophora japonica* FLD advanced at the lowest rate of −0.13 d yr^{-1}. Trends in last-frost date were between −0.51 and 0.10 d yr^{-1}, with a mean of −0.23 d yr^{-1} over the same time period. Frost damage to woody plants in spring is not decided by either the spring last-frost date or the timing of plant phenophases alone, but by the relationship between them. Based on previous studies, the frost index was used in this study to express the probability of frost risks in spring. The results showed that the frost index increased on average by 0.087 d yr^{-1} from 1963 to 2011 ($p < 0.01$), indicating a declining frost risk in the study area over the past 48 yr. Earlier phenophases, which have been seen to have stronger frost resistance, more closely followed the trends in last-frost dates. In contrast, later phenophases may be threatened more by early spring frosts, and have not advanced more than earlier phenophases. Therefore, the frost risk of frost-sensitive plant phenophases decreased more than that of plant phenophases with stronger frost resistance.

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