Journal of Global Change Data & Discovery. 2019, 3(4): 336-342
DOI:10.3974/geodp.2019.04.04
www.geodoi.ac.cn

Global Change Research Data Publishing & Repository

Autumn Phenological Grid Dataset of Five Deciduous Broad-leaved Woody Plants in the Warm Temperate Zone of China (1963–2015)

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Abstract: Plant autumn phenology is affected by many environmental factors, such as temperature, water, and daylight. Because of the sensitivity to environmental factors, changes in the timing and distribution of autumn phenology is more complicated and may be important indicators of global changes. In this paper, the leaf coloring date (LCD) of five woody plants, *Fraxinus chinensis* Roxb. (Oleaceae), *Salix babylonica* L. (Salicaceae), *Robinia pseudoacacia* L. (Leguminosae), *Ulmus pumila* L. (Ulmaceae Mirb.), and *Armeniaca vulgaris* Lam. (Rosaceae), from 1963 to 2015 was obtained from the Chinese Phenological Observation Network and used to establish and compare three LCD models (multiple regression, temperature–photoperiod, and spring-influenced autumn). The 0.5°×0.5° LCD grid data of the five species from 1963 to 2015 were developed by simulation and scale expansion. The cross validation results showed that the average simulation error of the LCD was approximately 10–18 days. The autumn phenological grid dataset of China is the basic data representing the spatial–temporal pattern and changes in autumn phenology in China over the last 50 years. The dataset includes three parts: header file, phenophase, and spatial distribution, which consist of 541 data files in three data folders. The data is archieved in .txt, GEOTIFF, and ARCGIS ASCII formats. The data size is 26.8 MB (4.86 MB after compression).

Keywords: warm temperate zone; autumn phenology; woody plants; leaf coloring date; China

1 Introduction

Plant autumn phenology is affected by both internal factors (e.g., growth hormones, age of reproductive development) and external environmental factors (e.g., temperature, water, daylight, nutrient deficiency)[1]. Compared with spring phenology, the changes of autumn

Received: 03-12-2019; **Accepted:** 16-12-2019; **Published:** 24-12-2019

Foundations: Chinese Academy of Sciences (XDA19020303); Ministry of Science and Technology of P. R. China (2018YFA0606102); National Natural Sciences Foundation of China (41771056)

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Data Citation: [1] Zhu, M. Y., Dai, J. H., Tao, Z. X., *et al*. Autumn phenological grid dataset of five deciduous broad-leaved woody plants in the warm temperate zone of China (1963–2015) [J]. *Journal of Global Change Data & Discovery*, 2019, 3(4): 336–342. DOI: 10.3974/geodp.2019.04.04.

[2] Zhu, M. Y., Dai, J. H., Liu, H. L., *et al*. Autumn phenological grid dataset of typical woody plants in warm temperate zone of China [DB/OL]. Global Change Research Data Publishing & Repository, 2019. DOI: 10.3974/geodb.2019.06.06.V1.

phenology are more complicated, and the mechanism has not been fully explored. In the absence of *in situ* observation data, phenological data can be interpolated by models of autumn phenology to provide data support for comprehensive studies on plant geography and global change[2]. In our previous paper, three models were established to examine spatial–temporal patterns of leaf coloring date (LCD) for three woody plants in China, and the results provided a better understanding of the autumn phenological process and its response to climate change[3]. Currently, great uncertainties remain in how to observe and model autumn phenology in China. Large systematic errors are associated with observations because of the difficulty in identifying the degree of autumn leaf coloring, and because of the complex relationship between autumn phenology and environmental factors, extensive validation of autumn phenological models is lacking[4]. Therefore, in this study, the applicability of three different models for the simulation and scale expansion of autumn phenology of five woody plants was evaluated. This paper aimed to publish the systematic development methodology and the basic results of a spatial–temporal distribution grid dataset of the autumn phenology of woody plants in China.

2 Metadata of Dataset

The metadata of "Autumn phenological grid dataset of typical deciduous broad-leaved woody plants in the warm temperate zone of China"[5] are summarized in Table 1, including the dataset full name, short name, authors, year of the dataset, temporal resolution, spatial resolution, data format, data size, data files, data publisher, and data sharing policy, etc.

Table 1 Metadata summary of "Autumn phenological grid dataset of typical deciduous broad-leaved woody plants in the warm temperate zone of China"

Items	Description
Dataset full name	Autumn phenological grid dataset of typical deciduous broad-leaved woody plants in the warm temperate zone of China
Dataset short name	AutumnPhenologyWoodyPlantWarmTZChina
Authors	Zhu, M. Y. AAA-7619-2019, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, zhumy.16b@igsnrr.ac.cn Dai, J. H., Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, daijh@igsnrr.ac.cn Liu, H. L., Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, liuhl@igsnrr.ac.cn Tao, Z. X. AAA-7688-2019, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, taozx.12s@igsnrr.ac.cn Wang, H. J. AAA-7674-2019, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, wanghj@igsnrr.ac.cn Dong, X. Y., Chang'an University, dongxy@igsnrr.ac.cn Hu, Z. AAE-4801-2019, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, huz.18b@igsnrr.ac.cn
Geographical region	China: 18 °N–54 °N, 72 °E–136 °E
Year	1963–2015
Temporal resolution	day
Spatial resolution	0.5 °×0.5 °
Data format	.txt, GEOTIFF, ARCGIS ASCII
Data size	26.8 MB
Data files	The datdset consists of header files, phenophase, spatual distribution Phenophase: the leaf unfolding date (LCD) Species: *Fraxinus chinensis*, *Salix babylonica*, *Robinia pseudoacacia*, *Ulmus pumila*, *Armeniaca vulgaris*

(***To be continued on the next page***)

(***Continued***)

Items	Description
Foundations	Chinese Academy of Sciences (XDA19020303); Ministry of Science and Technology of P. R. China (2018YFA0606102); National Natural Sciences Foundation of China (41771056)
Computing environment	MATLAB, campus license of Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences ArcGIS campus license of Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences
Data publisher	Global Change Research Data Publishing & Repository, http://www.geodoi.ac.cn
Address	No. 11A, Datun Road, Chaoyang District, Beijing 100101, China
Data sharing policy	***Data*** from the Global Change Research Data Publishing & Repository includes metadata, dataset (data products), and publications (in this case, in the *Journal of Global Change Data & Discovery*). ***Data*** sharing policy includes: (1) ***Data*** are openly available and can be free downloaded via the Internet; (2) End users are encouraged to use ***Data*** subject to citation; (3) Users, who are by definition also value-added service providers, are welcome to redistribute ***Data*** subject to written permission from the GCdataPR Editorial Office and the issuance of a ***Data*** redistribution license; and (4) If ***Data*** are used to compile new dataset, the 'ten percent principal' should be followed such that ***Data*** records utilized should not surpass 10% of the new dataset contents, while sources should be clearly noted in suitable places in the new dataset[6]
Communication and searchable system	DOI, DCI, CSCD, WDS/ISC, GEOSS, China GEOSS

3 Methods

3.1 Basic Data Collection

The LCD of five well-observed typical deciduous broad-leaved woody plants was derived from the Chinese Phenological Observation Network (CPON, www.cpon.ac.cn). The five species were *Fraxinus chinensis* Roxb. (Oleaceae), *Salix babylonica* L. (Salicaceae), *Robinia pseudoacacia* L. (Leguminosae), *Ulmus pumila* L. (Ulmaceae Mirb.), and *Armeniaca vulgaris* Lam. (Rosaceae). The spatial distribution data were obtained from the Atlas of Woody Plants in China: Distribution and Climate[7]. The daily air temperature data of both station and grid were obtained from the China Meteorological Data Service Center (data.cma.cn), which were used for model parameterization and scale expansion, respectively.

3.2 Algorithm Principle

The autumn phenological models are mostly based on different assumptions on the response of plants to environmental factors such as temperature and photoperiod[8]. Compared with spring phenological models, autumn phenological models include more drivers, such as photoperiod and spring phenophase, and thus, the process of parameter estimation is more complicated. In this study, three autumn LCD models were tested: multiple regression (MR) model[8] which considers the influence of temperature in different months, temperature–photoperiod (TP) model[9–10], and spring-influenced autumn (SIA) model[11] which considers the combined influence of temperature and photoperiod. The functional forms and structures of the relationship between phenophase and meteorological factors are different in these models[12].

(1) In the MR model, the influence of average temperature on autumn LCD is different in different months. Increasing temperature in May and June may lead to the advance of LCD, whereas increasing temperature in August and September may lead to the delay of LCD[8]. A multiple regression model (Equation 1) was established on the basis of the correlations (R_5–R_9) between LCD (P_l) and average temperature from May to September (T_5–T_9), where *a, b, c, d*, and *e* are model coefficients and ε is a constant term.

$$P_l = aT_5 + bT_6 + cT_7 + dT_8 + eT_9 + \varepsilon,\ if \left|R_{5,6,7,8,9}\right| < 0.3\ \ a,b,c,d,e = 0 \tag{1}$$

(2) The TP model assumes that the autumn LCD is affected by both temperature and photoperiod[7]. When the photoperiod is lower than the threshold P_{start}, the cold state $CDD(d)$ starts to accumulate (Equation 2). When the accumulated $iCDD(d)$ exceeds the threshold Y_{crit}, the day d is the exact date of leaf coloring (Y_{mod}, Equation 3). The daily cold state $CDD(d)$ is codetermined by daily temperature $T(d)$ and daily photoperiod $P(d)$ (Equations 4, 5).

$$iCDD(d)=\begin{cases}0 & P(d)\geqslant P_{start}\\ CDD(d-1)+CDD(d) & P(d)<P_{start}\end{cases} \quad (2)$$

$$Y_{mod}=d, iCDD(d)\geqslant Y_{crit} \quad (3)$$

$$if\ \ P(d)<P_{start}, CDD(d)=\begin{cases}0 & T(d)\geqslant T_b\\ [T_b-T(d)]^x\times f[P(d)]^y & T(d)<T_b\end{cases} \quad (4)$$

$$f[P(d)]=\frac{P(d)}{P_{start}}\ \ or\ \ f[P(d)]=1-\frac{P(d)}{P_{start}} \quad (5)$$

The TP model includes five parameters: P_{start}, Y_{crit}, T_b, x, and y, where x and y are 0, 1, or 2. x=0 or y=0 indicates that the LCD is independent of temperature or photoperiod; x=1 or y=1 indicates that the LCD is linearly correlated with temperature or photoperiod; x=2 or y=2 indicates a nonlinear correlation with temperature or photoperiod.

(3) In the SIA model, which is based on the TP model, the influence of spring phenology on autumn phenology is considered[11]. The model assumes that the threshold Y_{crit} at the beginning of the LCD in autumn is linearly correlated with spring phenological departure S_a (Equation 6). The SIA model has six parameters: P_{start}, T_b, x, y, a, and b.

$$Y_{crit}=(a+b\times S_a) \quad (6)$$

3.3 Technical Route

The steps in the development of the grid data include the building of phenological models, the comparison of models, and the simulation and scale expansion (Figure 1). First, the autumn LCD models were built using the LCD data from CPON and the station temperature data from the China meteorological data website. Second, the three LCD models were validated via internal validation using the LCD in odd years and via cross validation using the LCD in even years. The optimal LCD model was determined by the minimum root mean square error (RMSE). Finally, the LCD grid data of five woody plants in China were developed by simulation and scale expansion based on the optimal LCD model and the grid temperature data from the China meteorological data website.

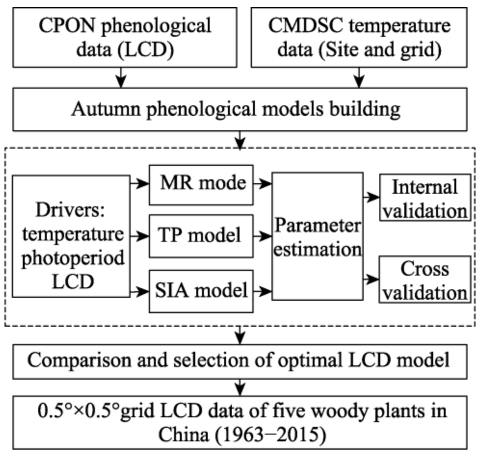

Figure 1 Technical route to develop autumn phenological grid data for five woody plants in China from 1963 to 2015

4 Results and Validation

4.1 Data Products

The autumn phenology grid dataset consists of header file, phenophase, and spatial distribution (Table 2). Each folder of the five species contains a total of 106 LCD files from 1963 to

2015. Data files are archieved in visual GEOTIFF and ARCGIS ASCII standard formats. The LCD data outside the spatial distribution range of a species need to be masked.

Table 2 Composition of the "Autumn phenological grid dataset of typical deciduous broad-leaved woody plants in the warm temperate zone of China"

Main files	Naming	Description	Format	File number	Data size
Header file	Headfile.txt	Column, row number, longitude, latitude, spatial resolution, null value	.txt	1	1 KB
Phenophase	Phenophase_ species_year.tif	Phenophase: day of year (DOY) No data value: 999	GEOTIFF ARCGIS ASCII	265 265	26.3 MB
Spatial distribution	Spatial_species.tif	Distributed value: 1 Undistributed value: 999	GEOTIFF ARCGIS ASCII	5 5	0.4 MB

4.2 Results

The results of autumn phenophase simulation showed that the LCD of all species was spatially different depending on latitude and altitude, with the latest LCD in the eastern and southern regions in China (Figure 2). The time distribution of each species indicated that the average LCD of *Armeniaca vulgaris* (Figure 2e) was relatively early, whereas that of *Robinia pseudoacacia* (Figure 2c) was relatively late. The LCD time range was also different. The range of LCD was larger for *Fraxinus chinensis*, *Salix babylonica*, and *Ulmus pumila* than that for other species. A linear regression between LCD and year was used to determine the trend of autumn phenology. The results of the trend analysis (Table 3) showed that the LCD was delayed in 83.7%–99.5% of the pixels for most species, except for *Ulmus pumila*. Among the other species, the delaying trends were most distinct for *Robinia pseudoacacia* and *Armeniaca vulgaris*, with 83.7% and 81.6%of the pixels showing significant delay, respectively. The LCD of *Ulmus pumila* was advanced in 70.8% pixels, but only in 3.2% of the pixels the advancing trends were significant (P<0.05). In general, except for *Ulmus pumila* (−0.4 d/10a), the LCD of all species showed a distinct delaying trend over the last 50 years, with an average trend of 0.5–0.8 days per decade.

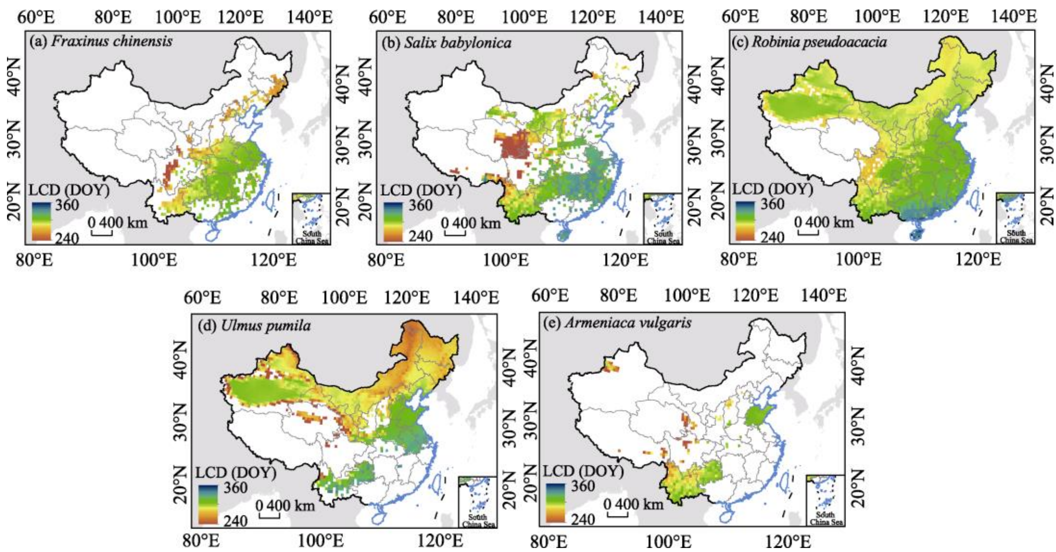

Figure 2 Average leaf coloring date (LCD) of five typical deciduous broad-leaved woody plants in the warm temperate zone of China from 1963 to 2015. Panels (a)–(e) represents mean LCD of each species. DOY represents the sequential day number in the Julian calendar.

Table 3 Statistics of the trend in variation of autumn phenological time of five typical deciduous broad-leaved woody plants in the warm temperate zone of China from 1963 to 2015

Phenophase	Species	Trend (d/10a)	Advanced	Delayed	Significantly delayed	Significantly advanced
LCD	*Fraxinus chinensis*	0.5	16.3%	83.7%	0.4%	22.7%
	Salix babylonica	0.7	8.3%	91.7%	1.4%	54.0%
	Robinia pseudoacacia	0.6	1.6%	98.4%	1.0%	83.7%
	Ulmus pumila	–0.4	70.8%	29.2%	3.2%	8.3%
	Armeniaca vulgaris	0.8	0.5%	99.5%	0.0%	81.6%

4.3 Data Validation

The validation results of the three autumn LCD models are shown in Figure 3. Internal validation results showed that the MR model was the best fit to the LCD of *Salix babylonica*, *Robinia pseudoacacia*, and *Armeniaca vulgaris* (R^2=0.34–0.51, RMSE=10.89–15.62 days). The SIA model was most suitable for *Fraxinus chinensis* (R^2=0.52, RMSE=10.45 days) and *Ulmus pumila* (R^2=0.64, RMSE=11.71 days). The cross validation results showed that the MR model had the highest simulation accuracy for *Fraxinus chinensis*, *Salix babylonica*, and *Armeniaca vulgaris* (RMSE=9.76–18.23 days), whereas the SIA model simulated the LCD of *Robinia pseudoacacia* and *Ulmus pumila* best (RMSE=11.49 and 11.05 days, respectively). Overall, the simulation of the autumn phenology data was less accurate than that of the spring phenology data[13], and the average simulation error was approximately 10–18 days.

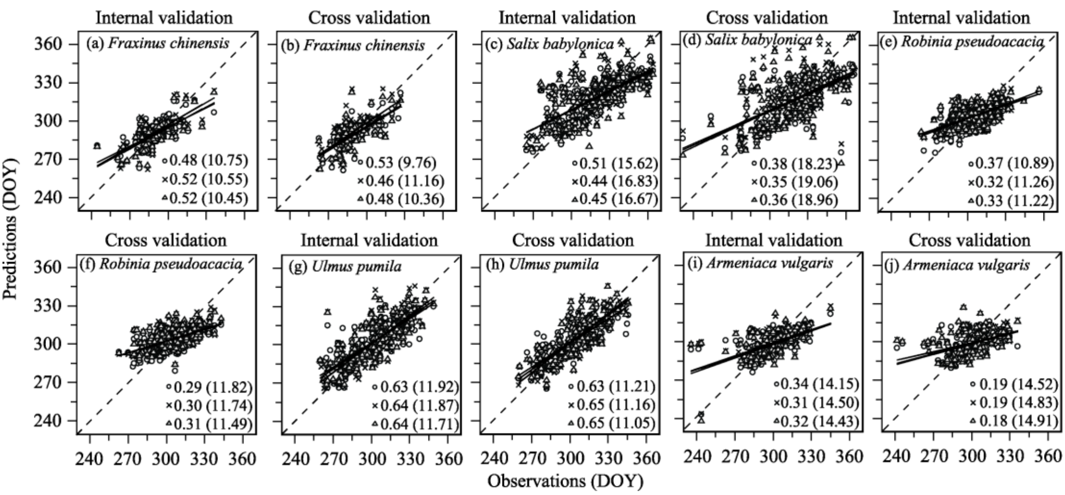

Figure 3 Internal and cross validation of three phenological models for the simulation of the leaf coloring date (LCD) of five typical deciduous broad-leaved woody plants in the warm temperate zone of China from 1963 to 2015. Panels (a)–(j) represents internal and cross validation on LCD of each species. DOY represents the sequential day number in the Julian calendar.

Note: The ○, ×, and △ represent the simulation results of the MR, TP, and SIA models, respectively. Solid lines are linear regression curves fit to observed and predicted values. The number after the symbol and the number in parentheses represent the R^2 and root mean square error, respectively. The root mean square minimum value represents the simulation result of the optimal phenological model.

5 Discussion and Conclusion

In this paper, the methodology and research results of autumn phenological data from the observations of CPON were systematically reviewed, and the LCD time series dataset of five typical deciduous broad-leaved woody plants in the warm temperate zone of China from 1963 to 2015 was presented for publication. The temporal resolution was 1 day, and the spatial resolution was 0.5°×0.5°. The average simulation error of the autumn LCD for each species was approximately 10–18 days, which was a greater error than that for the simulation of spring leaf unfolding date or first flowering date[13]. Research in North America[10], Europe[9], and Asia[14] based on a single site also showed great differences in the simulation accuracy of autumn models. In these previous studies of different species, the absolute error of simulation of the LCD varied from 1 to 13 days. Therefore, the simulation accuracy of the autumn phenology dataset in this paper was moderate and was within the range of previous measurements. Furthermore, the dataset showed the spatial–temporal distribution as well as the changes in the autumn phenology of woody plants in China. This dataset can provide the basis for a better understanding of the response of autumn phenology to global climate change.

Author Contributions

Dai, J. H. was responsible for the overall design and development of the dataset. Dong, X. Y. and Hu, Z. collected and processed autumn phenological data. Tao, Z. X. and Wang, H. J. designed the model and the algorithm. Zhu, M. Y. and Dong, X. Y. performed data validation. Zhu, M. Y. and Dai, J. H. wrote the data paper.

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