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Effects of Temperature, Precipitation, and CO_2 on Plant Phenology in China: A Circular Regression Approach

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Abstract: Leveraging circular regression, this study analyzed phenological data from China spanning the period 2003 to 2015, meticulously examining the effects of temperature, precipitation, and CO_2 concentrations on the phenological patterns of woody and herbaceous plants. For woody plants, the results showed that rising temperatures and increased precipitation notably advanced early growth phases, such as budburst, leaf unfolding, and first flowering ($p < 0.001$). Specifically, CO_2 concentrations had a pronounced impact on the leaf unfolding phase ($p < 0.001$). In contrast, autumnal events, particularly fruit maturity, autumn coloring, and leaf fall, were delayed by warmer temperatures and higher precipitation ($p < 0.001$), Of these events, only fruit maturity demonstrated sensitivity to CO_2 concentration variations. In the realm of herbaceous plants, elevated temperatures and precipitation collectively hastened the budburst phase ($p < 0.001$), which is an effect further accentuated by high CO_2 levels ($p < 0.001$). Moreover, rising temperatures and augmented precipitation were instrumental in advancing the flowering phase ($p < 0.001$). Conversely, warmer conditions slowed down the fruiting process ($p < 0.001$), with this delay somewhat mitigated by the effects of increased precipitation. Interestingly, while CO_2 concentrations had negligible influence on the flowering and fruiting stages, they noticeably delayed seed dispersal and the initiation of senescence ($p < 0.001$). Overall, the prevailing trend suggests that plants, whether woody or herbaceous in nature, tend to prolong their growth season under warmer and more humid conditions. The influence of CO_2 concentration, however, is contingent upon the specific phenological phase and plant type. Our findings emphasize the nuanced and stage-specific responses of plant phenology to temperature, precipitation, and CO_2, highlighting the value of using circular regression in ecological studies.

Keywords: circular regression; climate change; climate factors; woody and herbaceous plants; plant phenology

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1. Introduction

Human activities, such as burning fossil fuels and deforestation, have resulted in an increase in the emission of greenhouse gases, like CO_2, leading to an increase in the greenhouse effect and global warming [1]. In the 20th century, the global surface temperature rose by 0.8 °C, and it is expected that in the 21st century, the average temperature of the earth will increase by 1.4–5.8 °C [2]. Global warming will lead to sea level rise and an increase in extreme weather events, including heat waves, drought, flooding, and storms, which will alter the composition of plant species and impact human well-being [3]. Many plants are changing their life cycles to adapt to climate change, which is reflected in the changes in plant phenology [4].

Plant phenology is the seasonal phenomena of plants, such as budburst, leaf expansion, flowering, fruiting, and leaf fall. The duration of plant phenology is called plant phenological events [5]. Changes in plant phenological events are the result of a continuous process of exchange and accumulation of matter and energy between an organism and its external environment, which is closely related to plant growth and development [6]. It is also an important aspect of studying the way in which plants respond to climate change [7].

Plant phenology is closely related to temperature. Plant physiological activity is a series of biochemical reactions regulated by enzyme activity. Temperature changes enzyme activity. On one hand, higher temperature can increase enzyme activity and, thus, accelerate plant phenology processes. Studies have shown that the yellow withering period of plants in typical grassland areas is negatively correlated with the average summer temperature, and the yellow withering period begins about 2.25 days earlier for every 1 °C increase in temperature [8]. It has also been shown that the flowering and fruiting of Myrtiaceae plants in the Brazilian rain forest are temperature-dependent, tending to bloom during hot and humid seasons, while rising temperatures accelerate fruit ripening [9]. In Spain and Russia, the onset of foliation of *Pinus sylvestris* L. increased by 2.1 days per decade due to increasing temperatures [10]. On the other hand, lower temperatures also have a regulatory effect on plant phenology. Studies have shown that cooler temperatures are conducive to breaking winter bud dormancy in subtropical regions, and a lack of low temperatures can lead to the delayed leaf-out emergence of species [11].

Precipitation is a key factor affecting plant phenology. In arid and semi-arid areas, plants cannot benefit from heat and light, regardless of the favorability of the conditions. In this case, precipitation becomes the main factor affecting plant growth and development [5,12]. Studies have shown that annual precipitation determines the length of the growing season of sensitive alpine meadow vegetation [13]. The flowering time of plants in Gutian Mountains is obviously seasonal, and most plants bloom in the rainy season [14]. Generally, drought leads to a delay in onset of the phenological period [5]. For example, decreased precipitation will result in the delayed onset and prolonged duration of the *Stipa krylovii* Roshev. yellow withering period [15]. But other studies have shown that increased precipitation can delay the phenological period. For example, for every 10 mm increase in spring precipitation, the flowering of British Bramley apples was significantly delayed by 0.4 ± 0.1 days [16].

Increasing the CO_2 concentration has the effects of fertilization and warming on plants, and it will indirectly affect plant phenology, including having delayed, advanced or no effect. The consistent rise in atmospheric CO_2 concentration, along with climate warming, has resulted in the delayed maturation and senescence of six grassland plants, extending their growing seasons [17]. Elevated CO_2 concentration delayed the flowering period of *Populus tremuloides* Michx., advanced its leaf spread, and shortened the growing season [18]. Elevated CO_2 concentrations extended the flowering period of *Jatropha curcas* L. by 8–10 days, enhancing fruit and seed production [19]. In addition, the increased CO_2 concentration increased the photosynthesis of *Acer rubrum* L. in the whole growing season, but it had no effects on the start time, end time, and shedding time of leaf senescence [20].

Numerous studies have reported the effects of temperature, precipitation, and CO_2 concentration on plant phenology [21,22]. However, previous research has often focused on the impact of a single factor on plant phenology, and few studies have considered the combined effects of these factors on plant phenology. One of the reasons for this problem is that linear regression models are not well suited to addressing this issue [23,24]. Given the continuous nature of phenological events, it is imperative to perceive a year as an unbroken cycle when examining plant phenology [25]. Conventional linear regression models cannot handle periodic data. Therefore, we use circular regression to solve this problem.

Circular statistics transforms data into points on the unit circumference, making it well suited to handling circular data [26]. Phenological events are circular events that occur repeatedly throughout a plant's life. By converting a plant's phenological events to one day of the year, circular statistics uses the angle as the response variable to handle this time structure [25]. This approach allows any phenological event to be converted into an angle and represented as a point on the circle, and further statistical data (mean angle, median angle, mean vector length, and standard deviation) are based on trigonometric functions [27].

Circular statistics have been used in the field of plant phenology [28,29]. For example, a past study describes seasonal peak fruit yield and fruiting season length, as well as the circular correlation of geography and climate with fruit production time [30]. Furthermore, circular statistics can process directional data, like the flight patterns of inserts and wind directions [31,32]. In addition, the analysis of feeding time, the distribution of plant roots, and flood dynamics with circular statistics can be considered [33,34].

In this study, we utilize circular statistical regression methods to examine the influence of temperature, precipitation, and CO_2 concentration on various plant phenological events. This novel approach enables us to accurately capture the cyclic nature of these events and offer unique insights into how these critical environmental factors could potentially impact stages in a plant's life cycle, such as budburst, flowering, fruiting, seed dispersal, and senescence. The findings of our study contribute to a broader understanding of plant responses to climate change and offer valuable guidance for various fields, including ecosystem modeling, biodiversity management, conservation planning, and climate mitigation strategies.

2. Materials and Methods

2.1. Data Sources

Our phenological observation data were derived from the Chinese Ecosystem Research Network (CERN)'s plant phenology dataset. This comprehensive resource includes phenological observation records derived from 21 ecological stations (Figure 1, Table A1). For this study, we meticulously curated and organized data ranging from 2003 to 2015, resulting in a comprehensive dataset that included both woody and herbaceous plants. This dataset comprised 4134 records of woody plants, representing 335 species, and 2943 records of herbaceous plants, representing 308 species, with each record capturing critical phenological events. In the dataset for woody plants, we documented phenological stages, such as budburst, leaf unfolding, first flowering, peak flowering, fruit maturity, autumn coloring, and leaf fall. In the dataset for herbaceous plants, we also observed and recorded stages like budburst, flowering, fruiting, seed dispersal, and senescence [35].

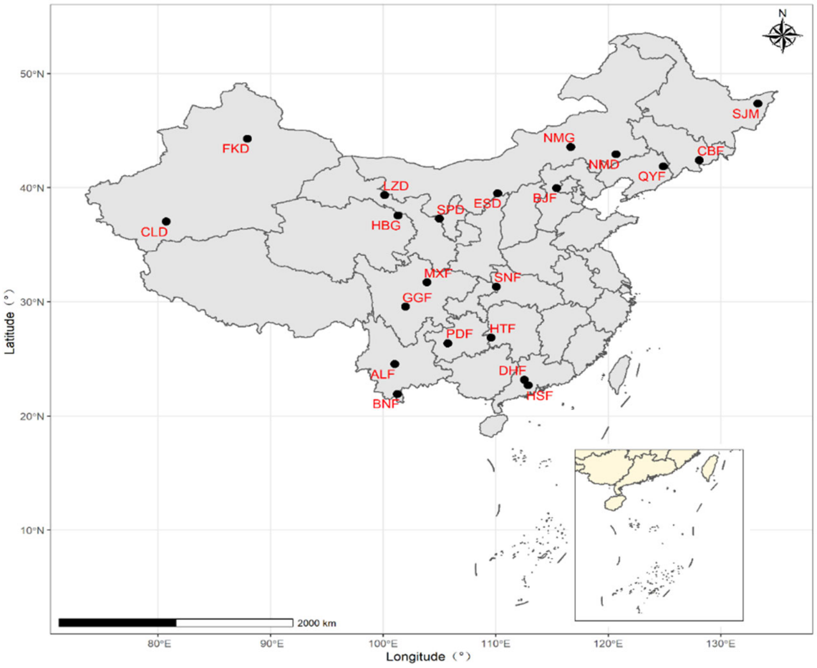

Figure 1. The locations of ecological stations.

Aligned with phenological events, our study focused on three primary indicators: the annual average temperature (°C), total yearly precipitation (mm), and annual average CO_2 concentration (ppm). To support this analysis, we sourced data from reputable sources. The temperature and precipitation data used in our study were sourced from the NOAA Physical Sciences Laboratory [36,37]. We obtained the CO_2 concentration data from a global dataset that represents atmospheric levels of carbon dioxide on a $2 \times 2.5°$ grid [38].

2.2. Descriptive Statistics in Circular Data

The statistical variables of circular statistics were as follows: The mean angle ($\bar{\theta}$) represented the average time of occurrence of various phenological events, which could be used to estimate the average phenological period or the middle point of phenological period. The median angle ($\widetilde{\theta}$) represented the median time of occurrence of phenological events. It could output more stable results when dealing with skewed sample data and is more commonly used in this field. The Mean date, which represented the average occurrence time of a specific phenological event across various species at the same station, could be derived from Formula (1). It was calculated using the average angle, which was obtained via the conversion of X. The mean vector length (r) was used as a measure of the concentration of phenological activity time, with a value range of 0–1. The larger the r value, the more concentrated the phenological period. Standard deviation (σ) was used as a measure of the dispersion of phenological activity time, with a value range of 0–1. The larger the σ value, the more dispersed the phenological events.

2.3. Circular Regression

The response variable of circular regression had to be an angle or radian, and the various phenological events of herbaceous and woody plants were transformed into angles according to Formula (1). The formula used was defined as follows:

$$rad = \frac{360 \times X}{k} \times \frac{\pi}{180} \tag{1}$$

Rad represents the radian on the circular scale, X represents the number of days of plants phenological events in a year, and k represents the total time unit. In this paper, k = 365 days, without considering the difference of a leap year.

The circular regression model used was proposed in 1992 [39].

$$Y = \mu + 2atan(\beta_i x_i) \tag{2}$$

In this study, 'Y' corresponded to the radian of the target variable on the circular scale, signifying the average occurrence of a phenological event in terms of the radian. The term 'μ' was utilized to denote the average angle direction. Meanwhile, 'β_i' stood for the regression coefficient, with 'x_i' representing various independent variables. In an effort to establish the optimal fit for parameters μ and β, we employed the weighted least squares algorithm combined with the maximum likelihood estimation technique, as advocated by Green [40].

It is important to note that if the coefficient had a negative sign, an upward shift in the predictor value would correspond to an earlier occurrence of the phenological event in relation to μ. Conversely, a positive coefficient signified that an increase in the predictor would result in a later event compared to μ. The coefficient was considered statistically significant in our study if the median of the p-value distribution was below the threshold of 0.05.

Circular statistics analysis was conducted using the circular package in R 4.2.2 [41,42].

3. Results

3.1. Descriptive Statistics

The descriptive statistics of the phenological events of woody plants are shown in Table 1. The mean date difference, which indicates the variability in event timings across stations and years, shows that leaf fall has the shortest span at 78 days. The mean date difference of fruit maturity is the longest, having a difference of 106 days. The mean vector lengths of budburst, leaf unfolding, autumn coloring, and leaf fall are all greater than 0.6, and their standard deviations are less than 0.6.

Table 1. Statistical variables of phenological stages in woody plants.

Variables	Budburst	Leaf Unfolding	First Flowering	Peak Flowering	Fruit Maturity	Autumn Coloring	Leaf Fall
Mean date	1 February–3 May	4 March–22 May	28 March–18 June	15 April–9 July	3 June–17 September	12 September–30 November	25 September–12 December
Mean angle $(\bar{\theta})$	31.98–121.42	62.21–139.99	86.04–164.09	103.27–202.15	152.32–256.07	251.89–329.2	264.57–340.81
Median angle $(\tilde{\theta})$	40.44–118.36	61.15–140.05	85.59–172.93	113.42–218.96	142.03–263.34	254.47–329.42	265.32–344.22
Mean vector length (r)	0.76–0.99	0.76–0.99	0.55–0.99	0.53–0.99	0.26–0.92	0.88–0.99	0.81–0.98
Standard deviation (σ)	0.06–0.49	0.06–0.49	0.06–0.67	0.06–0.68	0.28–0.86	0.06–0.35	0.12–0.44

The descriptive statistics of phenological events are shown in Table 2. Flowering is the shortest, having a difference of 72 days, while senescence has the longest difference, i.e., a difference of 153 days. The mean vector lengths of the budburst and senescence are greater than 0.6, and their standard deviations are less than 0.6.

Table 2. Statistical variables of phenological stages in herbaceous plants.

Variables	Budburst	Flowering	Fruiting	Seed Dispersal	Senescence
Mean date	22 February–4 June	11 May–22 July	11 June–17 September	30 June–30 October	20 July–20 December
Mean angle $(\bar{\theta})$	51.89–152.45	128.85–200.4	159.71–256.55	178.6–299.29	198.62–349.51
Median angle $(\tilde{\theta})$	47.34–182.47	127.23–212.05	150.9–271.73	159.78–300.16	179.51–359.01
Mean vector length (r)	0.72–0.99	0.47–0.95	0.5–0.95	0.55–0.96	0.65–0.98
Standard deviation (σ)	0.03–0.53	0.23–0.73	0.22–0.7	0.2–0.67	0.13–0.59

3.2. Phenological Events of Woody Plants

For the budburst, temperature exhibited a significant negative effect ($p < 0.001$), suggesting that an increase in temperature leads to an earlier budburst. Precipitation also showed a significant negative influence ($p < 0.001$), while the effect of CO_2 concentration was not significant ($p = 0.283$).

In the case of leaf unfolding and first flowering, both temperature and precipitation had significant negative impacts, while the influence of CO_2 concentration was statistically significant in the former case and not statistically significant in the latter case. For peak flowering, the trend is similar, with temperature and precipitation showing significant negative effects and CO_2 concentration demonstrating no significant influence.

In contrast, for fruit maturity, an increase in temperature, precipitation, and CO_2 concentration significantly delayed the event ($p < 0.001$ for all). For autumn coloring and leaf fall, an increase in temperature and precipitation significantly delayed these events ($p < 0.001$), while the influence of CO_2 concentration was not statistically significant (Table 3).

3.3. Phenological Events of Herbaceous Plants

In the case of budburst, both temperature and precipitation had a significant negative impact ($p < 0.001$), meaning that an increase in these parameters resulted in an earlier budburst. CO_2 concentration also had a significant negative influence ($p < 0.001$), suggesting that a rise in CO_2 concentration advances the onset of this phenological event.

Table 3. Results of circular regression models of phenological events in woody plants.

Events	μ	Parameters	Estimate	S.E.	*t*-Value	*p*
Budburst	1.542	temp	−0.065	0.005	12.036	<0.001
		prec	−0.055	0.005	10.366	<0.001
		CO_2	0.002	0.004	0.573	0.283
Leaf_Unfolding	1.717	temp	−0.097	0.006	16.030	<0.001
		prec	−0.082	0.006	13.730	<0.001
		CO_2	−0.050	0.005	10.980	<0.001
First_Flowering	2.049	temp	−0.062	0.008	7.790	<0.001
		prec	−0.096	0.008	12.391	<0.001
		CO_2	0.002	0.006	0.326	0.372
Peak_Flowering	2.252	temp	−0.047	0.008	5.648	<0.001
		prec	−0.092	0.008	11.384	<0.001
		CO_2	0.001	0.007	0.111	0.456
Fruit_Maturity	−2.801	temp	0.062	0.014	4.594	<0.001
		prec	0.062	0.013	4.662	<0.001
		CO_2	0.150	0.011	14.060	<0.001
Autumn_Coloring	−1.001	temp	0.229	0.007	31.440	<0.001
		prec	0.147	0.007	21.188	<0.001
		CO_2	−0.004	0.006	0.769	0.221
Leaf_Fall	−0.529	temp	0.326	0.009	35.812	<0.001
		prec	0.191	0.008	23.435	<0.001
		CO_2	−0.006	0.007	0.869	0.192

For flowering, an increase in temperature displayed a minor yet significant negative effect ($p < 0.001$). Precipitation had a significant negative influence ($p < 0.001$), while the effect of CO_2 concentration was not statistically significant ($p = 0.302$).

During the fruiting stage, the effect of temperature was significantly positive ($p < 0.001$), while the influence of precipitation was significantly negative ($p < 0.001$). The impact of CO_2 concentration was not significant ($p = 0.109$).

In the seed dispersal stage, both temperature and precipitation had significant positive impacts ($p < 0.001$). The influence of CO_2 concentration was significantly negative ($p < 0.001$).

Lastly, for senescence, both temperature and precipitation had significantly positive effects ($p < 0.001$). CO_2 concentration had a significant negative effect ($p < 0.001$) (Table 4).

Table 4. Results of circular regression models of phenological events in herbaceous plants.

Events	μ	Parameters	Estimate	S.E.	*t*-Value	*p*
Budburst	1.638	temp	−0.070	0.008	8.373	<0.001
		prec	−0.117	0.008	13.969	<0.001
		CO_2	−0.054	0.006	8.463	<0.001
Flowering	2.629	temp	−0.030	0.012	2.450	<0.001
		prec	−0.227	0.013	17.653	<0.001
		CO_2	−0.005	0.010	0.517	0.302
Fruiting	−2.816	temp	0.076	0.015	5.140	<0.001
		prec	−0.142	0.015	9.622	<0.001
		CO_2	0.014	0.011	1.234	0.109
Seed_dispersal	−1.806	temp	0.254	0.017	14.994	<0.001
		prec	0.107	0.016	6.720	<0.001
		CO_2	−0.058	0.013	4.574	<0.001
Senescence	−1.070	temp	0.311	0.011	27.600	<0.001
		prec	0.312	0.011	27.601	<0.001
		CO_2	−0.034	0.009	3.973	<0.001

4. Discussion

4.1. Effects of Temperature and Precipitation

For early phenological stages in woody plants, such as budburst, leaf unfolding, and first flowering, our study demonstrates the prominent negative effects of temperature and precipitation. This finding suggests that increased temperature or precipitation can expedite the occurrence of these events, leading to their earlier onset. Conversely, for autumnal events, like autumn coloring and leaf fall, the results differed. An increase in temperature and precipitation significantly delayed these events, hinting at an extended growth period under these conditions. This finding is consistent with previous studies, which report that an increase in temperature will advance the spring phenological stages and delay the autumn phenological stages [10].

For herbaceous plants, the early stages, such as budburst and flowering, exhibited similar trends to those observed in woody plants, where both temperature and precipitation showed a significant negative impact. During the final life cycle stage of senescence, our findings took an interesting turn. Both temperature and precipitation displayed significantly positive effects, suggesting that an increase in these factors might extend the life cycles of herbaceous plants, potentially providing a more extended window for essential physiological processes.

Our findings present an intriguing shift in the impacts of temperature as we progress to the fruiting and seed dispersal stages of herbaceous plants. A significant positive effect of temperature was observed, suggesting that increased temperatures may expedite these events. The influence of precipitation, on the other hand, shifted in its nature; it had a significantly negative impact on the fruiting stage, but became significantly positive during seed dispersal. This result implies a potential role played by precipitation in aiding the spread of seeds, a factor that could be crucial for species dispersion and ecosystem resilience [43].

These findings underline the complex and dynamic relationships between climatic factors and plant phenology [44]. Understanding these relationships is greatly important, especially in the context of climate change, where shifts in these factors could lead to significant changes in plant life cycles and, consequently, ecosystem dynamics [45,46].

4.2. Effects of CO_2 Concentration

When examining woody plants, the influence of CO_2 concentration on phenological events presents a stark contrast to the impacts of temperature and precipitation. Our study detected the nuanced role played by CO_2 concentration across various stages of woody plant development. During the fruit maturity stage, we found that an increase in CO_2 concentration significantly delayed this event. This observation is intriguing, suggesting a potential role played by elevated CO_2 in promoting reproductive success [47]. However, given the complexities of plant physiological responses and the potential interplay with other environmental factors, the exact mechanisms underlying the observed CO_2 effects need to be fully elucidated [48,49]. Furthermore, there is a need to consider the potential influence of CO_2 concentration on other aspects of plant physiology and overall plant health, which were not covered in this study.

In alignment with our observations on woody plants, the influence of the CO_2 concentration on flowering in herbaceous plants was not significant. This finding contrasts with previous studies, notably the work of Johnston and Reekie [50], which posited that an increase in CO_2 concentration advances the flowering period of Compositae plants by approximately four days. Several explanations might account for this discrepancy. Firstly, plant responses to increased CO_2 levels can be species specific, with some species reacting more strongly than others [51]. Therefore, it is possible that the herbaceous plants discussed in our study are less responsive to CO_2 changes than the Compositae plants investigated by Johnston and Reekie. Secondly, the effect of CO_2 on flowering could be moderated by other environmental factors, such as light intensity or soil nutrients, which were not controlled in our study [52,53]. Finally, it is also plausible that the impact of CO_2 on flowering varies depending on the specific timing and degree of CO_2 increases [54]. Future studies will need to disentangle these potential factors to provide a comprehensive understanding of how elevated CO_2 concentrations influence the flowering of herbaceous plants.

Contrary to its influence on flowering, the impact of CO_2 concentration on senescence was notable. A significant negative effect was found, which indicates that heightened levels of CO_2 might fast track the senescence process. This result is consistent with the results of previous studies, in which an increase in CO_2 concentration was found to significantly delay the senescence times of the leaves of grassland plants [55].

4.3. Circular Regression

The current study employs circular regression, which is a highly effective approach distinct from linear models, being particularly apt for handling cyclical and yearly data characteristics of many phenological events. This method offers a range of valuable descriptive statistical indices, such as the mean angle, median angle, and mean vector length and their respective standard deviations. Despite not offering predictive capabilities akin to those of linear models, circular regression bears a significant advantage—it enables a lucid representation of either the advancement or delay in phenological stages [7].

The utility of circular regression extends beyond merely cataloging phenological shifts, as it is especially well suited to investigating the key environmental factors influencing these shifts [29]. In the present study, we specifically probed the impacts of temperature, precipitation, and CO_2 on plant phenology. While the complexity of these environmental influences on plant life cycle stages varied, circular regression provided us with a robust and intuitive way to model and understand these effects [56].

Our research underscores the value of using circular regression as a tool in ecological research, significantly contributing to our comprehension of cyclical natural phenomena. Moreover, the versatility of this method implies that its applicability extends beyond plant phenology and can potentially be harnessed to investigate other cyclic data patterns. Moving forward, future studies could continue to exploit the potential of circular regression, enabling a deeper understanding of plant phenology and the intricate interplay between the environmental factors that govern it.

4.4. Phenological Events

Phenological patterns show clear differences between woody and herbaceous plants. In woody plants, the leaf fall event, with its shortest mean date difference of 78 days, indicates strong synchronization across species and locations. This outcome may be due to shared environmental triggers or biological adaptations [57]. On the other hand, the fruit maturity event has a longer mean date difference of 106 days, suggesting flexibility influenced by various environmental or biological factors in their reproductive strategies.

For herbaceous plants, the flowering events are notable, having a mean date difference of only 72 days. This brief period emphasizes the evolutionary pressures driving these plants to synchronize flowering, thereby optimizing their pollination opportunities within the most conducive conditions [58]. This alignment might arise from a collective reaction to specific environmental cues, guaranteeing an effective reproductive process [59]. In contrast, the mean date difference for senescence extends to 153 days, highlighting herbaceous plants' adaptability to different conditions, which might favor strategies used in nutrient distribution and the transition into dormancy [60].

Across both plant types, the consistently high mean vector lengths for events such as budburst, leaf unfolding, autumn coloring, and senescence, combined with their low standard deviations, paint a picture of phenological harmony across species and ecosystems. Such uniformity across varied conditions can attest to the resilience of plants, underlining their ability to uphold crucial lifecycle stages amid environmental changes [61].

Although this study illuminates general phenological patterns in woody and herbaceous plants, it also emphasizes the importance of examining species-specific trends over time. As shown in prior research, certain species consistently initiate their phenological events either ahead of or behind their counterparts. [62]. Such variations are likely driven by differences in adaptive strategies, which are potentially molded by environmental disturbances, such as grazing or other anthropogenic and natural impacts [63,64]. Moreover, species with unique phenological initiation patterns might progress through the subsequent phenological stages at different rates [65]. Investigating these species-specific phenological patterns can provide invaluable perspectives, particularly when forecasting the ecological impacts of shifting climatic scenarios.

5. Conclusions

Through the application of circular regression to phenological data from China spanning a period from 2003 to 2015, this study illuminates the complex influences of temperature, precipitation, and CO_2 concentration on plant phenology. Our exploration spans early phenological stages, fruiting and seed dispersal stages, and the final lifecycle stage of senescence in both woody and herbaceous plants.

In woody plants, elevated temperatures and precipitation consistently advance the onset of early growth stages, including budburst, leaf unfolding, and first flowering. However, these climatic variables lead to a noticeable delay in autumnal events, especially autumn coloring and leaf fall. This observed trend aligns with the prevalent consensus that rising temperatures and increased precipitation quicken spring phenological events while postponing those of autumn. Herbaceous plants, during their initial growth phases, like budburst and flowering, exhibit patterns similar to those of woody plants, with these stages being expedited under warmer and wetter conditions. Uniquely, under these heightened climatic conditions, herbaceous plants exhibit a prolonged senescence phase. Our study suggests that regardless of whether plants are woody or herbaceous in nature, increased temperatures and precipitation tend to extend their growth season, highlighting the significant influence of these environmental factors on ecosystem dynamics and plant species' adaptability.

In woody plants, early growth stages, such as budburst and first flowering, exhibited minimal sensitivity to variations in CO_2 concentrations. However, increased CO_2 levels accelerated the leaf unfolding phase while notably postponing the fruit maturity stage. In contrast, herbaceous plants more dynamically responded to changes in CO_2. Specifically, elevated CO_2 levels correlated with earlier budburst, seed dispersal, and onset of the senescence phase. Our study emphasizes that CO_2 concentrations exert a stage-specific influence on different plant types. This finding highlights the intricate relationship between atmospheric carbon levels and key phenological events in various plant species.

Our results highlight the crucial role played by circular regression in studying not only plant phenology but also other cyclical natural phenomena. As research methodologies continue to evolve, utilizing such specialized techniques will become crucial to enhancing our comprehension of the relationships between environmental factors and the cyclical dynamics of nature.

This study contributes to a more nuanced understanding of plant phenology, demonstrating the utility of circular regression in uncovering the diverse influences of temperature, precipitation, and CO_2 concentration on phenological events. The insights gained in this study underscore the complexity of plant–environment interactions, emphasizing the need for continued research in this domain to fully comprehend the ecological implications of climatic shifts.

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Data Availability Statement: No new data were created in this study. Data sharing is not applicable to this article.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. The information regarding ecological stations.

Code	Ecological Stations	Longitude (°)	Latitude (°)
ALF	Ailaoshan Forest Ecosystem Research Station	101.0281	24.5450
BJF	Beijing Forest Ecosystem Research Station (BFERS)	115.4300	39.9600
BNF	Xishuangbanna Tropical Rainforest Ecosystem Station	101.2647	21.9269
CBF	Changbai Mountain Research Station of Forest Ecosystems	128.1067	42.3989
CLD	Cele Desert Research Station	80.7275	37.0208
DHF	Dinghushan Forest Ecosystem Research Station	112.5494	23.1642
FKD	Fukang Desert Ecological Research Station	87.9328	44.2906
ESD	Ordos Sandland Ecological Research Station	110.1903	39.4947
GGF	Gongga Mountain Ecosystem Observation and Experiment Station	101.9983	29.5761
HBG	Haibei Alpine Meadow Ecosystem Research Station	101.3128	37.5608
HSF	Heshan Hilly Land Interdisciplinary Experimental Station	112.9003	22.6797
HTF	Huitong National Research Station of Forest Ecosystem	109.6053	26.8517
LZD	Linze Inland River Basin Research Station	100.1283	39.3497
MXF	Maoxian Mountain Ecosystem Research Station	103.8956	31.6961
NMG	Inner Mongolia Grassland Ecosystem Research Station	116.6778	43.5458
NMD	Naiman Desertification Research Station	120.7000	42.9297
PDF	Puding Karst Ecosystem Observation and Research Station	105.7500	26.3667
QYF	Qingyuan Forest Ecosystem Research Station	124.9150	41.8528
SJM	Sanjiang Mire Wetland Experimental Station	133.3008	47.3519
SNF	Shennongjia Biodiversity Research Station	110.0500	31.3167
SPD	Shapotou Desert Research and Experiment Station	105.0003	37.2803

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