

Research Article

Divergent Response of Leaf Coloring Seasons to Temperature Change in Northern China over the Past 50 Years

Zexing Tao ¹, Yunjia Xu ^{1,2}, Junhu Dai ¹ and Huanjiong Wang ¹

¹Key Laboratory of Land Surface Pattern and Simulation, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China

²University of Chinese Academy of Sciences, Beijing, China

Correspondence should be addressed to Junhu Dai; daijh@igsnr.ac.cn and Huanjiong Wang; wanghj.12b@igsnr.ac.cn

Received 26 December 2018; Accepted 21 February 2019; Published 8 April 2019

Academic Editor: Giacomo Gerosa

Copyright © 2019 Zexing Tao et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Autumn phenology plays a critical role in terrestrial ecosystem circulations. However, the changes in autumn phenology and their correlation with temperature remain uncertain because mean temperature alone was not able to determine the changes in autumn phenology at various sites. Here, the leaf coloring season (LCS) was defined as the period when the leaves of more than half of the species had recognized changes in color. We systematically studied the changes in peak, start, end, and duration of LCS and their correlations with five temperature parameters (mean temperature, accumulated cold temperature, day temperature, night temperature, and temperature difference between day and night) in four periods. Similarly to previous findings, the start date of LCS advanced and the end of LCS delayed over the past 50 years, which consequently led to a lengthened duration of LCS in Xi'an, Harbin, Minqin, and Shenyang. In general, the rise in mean temperature, day temperature, and night temperature would delay the peak, start, and end of LCS and lengthen the duration of LCS in most cases. We also proved that the changes in LCS metrics not only could completely be explained by mean temperature but also were influenced by day temperature, night temperature, temperature difference, and even other climatic factors such as precipitation, at different sites.

1. Introduction

Phenological study is critical for understanding the interactions between climate and terrestrial biosphere. The shifts in leaf unfolding date and leaf senescence date in the Northern Hemisphere caused by global warming profoundly influenced growing season length and altered many ecosystem biogeochemical circulations, such as the carbon cycle, nitrogen cycle, and water cycle [1–6]. The phenological changes in spring, such as earlier leaf-out and flowering, have been well documented on a global or national scale [7–9]. The changes in autumn phenology, by contrast, are more complex and have received much fewer concerns [10, 11]. Although some studies have used remotely sensed data to study the spatiotemporal patterns of autumn phenology, the results are sometimes inconsistent due to different data sources, data preprocessing, and phenophase extraction methods [12–14]. The autumn phenological trends derived from *in situ* observations were reliable but

highly spatially heterogeneous. In spite of the overall delaying trend of autumn phenophases, there were still about 1/3 of the sites in which the autumn phenology evidently advanced [15].

The question has arisen that what leads to the spatial difference in autumn phenological changes? With respect to the coherent environmental controls of autumn leaf phenology, some studies noted that mean temperature or accumulated temperature could be a reasonable determinant of autumn phenology [10, 16–18]. Low temperature, on the one hand, would force deciduous trees to shed their leaves to avoid freezing damage [19] and, on the other hand, accelerate the resolution of chlorophyll and formation of anthocyanin, leading to changes in leaf color [20, 21]. However, temperature changes, which tended to increase in almost all the areas of northern China over the past few decades, ignoring the difference in magnitude, could not perfectly agree with the trends of autumn phenology [22, 23]. The mismatch demonstrated that the mean temperature or accumulated

temperature alone was not sufficient to explain all the changes in autumn phenology at different sites [24, 25].

Some studies argued that the effect of temperature difference between day and night on autumn phenology was underestimated, since temperature difference above 15°C was propitious to color presentation of leaves [20, 26]. In addition, minimum temperature was also suggested as an influencing factor of autumn phenology that lower autumn minimum temperature would result in earlier leaf coloring date [27–30]. Although other environmental factors, such as precipitation, photoperiod, and insolation, would also influence autumn phenology through affecting the formation of leaf abscission meristems and plant carboxylation reaction [31], they were more likely to only constrain the temperature-induced changes. For example, photoperiod was thought to affect the tolerance of plants to low temperature [32, 33].

In addition, temperature in different periods might have divergent effects on autumn phenological changes [34]. The growing season temperatures were announced to play a greater role than the autumn temperatures in leaf senescence [27]. Regarding different phenophases, the August temperature could account for the start of leaf coloration, while the end of leaf coloration was likely determined by temperature in September and October [35].

In this study, we defined leaf coloring season (LCS) and investigated the change in peak, start, end, and duration of LCS at six sites in northern China. Subsequently, the correlations between LCS metrics and five temperature parameters in four periods were analyzed. The objectives of the present study are (1) to reveal the temporal changes of the leaf coloring season in northern China, (2) to identify the correlation between LCS metrics and different temperature parameters and how it is influenced by time intervals, and (3) to determine the main factor influencing the changes in LCS metrics.

2. Materials and Methods

2.1. Data Source. The start of leaf coloring date (LCD) and full-leaf coloring date (FLCD) during 1963–2010 was observed by the China Phenological Network (CNPN), which could be downloaded from the National Earth System Science Data Sharing Infrastructure (<http://www.geodata.cn>). Most of the observation sites were located at the edge of the city or in the suburbs; thus, the plant phenology was less susceptible to urbanization. The sites and species in the study had to meet the following criteria: (1) all the species were woody plants; (2) the leaves of the species shifted apparently in color; (3) in order to detect the interannual trends through the whole period, all the species needed to contain LCD and FLCD data of at least 5 years before and after 1980, respectively; and (4) each site included more than 20 species. After the filtering, our study consisted of six sites (Figure 1). The time series of LCD and FLCD were almost consecutive except for two periods (Figure 2). The numbers of records ranged from 429 (21 species) in Shenyang to 1903 (49 species) in Beijing for each phenophase.

The meteorological data were downloaded from the China Meteorological Data Service Center (<http://data.cma.cn/>).

We used the daily mean, maximum, and minimum air temperature at the above-mentioned six sites from 1963 to 2010 to study the relationship between temperature and phenology of the leaf coloring season. In this study, the maximum and minimum temperature was used to represent day and night temperature, respectively.

2.2. Methods. The leaf coloring season (LCS) was defined as the period when the leaves of more than half of the species had recognized changes in color. Thus, the LCS at a specific site was determined by the following steps (Figure 3): (1) we counted the daily numbers of species in leaf coloring (after the LCD and before the FLCD); (2) during the period when more than one plant had changed in color, a 5-day moving average was calculated to smooth daily fluctuations; and (3) a threshold of 0.5 was determined as the midpoint between the minimum and the maximum number of species in leaf coloring. The peak of the LCS was defined as the date with the maximum number of species in leaf coloring. If there were more than one date with the maximum number of species within a year (e.g., double peaks, or consecutive peaks), the peak of the LCS was identified as the average of the peak dates. The start and end of the LCS were the first and the last date when the number of species exceeded the threshold, respectively. The duration was the time span between the start and end of the LCS. Through these steps, the LCS metrics in each year at the six sites were decided.

We computed the annual mean peak, start, end, and duration of the LCS for the six sites. The duration of the LCS was depicted by days, and other LCS metrics were depicted by day of year (DOY). The trends of the LCS metrics for each site were also calculated through linear regression between the peak, start, end, and duration of the LCS and year.

Finally, we use Pearson's correlation analysis to examine the influences of five different temperature parameters (mean temperature, accumulated daily mean temperature less than 25°C, day temperature, night temperature, and temperature difference between day and night) in four periods (2 months before the start of LCS (2MS), 1 month before the start of LCS (1MS), 2 months before the end of LCS (2ME), and during the duration of LCS (D)) on the changes in start, end, peak, and duration of the LCS. Through the comparison of the correlation coefficient and significant level (p), we were able to identify which period and what type of temperature most influenced the start, end, peak, and duration of the LCS. The temperature sensitivity ($\text{days}/^\circ\text{C}$) was also calculated as the slope of the peak, start, end, and duration of LCS against its most correlated temperature parameters by the least squares method.

3. Results

3.1. Mean Peak, Start, End, and Duration of the LCS. The mean peak of LCS ranged from September 21 (day of year: 265) in Mudanjiang to October 25 (299) in Beijing (Figure 4). Both the mean start and end of LCS occurred later in Beijing (285 and 311) and Xi'an (273 and 311) but much earlier in Mudanjiang (248 and 281) and Harbin (249 and

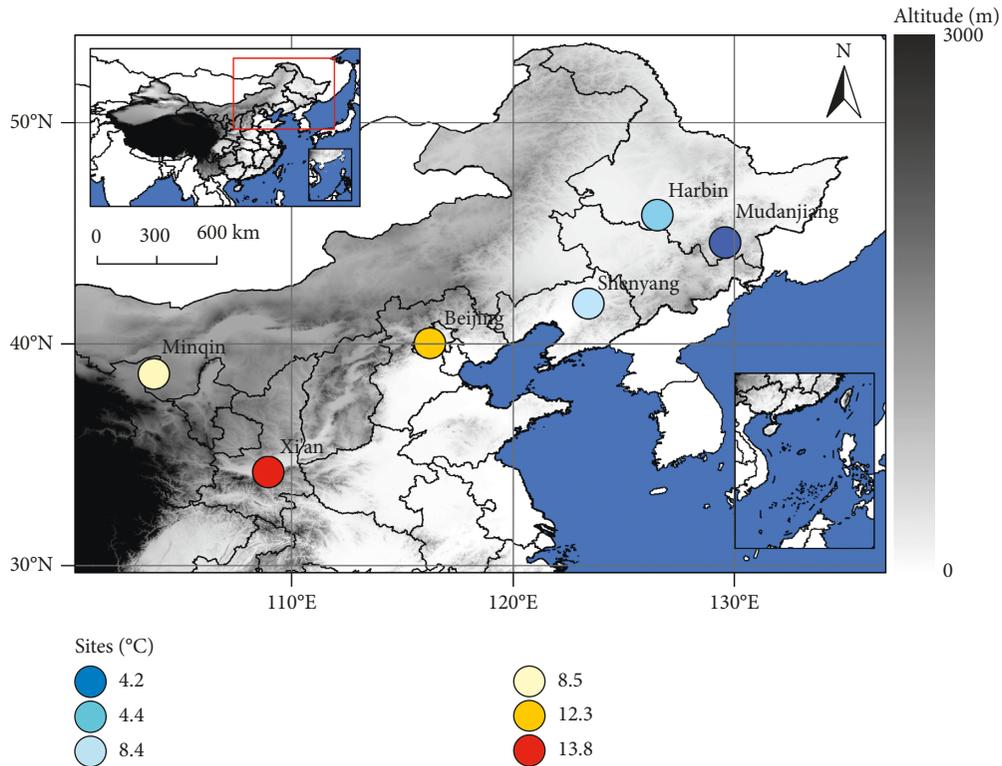


FIGURE 1: The location and the background of the phenological observation sites in this study. The colors of the circles indicate the annual mean temperature during 1960–1990 for each site.

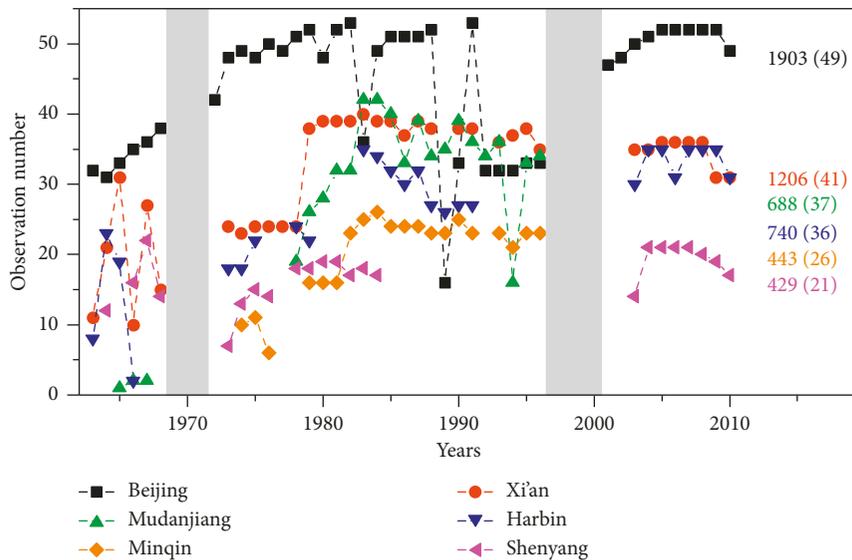


FIGURE 2: The numbers of phenological records at the six sites for each phenophase (leaf coloring date and full-leaf coloring date) during 1963–2010. The numbers at the end of the curves represent the total numbers of records for each phenophase. The numbers in the brackets are the number of species. The grey areas indicate the year lacking of observations.

282). The mean durations of LCS in all the sites were quite close (32–37 days) except for Beijing, where the mean LCS was shorter than a month (27 days).

3.2. *Interannual Variations of the LCS.* Figures 5(a)–5(f) display the interannual variations of the LCS metrics in

six sites. The amplitudes of the variations in the peak of LCS ranged from 17 days (standard deviation: 3.73 days) in Mudanjiang to 36 days (standard deviation: 7.56 days) in Xi’an during 1963–2010 (Figure 5). The start of LCS presented stronger fluctuations compared with the end of LCS in all the sites, in particular Xi’an and Shenyang, where the amplitudes (50 days in Xi’an and 57 days in Shenyang) and

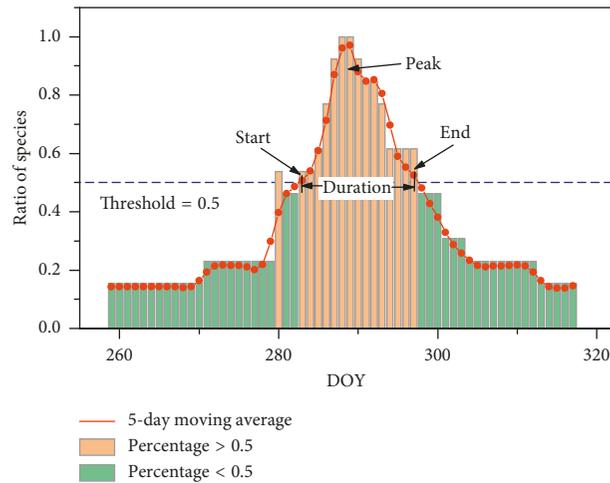


FIGURE 3: Schematic diagram for determining the leaf coloring season (LCS) metrics. Because large fluctuations (e.g., DOY280) may influence the determination of the LCS, we use a 5-day moving average (red line) to smooth the daily numbers of species in coloring.

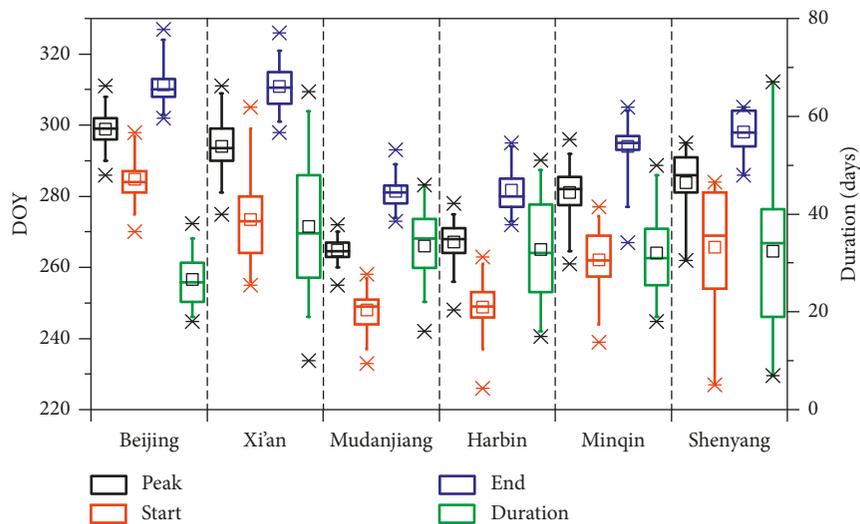


FIGURE 4: Boxplot of the peak, start, end, and duration of the leaf coloring season at six sites. The bottom and top of the boxes and the end of the whiskers are the 25th, 75th, and 95th percentiles, respectively. The bands and squares in the boxes show the median and mean value.

standard deviation (11.66 days in Xi'an and 15.81 days in Shenyang) of the variations in the start of LCS were around two to three times those in the end of LCS (amplitude: 28 days in Xi'an and 19 days in Shenyang; standard deviation: 6.29 days in Xi'an and 5.01 days in Shenyang). Drastic variations in the start of LCS also led to large variability in the duration of LCS. In Beijing, the duration of LCS varied less than 20 days with a standard deviation of 5.31 days during 1963–2010. However, the amplitude of variation in the duration of LCS for Xi'an (55 days) and Shenyang (60 days) almost reached 2 months, and the strongest fluctuations were mostly evident in the recent decade.

The signs and magnitudes of the trends of LCS also varied among different sites (Figure 6). Only two sites (Beijing and Shenyang) presented significant changes in the peak of LCS ($p < 0.01$) but with opposite trends. An advancing trend was revealed in Shenyang (-2.05 d/decade),

and a delaying trend was found in Beijing (2.63 d/decade). For the start of LCS, half of the sites showed advancing trends, but the shift was much more pronounced in Shenyang (-6.65 d/decade). And the most noticeable delaying start of LCS was found in Beijing (3.36 d/decade). However, all the sites exhibited a later end of LCS (0.31 – 2.66 d/decade) except for Mudanjiang. Notably, the magnitude of the delaying trend in most of these sites (2.17 – 2.87 d/decade) was similar, indicating a synchronized shift of the end of LCS across space.

With respect to the durations, the LCS in two sites (Beijing and Mudanjiang) experienced a shortening trend over the past 50 years with one significant site (Beijing: -1.12 d/decade; $p < 0.05$), while the LCS in other three sites (Xi'an, Harbin, and Shenyang) was significantly lengthened by 4.01 to 6.96 d/decade ($p < 0.01$). We also noticed that the lengthening trends in these three sites were all caused by an earlier start and a later end of LCS.

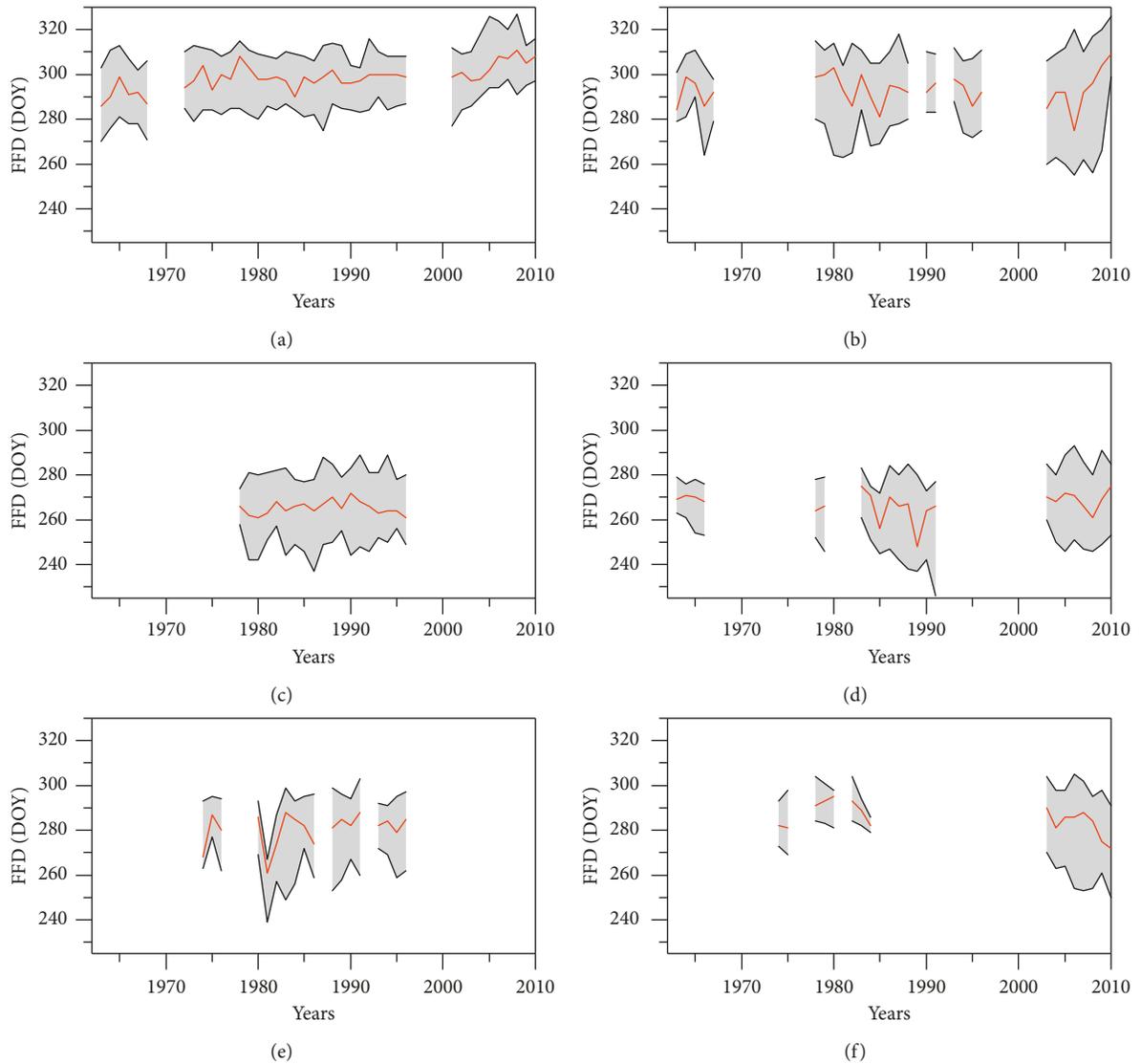


FIGURE 5: Interannual variations of the start, peak, end, and duration of the leaf coloring season (LCS) at six sites. The red line shows the peak of the LCS. The shadow area is the duration of the LCS. The upper and lower edges of the shadow area represent the start and end of the LCS, respectively. (a) Beijing. (b) Xi'an. (c) Mudanjiang. (d) Harbin. (e) Minqin. (f) Shenyang.

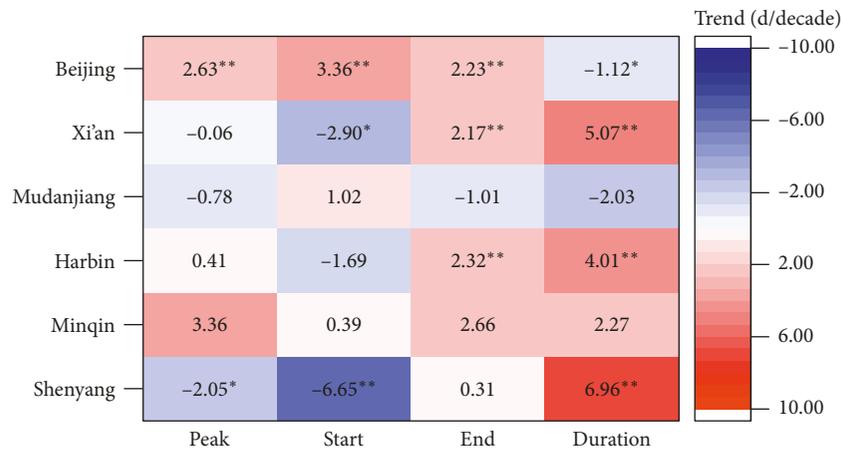


FIGURE 6: Trends of the peak, start, end, and duration of the leaf coloring season at six sites. Plus shows delay, and minus shows advance.

3.3. Correlation between LCS and Temperature Changes.

In most cases, the rise in mean temperature, day temperature, and night temperature would lead to a delayed peak, start, and end of LCS and a lengthened duration of LCS (Figure 7). Inversely, the temperature below 25°C and the temperature difference were negatively correlated with the peak, start, and end of LCS and positively correlated with the duration of LCS. For Beijing, the peak of LCS was most correlated with the mean temperature one month before the start of LCS ($r = -0.46$, $p < 0.01$), and the start, end, and duration of LCS were all mainly influenced by night temperature ($p < 0.01$). With respect to Xi'an, the temperature difference between day and night 2 months before the start of LCS was suggested to be the most significant factor determining the peak, start, and duration of LCS. The end of LCS in Xi'an was mostly influenced by the mean temperature 2 months before the end of LCS ($r = 0.63$, $p < 0.01$). The correlations between LCS and temperature were similar in Harbin and Mudanjiang. In both sites, the start of LCS was mainly driven by the day temperature, and the end of LCS was positively and significantly correlated with the night temperature. However, the correlation between the start of LCS and day temperature was positive in Mudanjiang but negative in Harbin. Regarding Minqin, the significant correlation was only found between the peak of LCS and the mean temperature 2 months before the end of LCS ($r = 0.48$, $p < 0.05$). The peak, start, end, and duration in Shenyang showed no significant correlations with mean temperature, temperature below 25°C, and night temperature. Instead, the day temperature was exhibited to be the most important factor influencing the start and duration of LCS in Shenyang ($p < 0.05$).

The sensitivity of the peak of LCS to temperature ranged from -2.45 d/°C ($R^2 = 0.12$, $p > 0.05$) in Harbin to 5.39 d/°C in Minqin ($R^2 = 0.12$, $p < 0.05$), with an average of 0.99 d/°C (Figure 8). The sensitivity of the start of LCS to temperature presented the maximum value in Xi'an (4.57 d/°C; $R^2 = 0.25$, $p < 0.05$) and the minimum value in Shenyang (-6.31 d/°C; $R^2 = 0.24$, $p < 0.05$). In terms of the sensitivity of the end of LCS, it showed a small difference among different sites (standard deviation: 1.49 d/°C). On the contrary, the response of duration of LCS to temperature differed evidently in space, with the sensitivity ranging from -4.77 d/°C in Xi'an ($R^2 = 0.25$, $p < 0.01$) to 7.79 d/°C in Shenyang ($R^2 = 0.32$, $p < 0.05$).

4. Discussion

Autumn phenology has great influence on the ecosystem and receives more and more concerns in recent decades. However, the change in autumn phenology still remains uncertain. In our study, we investigated the changes in the start, peak, end, and duration of the leaf coloring season (LCS) at six sites in China. We found an evident spatial difference in the changes in the start of LCS, with half of the sites showing an advancing trend and the others showing a delaying trend. This result is consistent with the study of Ge et al. [15], which suggested a large difference in autumn

phenology across China during 1960–2011. According to the definition of LCS, the changes in the start of LCS may show the overall phenological trend of species with earlier leaf coloration. We also noticed a delayed end of LCS for majority of the sites, indicating a unified delaying trend for the species with later leaf coloration. The delaying trend of 0.19 d/year on average is larger than the trend of leaf senescence (0.11 d/year) of deciduous trees in Eurasia and smaller than the trend (0.28 d/year) of that in North America over the last two decades [10]. In addition, the extending duration of LCS represents a more dispersed period of leaf coloration for different species, or vice versa. We found that the duration of LCS prolonged significantly in Xi'an, Harbin, and Shenyang, which was induced by an advanced start of LCS and a delayed end of LCS. On the contrary, the duration of LCS shortened in the other sites. Both the lengthening and shortening trend may indicate that the changes in leaf coloring are not synchronized among different species [11].

Our study exhibited an overall positive correlation between mean temperature and peak, start, and end of LCS; that is, increasing temperature would delay autumn phenology. This is in accordance with previous studies [16, 36]. However, the contribution of mean temperature to LCS variability is low when compared to spring phenology [30], with nonsignificant correlation existing between the mean temperature and LCS variability in most cases, particularly at Mudanjiang, Minqin, and Shenyang. As previous studies suggested, the night temperature has a predominant effect on the leaf coloring date for some deciduous trees [27, 37]. In this study, we found the largest correlation coefficient between night temperature and the end and duration of LCS in three sites, respectively. In Mudanjiang and Harbin, the changes in the LCS were quite different. The possible reason was that the night temperature two months before the LCS decreased in Mudanjiang (-0.86 °C/decade) but significantly increased in Harbin (0.39 °C/decade; $p < 0.01$) during 1963–2010. It is also noteworthy that the rise in temperature difference, rather than other factors, significantly accounted for the advance in the peak of LCS in Mudanjiang, demonstrating that the fluctuation in temperature would benefit for leaf coloration [20].

Many studies showed that the influence of temperature on autumn phenology varies in different periods. For example, Liu et al. [27] announced antagonistic effects of the growing season and autumn temperature on the leaf coloring date for four deciduous trees in China. Similarly, we notice that the correlation coefficient between temperature and autumn phenology is not completely consistent in the four periods. For instance, the end of LCS in Shenyang was positively correlated with mean temperature during the duration of LCS but negatively influenced by mean temperature 2 months before the start of LCS.

Furthermore, it is notable that, in Beijing and Xi'an, although the pre-season mean temperature, day temperature, night temperature, and temperature difference had a similar trend, the changes in the start of LCS in the sites were opposite. It suggests that other climatic factors, besides temperature, may contribute to the changes in LCS. To verify this assumption, we further calculated the trend of

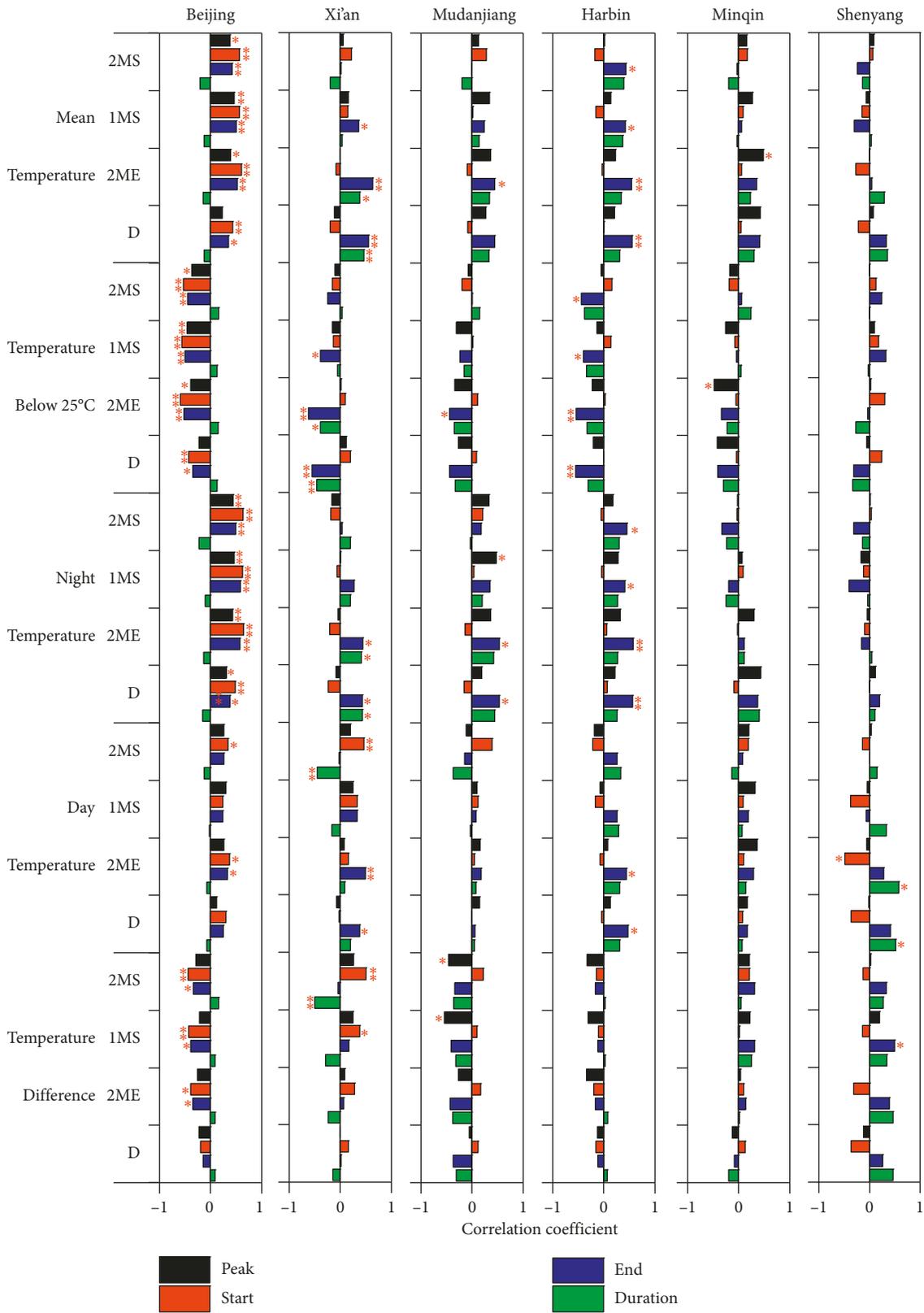


FIGURE 7: The correlation coefficient between the peak, start, end, and duration of the leaf coloring season and five temperature parameters in four periods at six sites. ** $p < 0.01$; * $p < 0.05$.

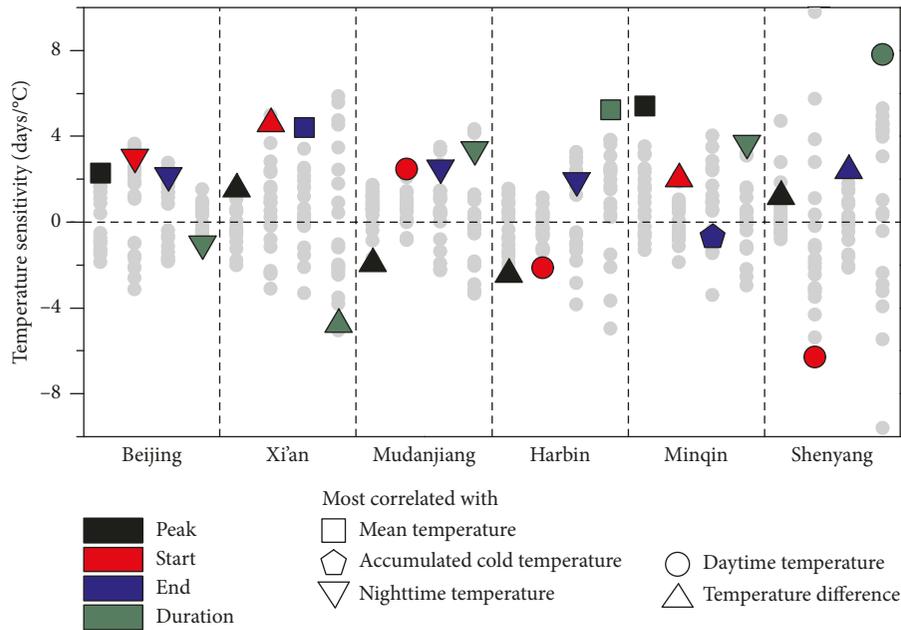


FIGURE 8: The sensitivity of the peak, start, end, and duration of the leaf coloring season (LCS) at six sites to temperature parameters. The colors in figures show the sensitivity of the peak, start, end, and duration of LCS to the most correlated temperature parameters, and the grey dots show the sensitivity of the peak, start, end, and duration of LCS to the other temperature parameters.

potential influencing factors, i.e., precipitation, relative humidity, wind velocity, and sunshine duration two months before LCS in Beijing and Xi'an. Subsequently, partial correlation analysis between the start of LCS and one of the potential factors, controlling mean temperature, day temperature, night temperature, temperature difference, and other potential factors was applied. The partial correlation coefficient clearly showed that increasing precipitation would delay the coloration of leaves (Table 1) probably because precipitation prolonged the growing season of plants and slowed down leaf senescence [31]. Thus, the increased precipitation in Beijing would lead to a delayed start of LCS. Meanwhile, the decreased precipitation would cause an advance of the start of LCS in Xi'an. In addition, the inconsistency of species types and numbers may also be one of the reasons for various trends between different sites.

Our study can not only provide better understanding on the response of autumn phenology to climate change but also be meaningful to guide tourism activities, since foliage coloration has become an important attraction for recreation and vacations in autumn [38]. The duration of LCS in this study represents the best period for foliage sightseeing in a particular area. It can be pointed out that tourists may enjoy a longer view of the coloration of the leaves in most sites with the global warming in the future.

5. Conclusions

In this study, we defined leaf coloring season (LCS) and investigated the changes in peak, start, end, and duration of LCS as well as their correlations with different temperature parameters. The results showed the following: (1) for most of

TABLE 1: The trend of potential influencing factors and their partial correlation with the start of LCS.

	Trend		Partial correlation coefficient (R)	
	Beijing	Xi'an	Beijing	Xi'an
Relative humidity	-0.15** (%/a)	-0.21** (%/a)	-0.31*	0.43*
Precipitation	0.46 (mm/a)	-1.39* (mm/a)	0.20	0.13
Wind velocity	-0.01 (m/s/a)	0.01 (m/s/a)	-0.04	0.19
Sunshine duration	-0.05** (h/a)	-0.01 (h/a)	-0.17	0.05

* $p < 0.05$; ** $p < 0.01$.

the six sites studied, the start date of the leaf coloring season (LCS) advanced and the end of LCS delayed over the past 50 years. As a result, a lengthened duration of LCS was found in Xi'an, Harbin, Minqin, and Shenyang. (2) In general, the rise in mean temperature, day temperature, and night temperature would lead to a delayed peak, start, and end of LCS and a lengthened duration of LCS in most cases. (3) The changes in LCS were not only determined by mean temperature but also influenced by day temperature, night temperature, and temperature difference in different sites. Other factors, such as precipitation, could explain the changes in LCS to some extent.

Data Availability

The phenological data could be downloaded from the National Earth System Science Data Sharing Infrastructure (<http://www.geodata.cn>). The meteorological data were

available from the China Meteorological Data Service Center (<http://data.cma.cn/>).

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Acknowledgments

This study was funded by the National Key R&D Program of China (Grant No. 2018YFA0606102), National Natural Science Foundation of China (Grant No. 41871032), and Key Programs of the Chinese Academy of Sciences (Grant No. KFZD-SW-310).

References

- [1] C. Wu, C. M. Gough, J. M. Chen, and A. Gonsamo, "Evidence of autumn phenology control on annual net ecosystem productivity in two temperate deciduous forests," *Ecological Engineering*, vol. 60, pp. 88–95, 2013.
- [2] M. E. Gonsamo, "Interactions of climate change and species," *Nature*, vol. 535, no. 7611, pp. 236–237, 2016.
- [3] E. Cleland, I. Chuine, A. Menzel, H. Mooney, and M. Schwartz, "Shifting plant phenology in response to global change," *Trends in Ecology & Evolution*, vol. 22, no. 7, pp. 357–365, 2007.
- [4] D. Xu and M. Fu, "Detection and modeling of vegetation phenology spatiotemporal characteristics in the middle part of the Huai river region in China," *Sustainability*, vol. 7, no. 3, pp. 2841–2857, 2015.
- [5] L. Wang, Z. Z. Ning, H. J. Wang et al., "Impact of climate variability on flowering phenology and its implications for the schedule of blossom festivals," *Sustainability*, vol. 9, no. 7, p. 1127, 2017.
- [6] X. F. Yu, Q. K. Wang, H. M. Yan et al., "Forest phenology dynamics and its responses to meteorological variations in Northeast China," *Advances in Meteorology*, vol. 2014, Article ID 592106, 12 pages, 2014.
- [7] F. Mo, J. Zhang, J. Wang et al., "Phenological evidence from China to address rapid shifts in global flowering times with recent climate change," *Agricultural and Forest Meteorology*, vol. 246, pp. 22–30, 2017.
- [8] Y. H. Fu, H. Zhao, S. Piao et al., "Declining global warming effects on the phenology of spring leaf unfolding," *Nature*, vol. 526, no. 7571, pp. 104–107, 2015.
- [9] A. Menzel, T. H. Sparks, N. Estrella et al., "European phenological response to climate change matches the warming pattern," *Global Change Biology*, vol. 12, no. 10, pp. 1969–1976, 2006.
- [10] A. L. Gill, A. S. Gallinat, R. Sanders-DeMott et al., "Changes in autumn senescence in northern hemisphere deciduous trees: a meta-analysis of autumn phenology studies," *Annals of Botany*, vol. 116, no. 6, pp. 875–888, 2015.
- [11] A. S. Gallinat, R. B. Primack, and D. L. Wagner, "Autumn, the neglected season in climate change research," *Trends in Ecology & Evolution*, vol. 30, no. 3, pp. 169–176, 2015.
- [12] W. Zhu, N. Jiang, G. Chen, D. Zhang, Z. Zheng, and D. Fan, "Divergent shifts and responses of plant autumn phenology to climate change on the Qinghai-Tibetan Plateau," *Agricultural and Forest Meteorology*, vol. 239, pp. 166–175, 2017.
- [13] J. I. Fisher and J. F. Mustard, "Cross-scalar satellite phenology from ground, Landsat, and MODIS data," *Remote Sensing of Environment*, vol. 109, no. 3, pp. 261–273, 2007.
- [14] H. J. Wang, J. H. Dai, and Q. S. Ge, "Comparison of satellite and ground-based phenology in China's temperate monsoon area," *Advances in Meteorology*, vol. 2014, Article ID 474876, 10 pages, 2014.
- [15] Q. Ge, H. Wang, T. Rutishauser, and J. Dai, "Phenological response to climate change in China: a meta-analysis," *Global Change Biology*, vol. 21, no. 1, pp. 265–274, 2015.
- [16] R. Dai, M. D. Schwartz, A. Donnelly, and L. Liang, "An observation-based progression modeling approach to spring and autumn deciduous tree phenology," *International Journal of Biometeorology*, vol. 60, no. 3, pp. 335–349, 2016.
- [17] S.-J. Liang, C.-H. Ho, H.-J. Gim, and M. E. Brown, "Phenology shifts at start vs. end of growing season in temperate vegetation over the Northern Hemisphere for the period 1982–2008," *Global Change Biology*, vol. 17, no. 7, pp. 2385–2399, 2011.
- [18] Y. Fracheboud, V. Luquez, L. Bjorken, A. Sjodin, H. Tuominen, and S. Jansson, "The control of autumn senescence in European Aspen," *Plant Physiology*, vol. 149, no. 4, pp. 1982–1991, 2009.
- [19] Z. Tao, H. Wang, J. Dai, J. Alatalo, and Q. Ge, "Modeling spatiotemporal variations in leaf coloring date of three tree species across China," *Agricultural and Forest Meteorology*, vol. 249, pp. 310–318, 2018.
- [20] W. Jiang, M. Zhuang, H. Han et al., "Progress on color emerging mechanism and photosynthetic characteristics of colored-leaf plants," *Acta Horticulturae Sinica*, vol. 32, no. 2, pp. 352–358, 2004.
- [21] S. Zhong, J. Zheng, and Q. Ge, "Change of autumnal leaf coloring of woody plants in eastern China for the last 40 years," *Chinese Journal of Agrometeorology*, vol. 31, no. 1, pp. 1–4, 2010.
- [22] P. D. Jones, D. H. Lister, T. J. Osborn et al., "Hemispheric and large-scale land-surface air temperature variations: an extensive revision and an update to 2010," *Journal of Geophysical Research-Atmospheres*, vol. 117, no. D5, 2012.
- [23] H. Wang, B. Zhang, C. Zhao et al., "The spatio-temporal characteristics of temperature change in recent 57 Years in Northern China," *Progress in Geography*, vol. 28, no. 4, pp. 643–650, 2009.
- [24] Q. Liu, Y. H. Fu, Z. Zeng, M. Huang, X. Li, and S. Piao, "Temperature, precipitation, and insolation effects on autumn vegetation phenology in temperate China," *Global Change Biology*, vol. 22, no. 2, pp. 644–655, 2016.
- [25] C. Olsson and A. M. Jönsson, "A model framework for tree leaf colouring in Europe," *Ecological Modelling*, vol. 316, pp. 41–51, 2015.
- [26] L. Tian, *The Impact of Temperature and Humidity on Five Kinds of Fall-Color Trees' Color Changing in Autumn of Beijing*, Beijing Forestry University, Beijing, China, 2012.
- [27] G. Liu, X. Chen, Q. Zhang et al., "Antagonistic effects of growing season and autumn temperatures on the timing of leaf coloration in winter deciduous trees," *Global Change Biology*, vol. 24, no. 8, pp. 3537–3545, 2018.
- [28] K. K. Tanino, L. Kalcsits, S. Silim et al., "Temperature-driven plasticity in growth cessation and dormancy development in deciduous woody plants: a working hypothesis suggesting how molecular and cellular function is affected by temperature during dormancy induction," *Plant Molecular Biology*, vol. 73, no. 1–2, pp. 49–65, 2010.

- [29] C. K. Park, C. H. Ho, S. J. Jeong et al., “Spatial and temporal changes in leaf coloring date of *Acer palmatum* and *Ginkgo biloba* in response to temperature increases in South Korea,” *PLoS One*, vol. 12, no. 3, Article ID e0174390, 2017.
- [30] C. Wu, X. Wang, H. Wang et al., “Contrasting responses of autumn-leaf senescence to daytime and night-time warming,” *Nature Climate Change*, vol. 8, no. 12, pp. 1092–1096, 2018.
- [31] J. X. Zu and J. Yang, “Temporal variation of vegetation phenology in northeastern China (in Chinese),” *Acta Ecologica Sinica*, vol. 36, no. 7, pp. 2015–2023, 2016.
- [32] C. Korner and D. Basler, “Phenology under global warming,” *Science*, vol. 327, no. 5972, pp. 1461–1462, 2010.
- [33] X. Morin and I. Chuine, “Will tree species experience increased frost damage due to climate change because of changes in leaf phenology?,” *Canadian Journal of Forest Research*, vol. 44, no. 12, pp. 1555–1565, 2014.
- [34] I. Ibáñez, R. B. Primack, A. J. Miller-Rushing et al., “Forecasting phenology under global warming,” *Philosophical Transactions of the Royal Society B: Biological Sciences*, vol. 365, no. 1555, pp. 3247–3260, 2010.
- [35] Y. Xie, X. Wang, A. M. Wilson, and J. A. Silander, “Predicting autumn phenology: how deciduous tree species respond to weather stressors,” *Agricultural and Forest Meteorology*, vol. 250–251, pp. 127–137, 2018.
- [36] Q. Silander, Y. H. Fu, Z. Zhu et al., “Delayed autumn phenology in the Northern Hemisphere is related to change in both climate and spring phenology,” *Global Change Biology*, vol. 22, no. 11, pp. 3702–3711, 2016.
- [37] D. L. Deal, J. C. Raulston, and L. E. Hinesley, “Leaf color retention, dark respiration, and growth of red-leafed Japanese maples under High Night temperatures,” *Journal of the American Society for Horticultural Science*, vol. 115, no. 1, pp. 135–140, 1990.
- [38] Q. Ge, J. Dai, J. Liu, S. Zhong, and H. Liu, “The effect of climate change on the fall foliage vacation in China,” *Tourism Management*, vol. 38, pp. 80–84, 2013.



Hindawi

Submit your manuscripts at
www.hindawi.com

