Effects of Climate Warming on Phenological Characteristics of Urban Forest in Shenyang City, China

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Abstract: Change in plant phenology is one of the most sensitive ecological responses to climate warming. Little information is known about the effects of climate warming on phenology of urban tree species in the northern forest of China. In this study, we investigated the phenological characteristics of the main tree species in the urban forest of Shengyang City in China and the correlation between phenology and atmospheric temperature from the discontinuous data during past 42 years over three time periods (from 1962 to 1965, 1977 to 1978, and 2000 to 2005). The results showed that the annual average temperature in Shenyang City showed an increasing trend and increased by 0.96℃ from 1962 to 2005 due to climate warming. The germination phenology of the urban trees was negatively correlated with the temperature in winter and early spring. The leafing phenology was mainly influenced by the temperature in spring before leafing. Influenced by climate warming, the germination, leafing, and flowering phenologies of this urban forest in 2005 were 14, 13, and 10 days earlier than those in 1962, respectively. We inferred that further warming in winter might prolong the growing season of urban trees in the northern forest of China.

Keywords: global climate change; global warming; plant phenology; urban forest; Shengyang City

1 Introduction

Global climate change has been recognized as one of the major environmental problems (Brown *et al*., 2012; Pasgaard and Strange, 2013; Kum and Çelik, 2014). The annual increase of greenhouse emission leads to climate warming and induces the change of plant phenology (Yaacoubi *et al*., 2014). Phenological changes, as important indicator that can be directly observed, are sensitive to global climate warming (Vitasse *et al*., 2009; Sparks and Menzel, 2013; Wang *et al*., 2015). In general, the responses of plant phenology to global warming are mainly characterized by the advancing of the spring phenophase, the delaying of autumn phenophase, and a prolonged growth season (Xu *et al*., 2004). In recent years, there are many studies on relationship between plant phenology and climate change in China (Zhang and Tao, 2013; Guo *et al*., 2013; Shen e*t al*., 2014; Guo *et al*., 2015; Wang *et al*., 2015). However, little information is known about the effects of the climate warming on the changes in phenology of urban trees in China. By contrast, the effects of the climate warming on the changes in forest phenology have been widely studied in the world, especially in Europe (Menzel and Fabian, 1999; Chmielewsky and Roetzer, 2001; Vitasse *et al*., 2009; Schleip *et al*., 2009; Yaacoubi

et al., 2014). In this study, we analyzed and discussed the effects of climate warming on urban forest phenology in the north-eastern China based on the communities of urban forest. We expected a better association between urban forest phenology and the local atmospheric temperature, which will provide a critical reference for urban forest construction in Northeast China under global change, particularly under climate warming.

2　Materials and Methods

2.1　Study site
The observation site was located in the Shenyang Arboretum of Chinese Academy of Sciences (41°46′N and 123°26′E), Liaoning of China. The arboretum with an area of 5 ha was founded in 1955 and mainly planted with native tree species from the north-eastern China. There are more than 300 tree cultivars and the forest coverage rate reached 53.7%. Nowadays, it has been a near-natural urban forest with a multi-level structure and ecological function (He *et al.*, 2003). In addition, an automatic weather station in the arboretum has been built for over 40 years to record atmospheric and soil temperatures, precipitation, wind speed. The average annual temperature and precipitation are 7.4℃ and 755.4 mm, respectively (Xu *et al.*, 2014).

2.2　Experimental materials
In accordance with the standards from ′Chinese phenological observation method′ (Wan and Liu, 1979), the phenological changes of plant samples were observed once a day through visual inspection, telescope, and other scientific methods. For comparison, the observations were carried out by using the plant samples from a southern orientation. The phenology data were discontinuous during past 42 years over three time periods (from 1963 to 1965, 1977 to 1978, and 2000 to 2005). Twenty-nine tree species in Shenyang urban forest were used for the analysis of phenological characteristics. These tree species include: *Quercus liaotungensis*, *Celtis bungeana*, *Forsythia viridissima*, *Fraxinus rhynchophylla*, *Robinia pseudoacacia*, *Lonicera maackii*, *Ligustrum obtusifolium*, *Syringa velutina*, *Prunus padus*, *Ailanthus altissima*, *Maackia amurensis*, *Salix matsudana*, *Acer ginnala*, *Juglans mandshurica*, *Phellodendron amurense*, *Tilia amurensis*, *Ulmus laciniata*, *Malus*

baccata, *Ulmus pumila*, *Viburnum sargenti*, *Rhododendron mucronulatum*, *Lonicera japonica*, *Syringa amurensis*, *Sorbus alnifolia*, *Grewia parviflora*, *Lonicera praeflorens*, *Rosa rugosa*, *Euonymus alata*, and *Xanthoceras sorbifolia*.

2.3　Study methods
The whole year in Shenyang was divided into four seasons: winter (from December to February), spring (from March to May), summer (from June to August), and autumn (from September to November). The anomaly (the difference values between a series recorded temperatures and the average temperature) from 1960 to 2005 was calculated. The seasonal temperature anomaly, the 10 year moving mean of the annual average temperature and seasonal temperatures were calculated. The linear regression equation using a least-squares method was obtained (Xia and Zhou, 2002). Coldness index (CI) was calculated by the Kira heat index formula: $CI = \sum (5 - T)$. Where, T is the yearly or monthly average temperature. CI is negative (Xu, 1983; 1986). In this study, T was transformed into a ten-day average temperature (℃ ten-day) (Xu *et al.*, 2006). Ten tree species with the most significant changes were chosen to investigate the relationship between phenophase and the mean temperature of each ten-day period.

Meteorological data were obtained from the data sharing websites of the Chinese Meteorological Bureau. The synchronous data for related meteorological factors corresponding to each phenophase were selected in this study. Data were statistically analysed using MS-Excel and the data processing system (DPS).

3　Results

3.1　Variations in atmospheric temperature of study area
Figure 1 shows the variations of annual average temperature in Shenyang City from 1962 to 2005. The annual average temperature increased by 0.96℃ during this period. The annual average temperature was 7.6℃ in the late 1950s and early 1960s, and 8.6℃ in the 1990s. The temperature in 1998 was up to 9.7℃, which is the highest value during the past 40 years and 1.3℃ higher than long-term average. The annual average temperature from 2001 to 2004 was 9.1℃, with an increase of 0.3℃ during this period. Figure 2 shows an
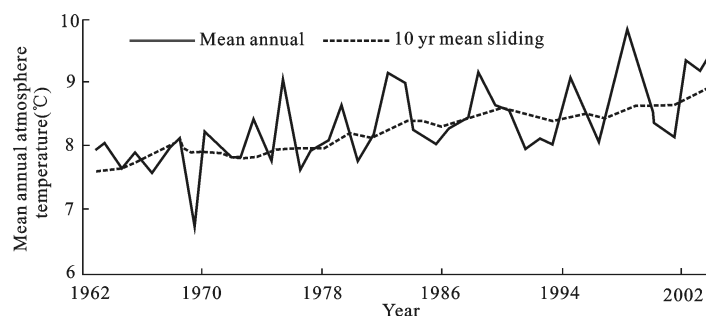
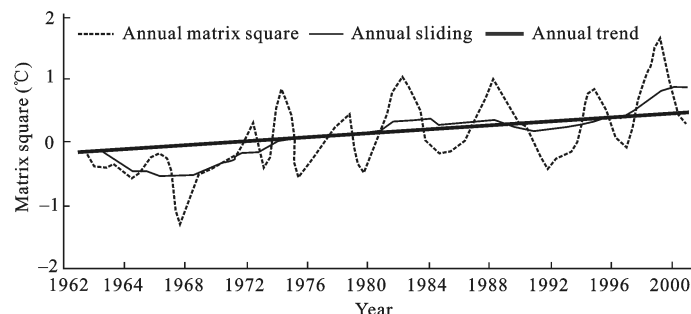**Fig. 1** Variations of mean annual atmospheric temperature

Fig. 2 Variation of matrix square for mean annual atmospheric temperature

anomaly for the 10-year moving average temperature. During the past 40 years in Shenyang City, the variation of average temperature can be divided into two phases. The phase before the early 1980s was colder, while the phase after the early 1980s was warmer (Xu *et al.*, 2006).

According to the linear regression equation for the annual average temperature in Shenyang City during the last 40 years: $Y = 0.0184x - 36.31$ and the variation curve of matrix square (the anomaly of air temperature) for mean annual air temperature (Fig. 2), the minimum temperature in the cold phase was $-1.95℃$, while the maximum temperature in the warmer phase was $1.60℃$. The seasonal temperature in Shenyang showed an increasing trend in the past 40 years, and the largest increase was in winter and spring (Fig. 3a, 3b). The large temperature variations in winter and spring exerted greater influences on the urban forest phenology, while the smaller temperature variations in summer and autumn exerted lesser influences on urban forest phenology.

According to the linear regression equations of winter ($Y = 0.0444x - 87.67$) and that of matrix square in spring temperature ($Y = 0.0266x - 52.60$), it can be found that the intercepts of the two equations exceeded that of the regression equation for annual mean temperature. It indicates that the increase of temperature in winter and spring ($2.31℃$ and $1.35℃$, respectively) was

higher than that of the annual average temperature.

3.2 Phenological response of germination to climate warming

As shown in Table 1, the critical low temperature phase of the main tree species in Shengyang urban forest was observed in the last ten-days of January to the last ten-days of February. Trees can not be relieved from their dormancy and quickly develop into the germination phase of bud unless certain suitable low-temperature conditions were satisfied in advance. The germination phase of buds was significantly negatively correlated with the temperature in spring (Table 1), that is, the temperature rise before germination promoted the germination phenophase of buds. In addition, the germination phenophase (Budding dates) was closely correlated with CI: the higher the absolute value, the later the germination.

To further analyze the influences of climate warming on the urban forest phenology in Shenyang City in the past 42 years, 10 tree species which show significant variations were selected from the 29 tree species for correlation analysis. The result showed that the germination phenophase of buds of the main tree species in this urban forest presented a significant negative correlation with the temperature in the time period from the last ten-days in March to the first ten-days in April,
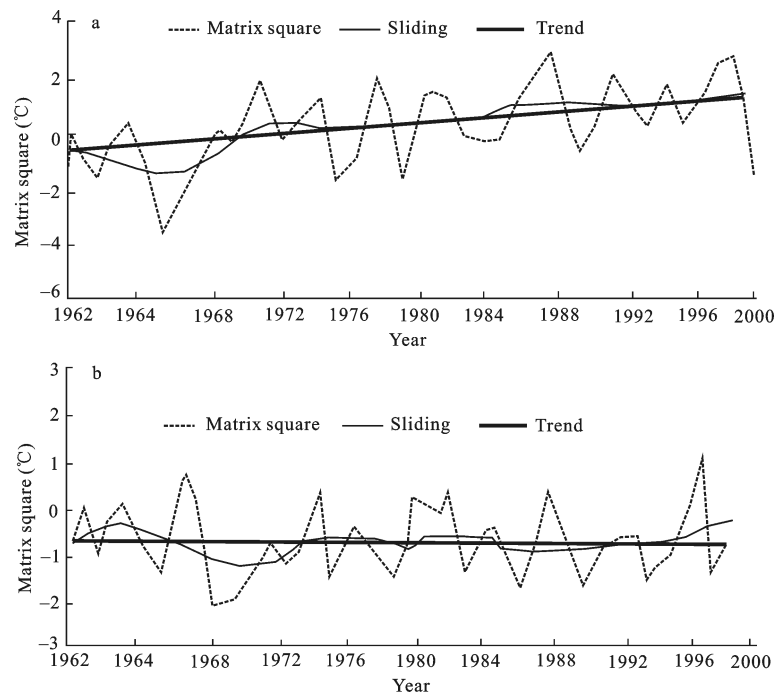
Fig. 3   Variations of matrix square for mean annual atmospheric temperature. a. Winter; b. Spring

while being slightly associated with winter temperature. Namely, the temperature increase in spring (From late March to early April) advances the germination. Figure 4a implies that the germination phenophase (budding-dates) of the urban forest in 2005 was 14 days earlier than that in 1962. Based on the correlations of annual average temperature with the germination of trees, this study fits the linear regression equation of the germination phenophase of the main tree species in Shenyang urban forest, that is, $Y_s = -8.979X + 163.695$ ($r = 0.485$; $P < 0.01$; $n = 319$); where Y_s refers to the day number of
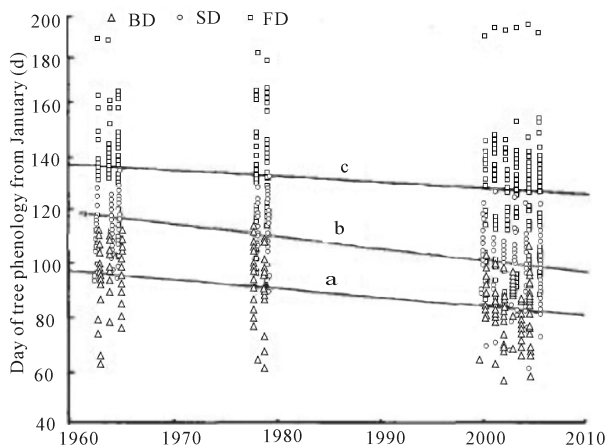

Fig. 4   Responding trends of tree phenology from 1962 to 2005 in Shenyang urban forest to regional warming. BD, budding dates (a); SD, sprouting dates (b); FD, flowering dates (c)

Table 1   Relationship between phenology of urban trees and mean air temperature in ten days ($n = 29$)

Time		BD	SD	FD
Nov	I	0.017	0.103	0.021
	II	−0.096	0.101	0.081
	III	−0.213**	−0.103	−0.032
Dec	I	−0.012	−0.037	−0.038
	II	0.272**	0.228**	0.061
	III	0.045	0.143**	0.083
Jan	I	−0.248**	−1.020	0.045
	II	−0.134*	−0.140*	−0.021
	III	−0.232**	−0.089	−0.009
Feb	I	−0.254**	−0.200**	−0.051
	II	−0.401**	−0.327**	−0.101
	III	−0.346**	−0.361**	−0.121*
Mar	I	−0.083	−0.111*	−0.052
	II	−0.268**	−0.288**	−0.114*
	III	−0.420**	−0.430**	−0.140*
Apr	I	−0.439**	−0.552**	−0.212**
	II	−0.291**	−0.453**	−0.159**
	III	−0.192**	−0.373**	−0.156**
May	I	−0.135*	−0.265**	−0.088
	II	−0.047	−0.163**	−0.069
	III	−0.119*	−0.123*	−0.069
−CI		0.343**	0.193**	0.031

Notes: I, II and III indicate for the first ten days, the second ten days and the third ten days in each month, respectively. BD, Budding dates; SD, Sprouting dates; FD, Flowering dates; CI, Coldness index. *, ** represent $P < 0.05$ and $P < 0.01$, respectively

the bud germination; X is annual average temperature (℃). The slope of the equation suggested that, per 1℃ temperature rise, the bud germination of the main trees in the urban forest in Shenyang was advanced by 9 days in spring.

3.3　Phenological response of leafing to climate warming

The leafing phenology of tree species in the urban forest in Shenyang showed large differences. For example, leaf sprouting occurred in mid-March for *G. parviflora, P. padus, L. praeflorens*, which is 30 to 35 days earlier than the late leafing species, including *A. altissima, C. bungeana, F. rhynchophylla*. This was attributed to the artificial selection of tree species for an urban forest. The tree species with late leafing phenophase mainly flowered first and then leafed, while those with an early leafing phenophase mainly leafed first and then flowered or leafed and flowered simultaneously (Hu *et al.*, 2006). Regardless of early or late leafing phenophases, 15 days after bud cracking, and all trees all generally reached a leafing rate of 57.4% in late April at a ten-day average temperature of 9.3 to 12.3℃ generally. As suggested by Table 2 and Fig. 5, the leafing phenophase (Sprouting dates) of the tree species were significantly

negatively correlated with the temperatures of late March and early April in the spring before leafing, and were unrelated to winter temperature. That is to say, the leafing phenophases of the tree species in the urban forest in Shengyang City were affected by temperature variations in the spring (late March and early April) before leafing instead of those in winter.

However, the beginning of the leafing phenophase was positively associated with the absolute value of CI. The higher the absolute value of CI is, the later the leafing phenophase of the tree species is. The temperature rise before leafing advanced the leafing phenophase. As shown in Table 2, only the leafing phenophases of *C. bungeana* and *L. obtusifolium* of the 10 tree species exhibited a negative correlation with winter temperature due to the genetics and adaptive strategies. This phenomenon also reflected the countermeasure in the life history of plants (Zhu *et al.*, 2005). The two species were typical of those distributed across the northern China and were introduced from south to north. In the past 42 years, Shenyang City witnessed a temperature rise of 1.35℃. Therefore, the leafing phenology (Sprouting dates) of the urban forest in Shenyang in 2005 was about 13 days earlier than that in 1962 and was affected by global climate warming (Fig. 4b). The

Table 2　Correlations between leaf expansion of ten main tree species and mean air temperature in ten days

Month		A	B	C	D	E	F	G	H	I	J
Dec	II	0.272	0.576	0.194	0.221	0.195	0.511	0.412	0.397	0.350	0.357
	III	0.202	0.212	0.461	0.066	0.332	0.229	0.069	–0.011	0.233	0.136
Jan	I	0.202	–0.119	–0.131	–0.428	0.095	–0.082	0.018	0.070	–0.220	–0.015
	II	0.137	–0.702	–0.188	–0.084	–0.099	–0.381	–0.154	–0.244	–0.252	–0.254
	III	0.047	–0.328	–0.219	–0.326	–0.042	–0.293	–0.159	–0.056	–0.330	–0.150
Feb	I	0.201	–0.646	–0.105	–0.359	–0.152	–0.461	–0.440	–0.438	–0.435	–0.312
	II	0.553	–0.438	–0.209	–0.617	–0.401	–0.543	–0.436	–0.600	–0.544	–0.439
	III	0.550	–0.508	–0.172	–0.287	–0.440	–0.398	–0.740*	–0.677	–0.482	–0.545
Mar	I	0.201	–0.132	0.274	0.316	0.261	0.122	–0.116	0.316	0.132	0.064
	II	0.243	–0.580	–0.115	–0.229	–0.270	–0.511	–0.625*	–0.523	–0.405	–0.420
	III	0.651*	–0.743**	–0.509	–0.566	–0.563	–0.710*	–0.519	–0.695*	–0.709	–0.629*
Apr	I	0.536	–0.757	–0.709*	–0.566	–0.816**	–0.885**	0.695	–0.774**	–0.799**	–0.802
	II	0.800**	–0.496	–0.410	–0.558	–0.613*	–0.600	–0.562	–0.737**	–0.451	–0.728
	III	0.521	–0.370	–0.643*	–0.230	–0.674*	–0.552	–0.193	–0.488	–0.413	0.050
May	I	0.358	–0.574	–0.055	–0.263	–0.299	–0.430	–0.558	–0.585	–0.299	–0.481
	II	–0.218	–0.191	0.146	0.161	–0.143	–0.193	–0.500	–0.328	0.029	–0.288
	III	0.095	0.077	0.065	–0.472	–0.210	–0.153	–0.548	–0.314	–0.335	–0.196

Notes: Ⅰ, Ⅱ and Ⅲ indicate for the first ten days, the second ten days and the third ten days in each month, respectively. A–J: *Quercus liaotungensis, Celtis bungeana, Forsythia viridissima, Fraxinus rhynchophylla, Robinia pseudoacacia, Lonicera maackii, Ligustrum obtusifolium, Syringa velutina, Prunus padus, Ailanthus altissima*. *, ** represent *P* < 0.05 and *P* < 0.01, respectively
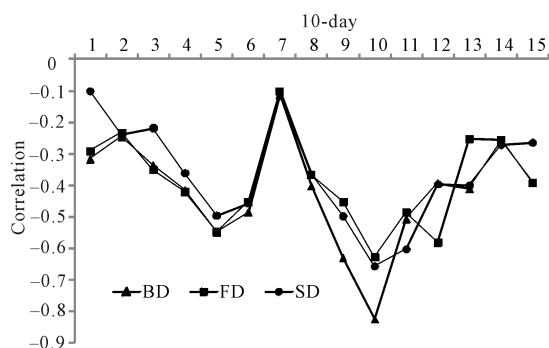
Fig. 5 Correlation between phenology of ten main tree species and mean air temperature in ten days. BD, Budding dates; FD, Flowering dates; SD, Sprouting dates. Three 10-day records (First, second and third) for each month from January to May in X-axis

slope of the linear regression equation for leafing phenology: $Y = -9.573x + 172.930$ ($r = 0.149$; $P < 0.01$; $n = 319$) suggested that the leafing phenology would be advanced by 9.6 days with each annual average temperature rise of 1℃.

3.4 Phenological response of flowering to climate warming

The flowering phenology (Flowering dates) of tree species in the urban forest in Shenyang City showed large differences. Flowering of tree species was observed from late March to mid-July, however, most of the tree species flowered in late April to mid-May, accounting for 54% of the total first flowering dates. Therefore, the flowering tree species in spring can be classified into two flowering patterns, early spring (March, April) and late spring (May) (Xu et al., 2008). To explore the relationship between first flowering date and temperature, we analysed the relationship between first flowering date and temperature in different seasons in the earlier stage of first flowering. As shown in Table 1 and Fig. 5, the first flowering date of the main species in the urban forest of Shenyang in early spring presented a significant negative correlation with the temperature in early April in the spring before first flowering date ($P < 0.01$). However, there was only a low correlation with the temperature in winter and early spring (March) and had no correlation with CI (Table 1). In later of April, the temperature was negatively associated with the first flowering date ($P < 0.01$). Therefore, in the past 42 years, the flowering phenophase of the urban forest in Shenyang has advanced by about 10 days with global climate change (Fig. 4c). The best-fit equation: $Y =$

$-5.363x + 172.930$ ($r = 0.149$; $P < 0.01$; $n = 319$) suggested that the flowering phenophase would be advanced by 5.4 days per annual average temperature rise of 1℃ in the future.

4 Discussion

Global climate warming is indisputable, and the increasing of atmospheric temperature is more significant in recent years (IPCC, 2007; Pasgaard and Strange, 2013; Manciocco et al., 2014). In this study, the average annual temperature in Shenyang City of China showed a significant increasing trend during the past 42 years. The temperature was more lower before the early 1980s, with a minimum value of –1.9℃, while that in the early 1980 was higher, with a maximum value of 1.6℃. Although the temperature presented an increasing trend in a year, the increasing amplitude of temperature varied with the different seasons, by which revealed that winter and spring showed an increasing of temperature by 2.31℃ and 1.35℃, respectively.

The increasing of temperature influenced greatly plant spring phenophase, which was also the focus of studies concerning the effects of global climate warming on plant phenology (Primack et al., 2009; Brown et al., 2012). Hannien (1995) pointed out that bud germination of tree in spring was mainly affected by the critical low temperature in winter and low temperature was conducive to break bud dormancy. Xu et al. (2004; 2005) considered that the bud germination of plants was negatively correlated with winter temperature. The temperature rise in winter advanced the germination phenophases. Moreover, the decrease of the minimum temperature in winter facilitated the breaking of bud dormancy and advanced the germination of buds. Zhang (1995) and Chen and Zhang (2001) reported that higher winter temperatures were unfavourable to the dormancy of the buds in winter. Han et al. (2007) analysed the characteristics of the phenology variations in spring in the past 40 years and proved that the average temperatures in January to April increased by 2.3℃ and 1.7℃, respectively. Moreover, they believed that spring was extended by 5 days with the beginning and ending dates of spring advanced by 9 days and 4 days, respectively. The result in our study suggested that lower winter temperature was more conducive to the dormancy breaking of trees. Instead, the breaking of dormancy was

merely conducive to advancing germination in suitably cold conditions. Moreover, this study explored how the temperature before breaking of dormancy affected the plant phenology and how plant phenology responded to the temperature. By introducing a CI from the Kira heat index and substituting the monthly average temperature with a ten-day average temperature, the correlations between the germination, leafing, flowering phenolpheases and CI were investigated in this study, respectively. The results showed that CI was of ecological significance for studying spring phenology. The leafing phenophase was negatively correlated with the temperature in the spring (late March to late April) before this phenophase, while being slightly associated with the winter temperature. Therefore, the higher the temperature in spring, the earlier the leafing phenology. In addition, bud germination was of significant relevance to the absolute value of CI. The higher the absolute value of CI, the later the bud germination.

Many studies have been carried out on the response of leafing phenology of plants to climate warming. Zhou *et al.* (2001) analysed the NDVI data and found that leafing of vegetation in early spring was advanced by 7 days, while the growth season was extended by 18 days in Eurasia north of 40 °N. Zhang *et al.* (2005) studied the spring phenology changes in Beijing in the past 150 years. They pointed out that in the case of a 1℃ increase in the annual average temperature, the spring phenophase would be advanced by 2.8 to 3.6 days. Zhang (1995) used a linear statistical model and found that, with a 1℃ future global temperature, the spring phenology of woody plants in China would be advanced by 3 to 4 days, the autumn phenology would be postponed by 3 to 4 days, and the leafing phenology would be extended by 6 to 8 days. In our study, the leafing phenology of Shenyang urban forest would make an advance of 10 days if there was an increasing of 1℃ for future atmospheric temperature. This result was inconsistent with the conclusion of Zhang (1995). The possible reason was that Shenyang area is more sensitive to global warming because it is located to the northern China. Moreover, Zhang (1995) reported that the average temperature of China and global warming exerts less influence on the temperature over that scale.

The research regarding the response of flowering phenology to climate warming has been repeatedly reported with conclusions that are more consistent across

studies. The flowering phenology was advanced by about a week in the Mediterranean region from 1952 to 2000 (Penuelas and Filella, 2001), in Hungary from 1852 to 1994 (Walkovszky, 1998), in Wisconsin from 1936 to 1998 (Bradley *et al.*, 1999), and in Washington (state) from 1970 to 1999 (Sparks *et al.*, 2000) and Morocco from 1986 to 2012 (Yaacoubi *et al.*, 2014). In China, many researchers indicated that, with annual average temperature increasing by 1℃, the flowering phenology of most plants was advanced by 3 to 6 days (Xu *et al.*, 2004; Jiang *et al.*, 2004; Lu *et al.*, 2006; Guo *et al.*, 2015). In this study, it was shown that, in the case of a 1℃ rise in the annual average temperature, the flowering phenophase of the Shenyang urban forest would be advanced by 5 days. Our result was in accordance with the aforementioned results of many studies in the flowering phenology of plants.

Furthermore, the results in this study verified the mode of the responses of plant phenology to temperature proposed in previous studies. However, some researchers pointed out that the advance or delay of plant phenophase was not merely affected by temperature (Fang and Yu, 2002; Xu *et al.*, 2005). Sometimes, a phenophase was initiated photo-period rather than temperature. While other researchers believe that the interaction of water, light, and temperature would promote or delay the occurrence of phenology. Therefore, a dynamic phenological model (Li *et al.*, 2006) was more objective for phenology prediction to reflect the relationship between plant growth process and the environmental condition. Similar studies have been reported in China (Chuine *et al.*, 2003; Picard *et al.*, 2005). However, some factors including sunshine duration, precipitation and other microclimatic conditions should be taken into consideration in forecasting urban tree phenology and in improving the accuracy of predictions of carbon cycle of urban forest under the projected climate warming.

5 Conclusions

The observed atmospheric temperature has changed in Shenyang City from 1962 to 2005. According to our study, the annual average temperature in Shenyang showed a similar increasing trend with that of climate warming over the past 42 years, and it was associated with changes in the phenology of an urban forests. The

phenological advance of the main species in Shenyang urban forests in the terms of germination, leafing, and flowering periods showed an increasing trend with the increasing of atmospheric temperature, respectively. The germination phenology of the urban trees was negatively correlated with the temperature in winter and early spring. The leafing phenology was mainly influenced by the temperature in spring before leafing. We inferred that further warming in winter might prolong the growing season of urban trees in the northern forest of China.

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