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Effects of changes in spring temperature on flowering dates of woody plants across China

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ABSTRACT. In China, changes in the timing of plant phenological phases are influenced greatly by monsoonal climate fluctuations, and also vary with species and region. Observations of phenological phases of trees were conducted in the Phenological Observation Network of China from 1963 to 1988. Records of flowering dates of four species (*Syringa oblata* Lindl., *Cercis chinensis* Bunge, *Robinia pseudoacacia* L., *Albizzia julibrissin* Durazz) at ten sites, together with corresponding climate data, were used to investigate phenophase responses to variation in temperature. The ten sites extend over a wide area, with latitudes ranging from 25ºN to 46°N, and altitudes ranging from 17 to 1,922 m a.s.l. Spring temperature was significantly related to flowering date of the trees under the monsoonal climate in the eastern Eurasian Continent. The period during which temperature influences flowering time varies from 60 to 90 days for *Robinia pseudoacacia* in the south to 30 to 40 days in the north, due to the shorter warm period before flowering in the north. The three other species showed similar trends of changes with latitude in the length of the period of temperature influence. The flowering season for *Cercis chinensis* in response to a temperature increase 30-60 days prior to flowering advanced from 2.7 to 5.9 days/°C in the low plain, and in response to a temperature increase 60-90 days prior to flowering, advanced from 7.1 to 14.8 days/°C in the Yunnan-Guizhou Plateau. The flowering for *Syringa oblata, Robinia pseudoacacia* and *Albizzia julibrissin,* in response to a temperature increase advanced in the range 2.7-4.9, 2.5-6.5, and 2.4-6.0 days/°C in the low plain, respectively. Flowering advanced by 4.7-12.4 days/°C for *Robinia pseudoacacia* and 13.1 days/°C for *Albizzia julibrissin* in the plateau.

Keywords: China; Flowering date; Phenology; Temperature.

INTRODUCTION

Phenology has emerged recently as an important focus for ecological research (Schwartz, 1999, 2003). Because phenological phenomena are visible and responses are closely related to climate, increasing attention is being paid to the analysis of phenological variation and growth length in the context of climatic change. Most phenological events are significantly related to climatic variables and change through time (Walther et al., 2002; Parmesan and Yohe, 2003). A good example of this is the Marsham phenological record from 1736 to 1947 in England (Sparks and Carey, 1995). In general, higher temperatures in the late winter and early spring promote earlier leafing and flowering of plants. There are numerous observations and investigations on the shifting of phenological events in response to climate change in different regions (Walther et al., 2001). In Europe, the lengthening of growing season has been described by Menzel and Fabian (1999). It has also been documented that spring events, such as leaf unfolding or needle flush, are particularly sensitive to temperature (Walkovszky, 1998; Beaubien and Freeland, 2000; Sparks et al., 2000; Rötzer et al., 2000; Defila and Clot, 2001; Ahas et al., 2002; Van Vliet et al., 2002; Sparks and Menzel, 2002). In addition, a number of papers have looked at the effects of temperature on the phenological timings of plants at single study sites (e.g. Fitter et al., 1995; Sparks et al., 1997). In the British Isles, Sparks et al. (2000) reported that the timing of spring and summer species gets progressively earlier as the climate warms, and 25 phenological events studied were significantly related to temperature. Fitter et al. (1995) reported that warmer spring temperatures advanced flowering dates by about 4 days/°C increase in the mean monthly temperatures. Warmer than average winter and spring temperatures have been noted over the

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last century in Western Canada (Beaubien and Freeland, 2000). First-bloom dates for Edmonton (Alberta) were extracted from four historical data sets, and a spring flowering index showed progressively earlier development.

Using data from the International Phenological Gardens for the period 1969-1998 across Europe, Chmielewski and Rötzer (2001) noted that a warming in the early spring (February-April) by 1°C induced the growing season to begin 7 days earlier. The observed extension of the growing season was mainly the result of an earlier onset of spring. An increase in mean annual air temperature by 1 °C led to an extension of 5 days. Using the phenological data from ten central European regions, Rötzer et al. (2000) analyzed and quantified the influence of large-scale climate change and urban climate effects on four spring phenophases for the years 1951-1995. The trends for the period from 1980-1995 were much stronger: the pre-spring phenophases on average became earlier by 13.9 days/decade in the urban areas and 15.3 days/decade in the rural areas. In Estonia, Ahas (1999) analyzed a long-term phenological time series for the impact assessment of climate changes. The study showed that Estonian springs had advanced 8 days on average over the last 80-year period, rates of change being faster in the last 40 years. Kramer et al. (2000) noted that the phenology of the boreal and temperate zone forests is mainly driven by temperature, affecting the timing of the start of the growing season and its duration.

China is located in the eastern edge of the Eurasian Continent. The climate in the eastern part is influenced predominantly by monsoons. The maximum monthly mean temperature of the region is 26 to 30°C in July. The minimum monthly mean temperature decreases greatly from south to north, which occurs in January, and ranges from 7 to -12°C. As the climate in eastern China is controlled by interactions between oceanic and continental air masses, variations in temperature, precipitation and solar radiation are much greater than at the same latitude on the American continent or west Eurasian Continent (Domros and Peng, 1988). Therefore, there are potentially pronounced inter-annual variations within this region, causing significant variations in phenology.

The objectives of this study are (1) to investigate relationships between plant development and temperature in eastern and central China, based on observations from 1963 to 1988; and (2) to identify climatic factors causing inter-annual variations in phenology in monsoonal climate. This study tries to answer how the phenology of flowering responds to temperature change and attempts to identify periods within a year when plant phenophases are significantly affected by temperature.

MATERIALS AND METHODS

The Phenological Observation Network of China was initiated in the early 1960s, but was interrupted after 1988, except for Beijing. There are about 35 stations across China, mainly concentrated in the east. The methodology of the Phenological Observation Network of China has been described in detail by Wan and Liu (1979) and Lu et al. (2006). The observation guidelines state that plant species were chosen for their dominance in regional vegetation and for the existence of records about their growth in ancient times and/or in other countries for comparison. The plants were local varieties older than four years, and five individual plants per species were observed at each site. Some stations have continuous records during 1963-1988. Phenological records from 1963-1988 were available in the form of annual reports (Institute of Geography, Chinese Academy of Sciences, 1989). Four species, *Syringa oblata, Cercis chinensis, Robinia pseudoacacia* and *Albizzia julibrissin*, which have a wide distribution, were selected. We used the observations from ten sites distributed all over China, which had continuous observation records. The distribution of the sites and their latitude, longitude, and altitude are shown in Figure 1 and Table 1. The sites are located over a wide range of geographic regions. In general, altitude in mainland China increases from the coast in the east to the Tibetan Plateau. Consequently, the topography can be divided into three tablelands. The selected sites are on the low plains in the east, the first tableland, including northeast China (Harbin and Shenyang), the North China Plain (Tai'an and Beijing) and the lower and middle reach of Yangtze River (Hangzhou and Wuhan), and on the second tableland, i.e. Inner Mongolia Plateau in north China (Huhehaote), the Loess Plateau in central China (Xi'an) and Yunnan-Guizhou Plateau in the southwest (Kunming and Guiyang). There are no records from the Tibetan Plateau, the third table land with an average height of over 4,000 m above sea level, inland desert in the west and the plain in southeast.

Daily average temperature data during the 1963-1988 period were provided by the Meteorological Bureau of China. The meteorological stations are located in places representative of regional climate. They are within 5 km of phenological observational sites, and their height differences are lower than 20 m in the low plain and 70 m on the plateaus. The temperature influence was assumed to start when the daily temperature rose over 0ºC from winter to spring and to end on the day of blooming. This period was divided into several sub-periods, and the average temperature within each sub-period was calculated. Temperatures in these sub-periods were considered as independent variables with variable lengths, i.e. 20, 30 and 40 days. Ten days were taken as a basic unit. For example, the period from March 1 to April 10 was divided into ten sub-periods of different lengths, i.e., March 1-10, March 11-20, March 21-31, April 1-10 for 10 days (or 11 days), and March 1-20, March 11-31, March 21-April 10 for 20 days (or 21 days), and March 1-31 and March 11-April 10 for 30 days (or 31 days), and March 1-April 10 for 40 days (or 41 days).

To determine the significant period of temperature

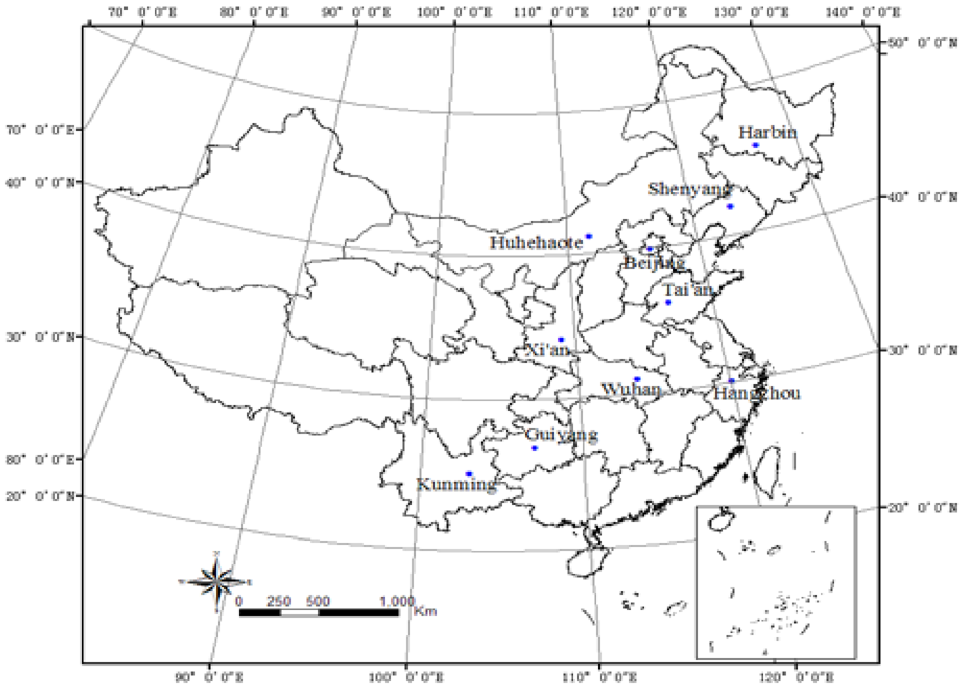

Figure 1. Distribution of the 10 observational sites in eastern China (latitude, longitude, and altitude of each station are listed in Table 1).

influence on flowering date, linear regression analysis was applied. Since the period of temperature influence on flowering dates can start when the temperature rises above 0ºC, statistical analysis ranged from the day temperature rose above 0ºC in winter to the day of flowering although this period changes annually. Based on the time series of average temperatures in each year during the 1963-1988 period, significant periods of temperature influence are obtained in accordance with the highest correlation coefficient, after linear regression between flowering dates and average temperature in the specific period is conducted (Xu et al., 2005).

RESULTS

There were large differences in climate between the stations due to the large differences in geographic position and altitude. Climate in the east is dominated by monsoons. Rainfall is concentrated in summer and decreases from southeast to northwest. There is abundant sunshine in winter and spring. The spatial difference in temperature is highest in winter and lowest in summer. Therefore, seasonal variation of temperature in the south is much lower than in the north (Figure 2) according to the variation pattern of solar radiation. In the spring, temperature rises rap-

Table 1. Distribution of the phenological observation sites.

Site	Latitude	Longitude	Altitude (m)	Average temperature (ºC)	Average rainfall (mm)	Observation period
Kunming	25°0′	103°0′	1922	14.6	993	1963-1988
Guiyang	26°42′	107°0′	1050	15.3	1120	1963-1988
Hangzhou	30°5′	120°4′	17	16.2	1317	1963-1988
Wuhan	31°0′	114°0′	33	16.3	1169	1963-1988
Xi’an	34°4′	109°4′	437	13.4	563	1963-1988
Tai’an	36°2′	116°55′	137	12.7	683	1963-1988
Beijing	39°55′	116°18′	50	11.7	578	1963-1988
Huhehaote	41°12′	111°43′	1063	6.1	391	1963-1988
Shenyang	41°59′	123°11′	44	8.2	681	1963-1988
Harbin	46°43′	126°42′	149	3.7	523	1963-1988

idly in northern China. The growth period is short in the north, but extends to almost the whole year in the south. For example, the annual amplitude in mean monthly temperature is 35.7ºC in Shenyang (northeast), with mean monthly maximum and minimum of 24.7ºC and -11.0ºC, respectively, and 18.7ºC in Guiyang (Yunnan-Guizhou Plateau) with a maximum temperature of 24.6ºC and a minimum of 5.9ºC. Variation in altitude also results in site differences in temperature regimes, particularly in winter. In the south, Guiyang is substantially the warmest among the study sites in winter, with an average daily temperature of 5-7ºC (Figure 2) because it is less influenced by cold air masses from the north due to its high elevation. These seasonal characteristics in temperature and annual ranges may determine patterns of flowering.

There are three sites (Kunming, Guiyang, Huhehaote) over 1,000 m, and all of them are located in western regions, far away from the sea (Figure 1 and Table 1). Nevertheless, the temperatures in the winter and early spring in the Yunnan-Guizhou Plateau (Kunming, and Guiyang), southwest China, are not as low as at other sites at the same latitude. The low plain in eastern China is indeed very cold due to advection of winter monsoons from the north and inner Eurasian Continent. Guiyang is the warmest site in winter (Figure 2). Kunming, at 1,922 m a.s.l. in the Yunnan-Guizhou Plateau (Table 1), is known as the "Spring City," with warm winters and moderate summers. On the other hand, Huhehaote, at 1,063 m a.s.l. in north China, is 12ºC colder than Guiyang (1,050 m) in winter, as cold air masses from the north of the Eurasian Continent pass through it. This effect of altitude and longitude on temperature enhanced the trend of flowering dates along with latitude. As there are only three sites on plateaus, the general trend displays the influence of latitude.

Average flowering dates were delayed linearly with increasing latitude (Figure 3). Flowering of *Syringa oblata* Lindl., *Cercis chinensis* Bunge, *Robinia pseudoacacia* L., and *Albizzia julibrissin* Durazz were delayed with an increase in latitude, at rates of 3.3, 2.9, 2.3 and 2.2 days/ºN, respectively (Figure 3). *Cercis chinensis* is widely distributed in China, and its delayed rate of flowering was similar to *Albizzia julibrissin, Robinia pseudoacacia* and *Syringa oblata*. The four species bloom successively from early spring to summer. *Syringa oblata* blooms slightly before *Cercis chinensis* at a low latitude, but flowering date was delayed rapidly at high latitudes, where there is no *Cercis chinensis* (Figure 3). Flowering dates may be also influenced by altitude and longitude, but latitude dominantly determines phenophases distribution in this region (Zheng et al., 2002).

Standard deviation (δ) of flowering dates of the four trees was calculated for each site separately. Figure 4 illustrates changes in δ with latitude. It is shown that δ decreases with latitude, which means flowering dates fluctuated more in southern China than in northern China. The line of 34ºN divides eastern China into subtropical and temperate zones, or the south and the north. The decrease rate of δ with latitude was 3.2 days per 10-degree, i.e. about 6-10 days in the north and 2-6 days in the south. The significant decrease in δ with latitude demonstrated that inter-annual changes in flowering dates increase gradually from the north to the south. However, the deviation from the regression line may be explained by altitude or longitude (Figure 4). Latitude apparently has greater influence on flowering dates than altitude and longitude in eastern China (Zheng et al., 2002).

As indicated in Materials and Methods, average temperatures over different non-freezing periods were used to calculate the correlation of temperature with

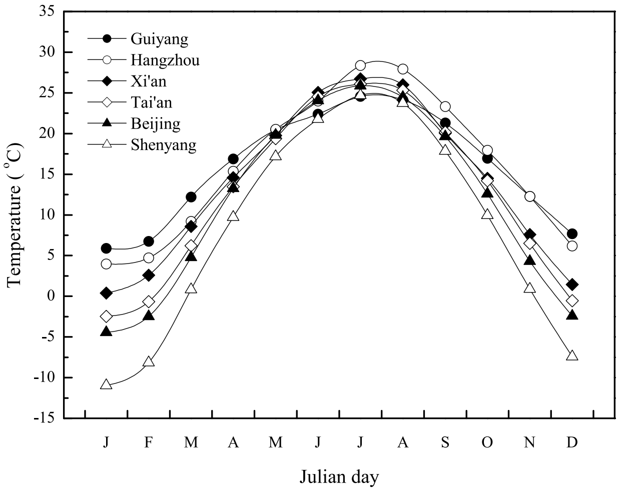

Figure 2. Variation in average daily temperatures between 1963 and 1988 at observation sites, demonstrating the influence of latitude and altitude.

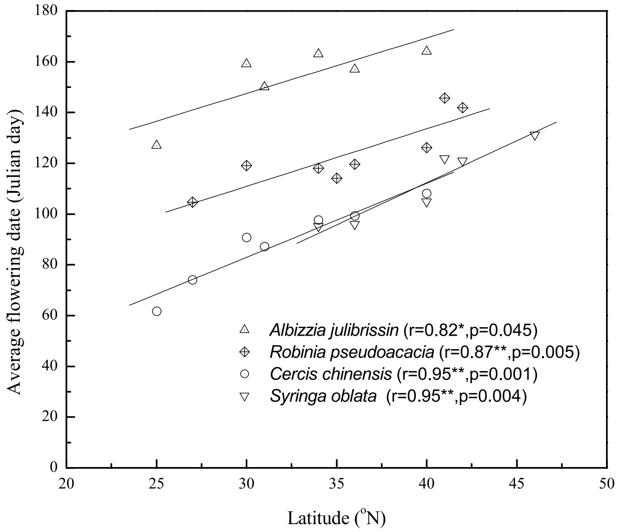

Figure 3. Changes in average flowering dates with latitude for the four woody plants, *Cercis chinensis, Albizzia julibrissin, Syringa oblata* and *Robinia pseudoacacia*. Average flowering dates show a significant trend with latitude although the influence of altitude and longitude was not excluded, which may induce the dates to fluctuate along with the latitude trend.

flowering dates. It was assumed that the temperature period that influenced flowering the most corresponded to the highest correlation coefficient. The significant periods of temperature influence were illustrated in Figures 5 and 6. The period when temperature had a significant influence on the flowering time was mainly from 30 to 50 days in northern China and 50 to 80 days in the south (Figure 5), where the growing season is longer (Figure 6), especially in the Yunnan-Guizhou Plateau (Kunming and Guiyang). The time when temperature could affect the date of flowering started later and ended sooner; therefore, the sensitive period is generally shorter in the north. *Syringa oblata* and *Cercis chinensis* are widely distributed in China, and they bloom approximately at the same time. Although the sensitive periods for the two species differ somewhat, their durations are usually similar (Figure 5).

For each species, flowering dates were significantly related to the average temperature of the specific period prior to flowering (Figures 7-10). The degree of sensitivity of *Syringa oblata's* flowering to temperature ranged from 2.7 to 4.9 days/°C in the eastern low plain, including Harbin, Shenyang, Beijing, Xi'an, and Tai'an (Figure 7).

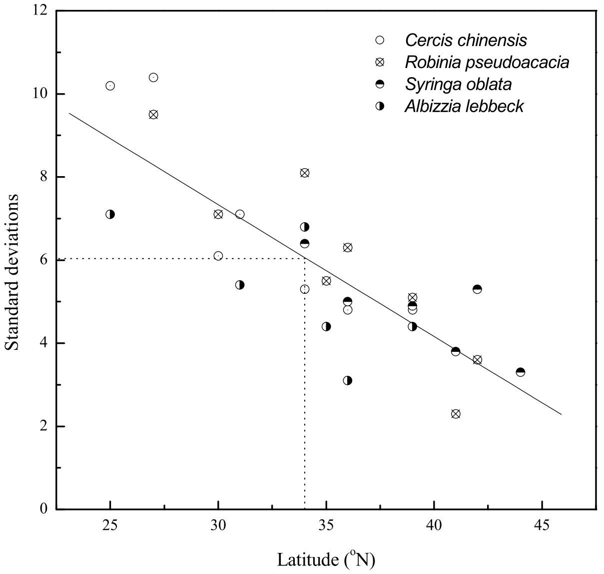

Figure 4. Variations in standard deviations for *Cercis chinensis, Albizzia julibrissin, Syringa oblata* and *Robinia pseudoacacia* with latitude.

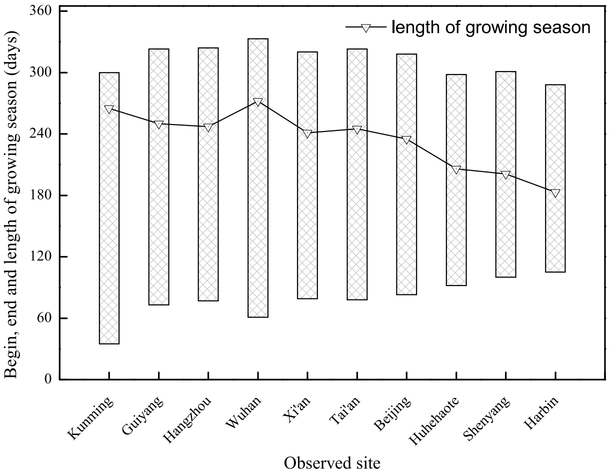

Figure 6. Length of growing season at the different observational sites. The vertical axis is day of year; the bar represents growing length from 0ºC in winter to the day of flowering, and ▽ is the length of the bar, i.e. the growing length.

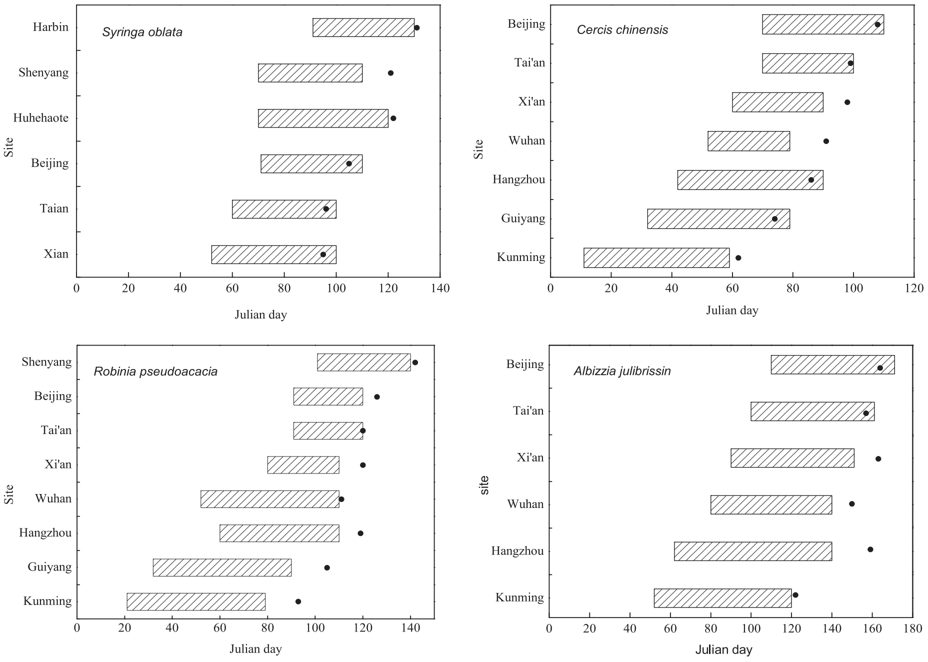

Figure 5. Periods of significant temperature influence on flowering date at different sites for the four woody plant species. Points indicate average flowering dates.

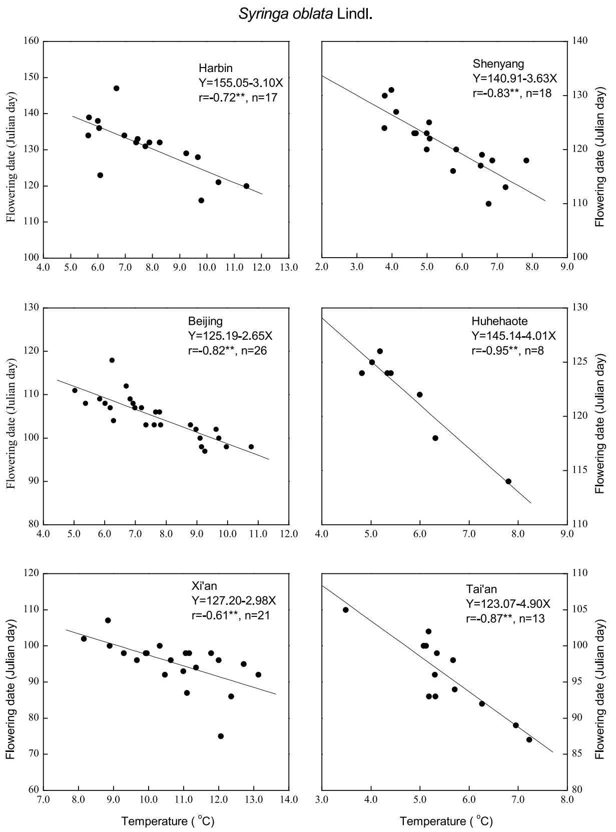

Figure 7. Relationship between flowering date and average temperature in significantly sensitive periods (indicated in Figure 5) at different sites for *Syringa oblata* during 1963-1988 (** and * stand for significance levels of 0.01 and 0.05, respectively).

The rate of advance of *Cercis chinensis* was from 2.7 to 5.9 days/ºC in the low plain and from 7.1 to 14.8 days/ºC in the plateau (Kunming and Guiyang) (Figure 8). The rate of *Robinia pseudoacacia* was from 2.5 to 6.5 days/ºC in the low plain and 4.7-12.4 days/ºC in the plateau (Figure 9). For Hungary, Walkovszky (1998) reported that a rise in the average spring temperature from March 15 to May 15 by 1ºC caused the flowering of *Robinia pseudoacacia* to advance by 6.8 days. This rate is higher than that of the low plain and lower than on the plateau in China. The rate of *Albizzia julibrissin* was from 2.4 to 6.0 days/ºC and 13.1 days/ºC in the low plain and the plateau, respectively (Figure 10). Flowering dates for *Cercis chinensis* varied from 30 to 50 days with a temperature variation of 2-6ºC, in Kunming and Guiyang in the Yunnan-Guiyang Planteau while it was 15-25 days, with temperature variation of 3-5ºC, in the low plain (Figure 8). *Robinia pseudoacacia* (Figure 9) and *Albizzia julibrissin* (Figure 10) yielded similar results. The sensitivity of flowering to temperature is thus higher in the south than in the north.

DISCUSSION AND CONCLUSION

Plant development is determined by both temperature and day length on the basis of sensitivity to thermal conditions and photoperiod (Thomas and Vince-Prue, 1997). The change in flowering dates of the species with latitude may be partially attributable to the effect of day length. In a monsoonal climate, temperature is the dominant factor controlling the timing of phenological events in the spring (Zhang, 1995). Using the phenological data of Europe for the 1951-1996 periods, Menzel (2000) reported that spring events, such as leaf unfolding, have advanced, on average, by 6.3 days while autumn events, such as leaf coloring, have been delayed, on average, by 4.5 days. Thus, the average annual growing season has lengthened, on average, by 10.8 days. Chmielewski and Rötzer (2001) reported that a nearly Europe-wide warming in the early spring over the last 30 years (1969-1998) led to an earlier beginning of the growing season by 8 days. They found good correlations between the average temperature of February to April (about 90 days) and the beginning of the growing season in European regions. In this study, we found significant correlations within regions between flowering and average temperature over the period of 60-90 days prior to flowering for *Robinia pseudoacacia* in the south and 30-40 days in the north. However, there were some differences in varieties of each species among the different regions. Genetic differences

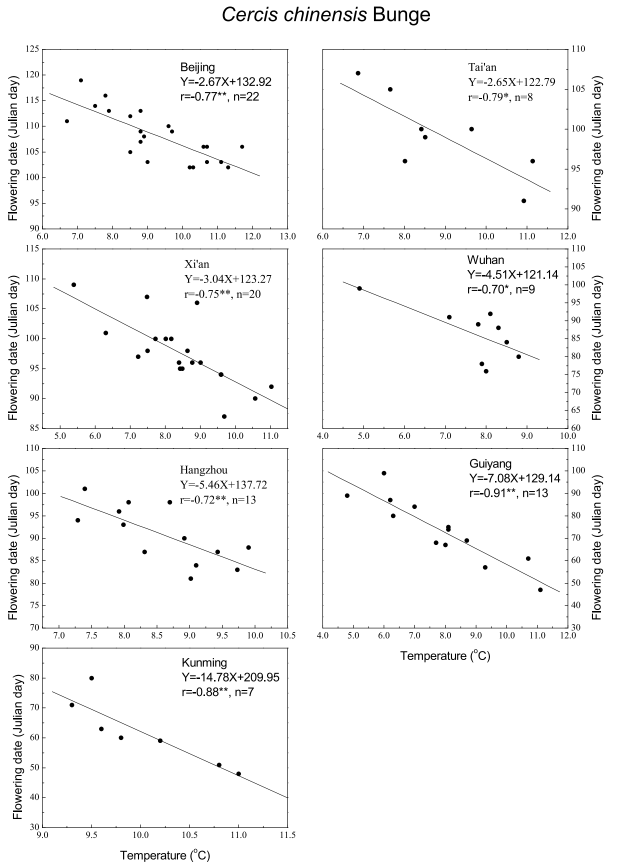

Figure 8. Relationship between flowering date and average temperature in significantly sensitive periods (indicated in Figure 5) at different sites for *Cercis chinensis* during 1963-1988 (** and * stand for significance levels of 0.01 and 0.05, respectively).

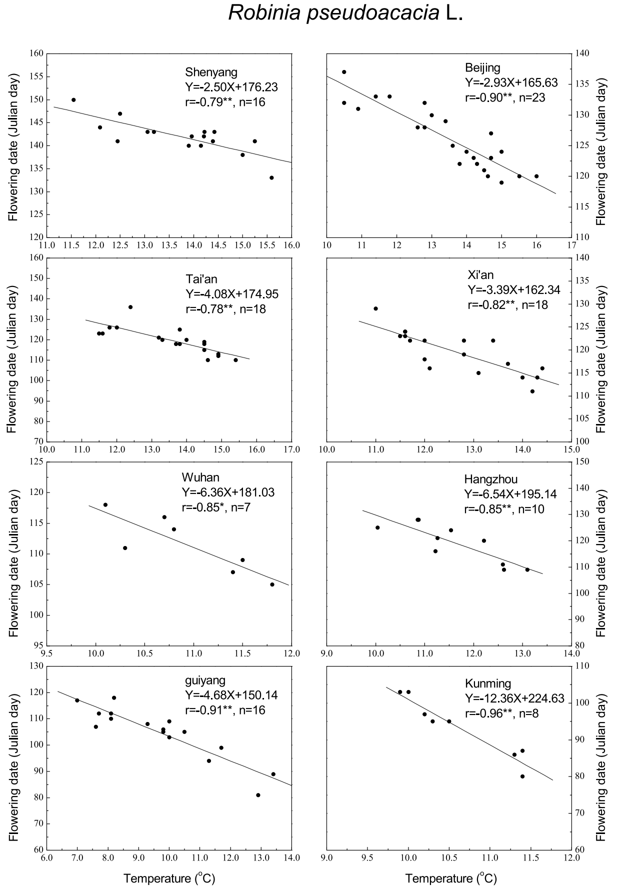

Figure 9. Relationship between flowering date and average temperature in significantly sensitive periods (indicated in Figure 5) at different sites for *Robinia pseudoacacia* during 1963-1988 (** and * stand for significance levels of 0.01 and 0.05, respectively).

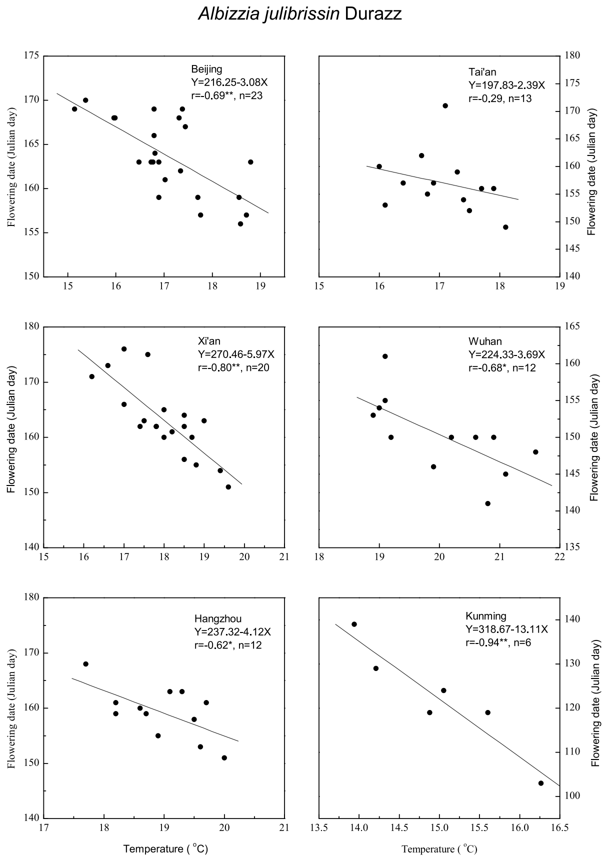

Figure 10. Relationship between flowering date and average temperature in significantly sensitive periods (indicated in Figure 5) at different sites for *Albizzia julibrissin* during 1963-1988 (** and * stand for significance levels of 0.01 and 0.05, respectively).

among varieties probably generated differences in the flowering response to temperature increase (Rötzer and Chmielewski, 2001). Day length, rainfall, and sunshine hours may also have influenced flowering and need to be considered in future analysis (Zhang, 1995).

Flowering dates fluctuate from year to year as a consequence of multiple interactions between physiological processes and physical constraints imposed by the environment. Temperature is an important factor influencing phenophases under the monsoonal climate in China (Zhang, 1995), as well as in most parts of the world where soil water is not a dominant factor in growth, e.g. Europe and North America. The growth of plants may be stimulated when the temperature is higher than 0°C in the spring, and sap flow can be observed in the stem (Wan and Liu, 1979). Therefore, the significant period of temperature influence increases from north to south due to longer growing seasons in the south, in both low plain and plateau. The results of this study show that temperature influences flowering 30 to 80 days prior, depending on the species and region. The temperature over shorter or longer periods, such as 10 or 90 days, was less related to flowering time, probably because shorter periods do not represent climatic characteristics well in a growth stage, and longer time scales smooth out climate fluctuations.

The geographical elements—altitude, latitude, and longitude—may influence distribution of temperature, rainfall as well as day length, so that further multiple regression analysis should be applied to determine their influence on flowering. The work of Zheng et al. (2002) indicated phenophases change most significantly with latitude in the range of eastern China. The present work focuses on the periods when temperature might have a significant influence on plant flowering.

It can be concluded that (1) interannual variation of flowering dates increases from north to south, and (2) sensitive period of flowering dates to temperature is longer in the south than in the north. The advance rate of flowering dates in response to temperature increase ranges from 2-7 days/ºC in the low plain to 5-15 days/ºC on the plateau. Due to low daily temperature during growing seasons on the plateau, the advance of flowering dates is more sensitive to temperature increase than that in the low plain.

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春季溫度變化對中國木本植物開花日期的影響

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在中國，植物物候期的發生時間受季風性氣候波動的影響。同時，物候期隨植物的種類和生長的地區而變化。中國物候網從 1963 到 1988 年對主要植物物候進行了觀測。本文利用 4 個植物種類：紫丁香 (*Syringa oblata* Lindl.)，紫荊 (*Cercis chinensis* Bunge)，刺槐 (*Robinia pseudoacacia* L.) 和合歡 (*Albizzia julibrissin* Durazz)，在 10 個測點的開花期記錄和相應的氣候資料，研究物候期對溫度變化的回應。這 10 個測點覆蓋了大範圍的區域，緯度變化於 25-46ºN，高度從海拔 17 m 到 1,922 m。在歐亞大陸東部季風氣候條件下，春季溫度對植物開花期的影響占主導地位。春季溫度對紫丁香開花期的顯著影響階段隨地區而變化。中國南部地區在開花前的 60-90 天，北部地方在開花前的 30-40 天。這種差異是由於華北地區在開花前的溫暖季節較為短促造成的。其餘 3 種植物也有類似的情況。紫荊的開花期隨開花前 30-60 天內平均溫度升高提前的速率變化於 2.7-5.9 天/ºC（平原地區），和開花前 60-90 天內的平均溫度 7.1-14.8 天/ºC（雲貴高原地區）。紫丁香，刺槐和合歡的開花期對溫度增加的回應在平原地區分別為2.7-4.9，2.5-6.5 和 2.4-6.0 天/ºC，而在高原，刺槐的變化率為4.7-12.4天/ºC，合歡為 13.1 天/ºC。

關鍵詞：中國；開花期；物候；溫度。