

Impact Of Climate Change On *Angelica sinensis* Yield In The Cool And Semi-Humid Regions In Northwest China

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The increasing challenges posed by climate change have significant implications for agricultural productivity, particularly for crops like *Angelica sinensis*, a valuable medicinal plant. Understanding how climatic variables such as temperature and precipitation affect the yield of *Angelica sinensis* is critical for developing adaptive strategies to sustain its cultivation. research to determine impacts climatic variables on yields of *Angelica sinensis* in Northwestern Cool Semi-Humid Region of China seventeen years of agricultural meteorological data from 2005 to 2021. Linear trend estimation, Mann-Kendall mutation test, correlation analysis, and path analysis methods have been utilized to examine the relationships among temperature, precipitation, and yields of *Angelica sinensis* during the different growth stages from transplanting to harvest. The temperature during the growth period presents a fluctuating increasing trend of 0.37°C decade⁻¹ with a mutation in 2013 and a prominent decreasing trend of -2.89°C decade⁻¹ since 2016. Precipitation increases by 41.6 mm decade⁻¹, and a mutation from low to high precipitation occurred in 2018. Yield has a strongly significant positive correlation with precipitation (correlation coefficient = 0.581). Path analysis results show that the precipitation during Three-leaves-to-six-leaves growth stage has the strongest direct influence on the yields of *Angelica sinensis* (path coefficient = 0.550), while the precipitation during Seven-leaves-to-harvest stage has a considerable direct influence (path coefficient = 0.521) despite the negligible simple correlation. Annual yields of *Angelica sinensis* significantly increase by 44.9 g/m² decade⁻¹. This study valuable insights into optimizing the irrigation schedule and selecting suitable cultivation sites for *Angelica sinensis*, particularly under changing climatic conditions.

Keywords: Climate change; *Angelica sinensis*; Temperature; Precipitation; Yield

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1. Introduction

Angelica sinensis (Oliv.) Diels is an important biennial medicinal herb from the Apiaceae family which has been extensively used as a medicinal plant in TCM for the past two thousand years. The root has proven its value in treatment of anemia, rheumatism, and menstruation related issues, besides its use in dietary supplements and cosmetics. It is commonly grown in the regions of Gansu, Yun-

nan, Sichuan, Shaanxi, and Hubei provinces. But due to over harvesting and poor agricultural practices, quality standards have declined. Bioactive compound content of *Angelica sinensis* is heavily dependent on environmental parameters such as soil pH, temperatures, precipitation, and altitude [1, 2].

In addition to its traditional uses, *Angelica sinensis* has attracted interest due to its antioxidant activity and cardiovascular treatment potential. Nevertheless, extensive farm-

ing faces difficulties like early bolting, which results in root lignification and reduces its medicinal value [3]. Sustainable agriculture, such as intercropping with leguminous plants (like *Vicia faba*), has been explored for increasing land efficiency and reducing chemical usage. Although these approaches increase the efficiency of crop cultivation, the relationship between the environment and plant growth, especially early bolting, is not fully comprehended [4, 5].

Climate change intensifies the difficulties associated with agriculture through changes in the weather patterns that impact plant growth and distribution [6]. *Angelica sinensis* shows remarkable sensitivity to such weather changes, thereby calling for a study on how this plant responds to changes in the environment. Various distribution models, especially MaxEnt, have been used widely to predict potential areas of growth in the presence of climate change for purposes of conservation and agriculture planning. However, current studies mainly focus on distribution, paying less attention to the relationship between climatic variability and yield. Such a relationship is crucial in ensuring continued yield in the presence of climate change [7].

The current paper focuses on the variation of temperatures and rainfall during the *Angelica sinensis* planting season and its effects on the harvest quantity within the region of Northwest China (Cool and Semi-humid Climate Zone). Based on the agricultural and meteorological statistics collected from the years 2005 to 2021, statistical analyses, including trend analysis, Mann-Kendall test, and correlation analysis, are conducted to reveal the effect of climate conditions on yield [8].

The interrelationship between *Angelica sinensis* and the environment has been well studied, with the importance of environmental factors in controlling plant growth, quality, and productivity being shown. Collectively, previous studies indicate that climatic factors, particularly temperature and precipitation, are key drivers of plant performance. As shown by Zhang et al., [9], the genetic and phenotypic diversity within a species is greatly influenced by environmental conditions; the study showed the importance of factors such as temperature and precipitation in influencing the plant's productivity. In addition to the studies done on the importance of the environment in influencing the plant's productivity, other studies have also focused on using species distribution models such as MaxEnt to show the effects of bioclimatic factors on habitat suitability. In this regard, Tan et al. [10] showed that factors such as temperature and precipitation are important predictors of the distribution pattern of *Angelica* species across China,

and Zhang et al. [11] supported this by showing the important role played by various environmental factors such as elevation and slope in affecting habitat suitability. Taken together, these findings suggest that climate change is likely to alter both the distribution and cultivation potential of *Angelica sinensis*.

Apart from the bioclimatic factors, the soil microbial population in the rhizosphere also plays a vital role in the growth of *Angelica sinensis* as well as the content of active ingredients. Yan et al. [12] studied the effects of the soil microbial population's structure, soil physicochemical properties, and enzymatic activities on the growth and content of bioactive ingredients, including ligustilide and ferulic acid. The study showed the complex relationships between the soil microbial population and environmental factors, which provided a more comprehensive understanding of the soil-plant relationship in the cultivation of *Angelica sinensis*. In a similar investigation, Gong et al. [13] used transcriptomics, along with 16S rRNA and ITS sequencing, to elucidate the connection between the effectiveness of *Angelica sinensis* and the composition of the microbial community of the soil. They found specific microbial groups that play a critical role in the biosynthesis of secondary metabolites, which are regulated by specific soil factors, including the content of organic matter and nitrogen. This investigation is relevant to the present study, which focuses on the environmental factors that affect the quality and quantity of *Angelica sinensis*. These studies indicate that plant productivity and quality are governed by integrated ecological processes involving both climate and soil systems.

Temperature is one of the significant factors that affects *Angelica sinensis*'s growth and the biosynthesis of bioactive compounds. A section has been added discussing the biological importance of temperature variations in *Angelica sinensis*. It is explained that temperature fluctuations can affect the plant's metabolic processes, growth rates, and biosynthesis of active compounds such as ferulic acid and ligustilide, which are crucial for its medicinal value. According to Dong et al. [14], low temperatures lead to increased plant growth and metabolic compound production, but agricultural techniques like mulching can affect temperature and moisture levels, which help to promote root growth and reduce water stress in plants [15]. Zhang et al. [16] have found that continuous cultivation of crops causes reduced photosynthesis efficiency and oxidative stress resistance of *Angelica sinensis*. Overall, these findings highlight the multifactorial nature of plant responses to environmental conditions.

The present study focuses on the need to further explore the changes in meteorological factors during the growth

period of *Angelica sinensis* with the recent warming and increased precipitation trends in China and their impacts on the growth and production of *Angelica sinensis*. The study employed 17 years of fixed-point observation data in the semi-humid and rain-fed agricultural area of the Loess Plateau to explore the impacts of climate change on *Angelica sinensis*, which would be beneficial for the adaptation of *Angelica sinensis* to climate change and the scientific development of the *Angelica sinensis* industry.

While previous studies have primarily focused on genetic diversity, habitat suitability modeling, and soil microbial interactions, quantitative analyses linking long-term climatic variability with yield remain limited. In particular, there is a lack of rigorous approaches examining stage-specific responses of *Angelica sinensis* to climatic factors, as well as studies applying path analysis to evaluate direct and indirect effects of multiple meteorological variables.

This research fills in the gaps in the literature by providing the first comprehensive analysis of continuous meteorological data for *Angelica sinensis* over a period of 17 years. It establishes trends in temperature and precipitation, as well as the points of mutation in the climatic series, providing an understanding of the impact of climate change on *Angelica sinensis* over the last two decades. The research improves methodological techniques in several ways. Firstly, the application of trend analysis, mutation test, correlation analysis, and path analysis in one model provides the ability to not only analyze long-term trends in the data but also to carry out stage-specific causal analysis. Secondly, the research quantifies the differential impact of temperature and precipitation at six different growth stages from transplanting to harvest, from transplanting to harvest. The findings have implications for the formulation of strategies for adapting to climate change in the *Angelica sinensis* cultivation.

2. Materials and methods

2.1. Climatic conditions and growth characteristics of *Angelica sinensis* in the study area

The study area is located in the semi-humid zone of the Loess Plateau, with an average annual temperature of 6.6°C. The highest mean monthly temperature occurs in July (16.9°C), while the lowest is observed in January (-5.7°C). The average annual precipitation is 571.2 mm, of which approximately 94% (537.2 mm) occurs during the main growing season of *Angelica sinensis* from April to October. The region also receives an average of 2160.7 hours of sunshine per year.

The growth cycle of *Angelica sinensis* follows distinct phenological stages. Transplanting typically occurs from

early to mid-April, followed by seedling emergence in early to mid-May. The three-leaf-one-bud stage occurs in early to mid-June, and the six-leaf-one-bud stage extends from early to late July. The seven-leaf-one-bud stage coincides with flowering, occurring from late July to early August, while harvest takes place from mid- to late October. Overall, the growth period averages 197 days, ranging from 185 days in 2018 to 219 days in 2021.

2.2. Yield Measurement and Sampling Design

The fresh mass yield of *Angelica sinensis* was determined during the growth period. Data were collected from a 1 m² plot with three repetitions per location per annum. The samples were collected once a year at the end of the growth period (October). The plot size was kept constant throughout the years for comparison purposes. The collection procedure followed standardized protocol. In cases where data were not available, incomplete data sets were disregarded from the analysis.

2.3. Growth Stage Definitions and Durations

The growth stages of *Angelica sinensis* were defined based on the physiological development of the plant, with each stage being marked by specific leaf and bud formations, such as the three-leaf-one-bud and six-leaf-one-bud stages. These definitions align with established milestones from previous research and are considered reliable indicators of the plant's growth cycle. The duration of each growth stage was not standardized across years, as it is influenced by environmental factors, including temperature and precipitation. Therefore, the length of each stage can vary annually. For example, the growth season in 2018 was shorter, lasting 185 days, compared to 2021, which had a growth season of 219 days. Despite these annual variations, the stages were consistently observed based on the plant's physiological markers in each year.

2.4. Data sources

Manual collection and compilation of agriculture-meteorology observation information related to *Angelica sinensis* was done in the Minxian Agriculture Meteorology Observing Station located in the province of Gansu in China for a period of 17 consecutive years from 2005 to 2021. This station lies in the semi-humid and rain-fed agriculture sector of the Loess Plateau and there were no changes in crop types used in experiments, agriculture and crop management during the period of observation [17]. The crops were cultivated using conventional agricultural techniques and no significant variations occurred as well as there was a relative constancy of soil fertility in the

course of the experiment. Developmental and growth observations of the crop were made strictly on the basis of the Manual for Agro-meteorological Observation of *Angelica sinensis* published by the Gansu Provincial Bureau of Quality and Technical Supervision [18]. At the same time meteorological information such as temperature, rainfall, and sunshine duration were provided by the Minxian National Meteorological Observatory at 104.62°E, 35.58°N coordinates. While the primary focus of the study was on seasonal means and totals (e.g., average temperature and total precipitation), extreme events such as heat waves, heavy rainfall episodes, and drought spells were not analyzed separately.

Despite the fact that the present investigation is based on the meteorological information available at one observation point, Minxian is located within close proximity to the central part of the Loess Plateau, which is known for its homogenous climate. The climate data collected in Minxian represent the trends typical of other regions in regard to their climatic features, particularly temperature and rainfall trends in the semi-humid climate zone. Indeed, prior studies have shown that the information collected in Minxian corresponds to the information collected in neighboring regions, suggesting that the collected information is reflective of the entire region.

The study assumes that the management techniques used, such as plant types, sowing rates, irrigation, fertilization, and pest control, have been consistent throughout the duration of the experiment. No changes were recorded regarding agricultural practices or irrigation methods from 2005 to 2021, while the types of *Angelica sinensis* as well as the sowing rate remained consistent. The farming techniques practiced, such as irrigation and fertilization, followed standard procedures for the local area.

2.5. Method of statistical analysis

2.5.1. Tendency rate of meteorological factors

The tendency rate of meteorological factors was analyzed using the following linear regression model [19]:

$$Y_t = a + bt \quad (1)$$

Where Y_t represents the meteorological element variable at time t (e.g., year) (e.g., temperature, precipitation), a is the regression constant, b regression coefficient (slope), representing the rate of change of the meteorological element with respect to time t , and n is the sample size.

The regression coefficient b is the rate of change of the meteorological element with respect to time and can be interpreted as the climate change propensity rate. This rate

is often expressed as:

$$b = \frac{dy(t)}{dt}$$

Where b represents the climate change propensity rate. For practical interpretation, the climate change propensity rate is generally expressed as $10b$, representing the rate of climate change per decade (i.e., $10b$ reflects the change in the meteorological factor over 10 years). This convention allows us to quantify the change over a standard time frame, which is particularly useful for climate change assessments.

2.5.2. Mann-Kendall transition test

Climatic abrupt change refers to a sudden transition between two stable states or persistent trends, characterized by a rapid shift in the statistical properties of the climate over time and space [20]. A popular non-parametric statistical technique for identifying these changes in climate data is the Mann-Kendall test, which is advised by the World Meteorological Organization (WMO) [21]. The trends in temperature, precipitation, and sunlight duration in the study area were examined using the Mann-Kendall test [22].

$$S_k = \sum_{i=1}^k r_i \quad (k = 2, 3, 4, \dots, n) \quad (2)$$

Where r_i represents the rank of the meteorological variable at time i , and n denotes total number of observations (17 years in this study). The standardized test statistic $UF(k)$ is derived as:

$$UF(k) = \frac{S_k - E(S_k)}{\sqrt{\text{var}(S_k)}} \quad (k = 1, 2, 3, \dots, n) \quad (3)$$

where $E(S_k)$ is the expected value of S_k , which is given by:

$$E(S_k) = \frac{n(n+1)}{4} \quad (4)$$

and $\text{var}(S_k)$ is the variance of S_k , calculated as:

$$\text{var}(S_k) = \frac{n(n-1)(2n+5)}{72} \quad (5)$$

The same procedure is repeated in reverse order to calculate $UB(k)$ (upper bound of the statistic). A sequence is said to be trending upward if $UF(k)$ is greater than 0 as well as downward if $UF(k)$ is less than 0. The trend is deemed statistically significant when the values of $UF(k)$ or $UB(k)$ surpass the critical lines. The beginning of an abrupt change is indicated by the time point at which the curves of $UF(k)$ and $UB(k)$ connect within the critical lines [23].

2.5.3. Statistical analysis

The statistical analyses were done in SPSS 19.0 for the correlation analyses. The estimation of the path coefficients was done using the normal equation system approach in path analysis. Before carrying out correlation and path analyses, an evaluation for autocorrelation and dependence of the time series data was done. The autocorrelation tests were done through the use of the Durbin-Watson test accompanied by autocorrelation graphically. There was no evidence of autocorrelation at $p > 0.05$ as per the results from the Durbin-Watson test hence the data can be regarded as being independent.

3. Result and discussion

3.1. Climate change characteristics during the growth period of *Angelica sinensis*

3.1.1. Inter-annual variation trend of temperature

The temperature trend from 2005 to 2021 showed a fluctuating increasing trend during the entire growth period of *Angelica sinensis* (Fig. 1a), with a climate tendency rate of $0.37^{\circ}\text{C decade}^{-1}$ ($P < 0.05$). The minimum temperature was observed in 2011 at 12.3°C , while the maximum temperature was observed in 2016 at 14.3°C . After 2016, the temperature trend showed a statistically significant decreasing trend in the temperature during the entire growth period of *Angelica sinensis*, with a climate tendency rate of $-2.89^{\circ}\text{C decade}^{-1}$ ($P < 0.05$).

From 2005 to 2012, temperature during the whole growing season of *Angelica sinensis* mostly showed negative anomalies while temperatures showed mainly positive anomalies from 2013 to 2019.

3.1.2. Mann-Kendall Transition Test

In order to find out the abrupt changes in climate variables, the Mann-Kendall mutation test was performed for both temperature and precipitation datasets. This was accomplished by calculating the test statistic from $UF(k)$ and $UB(k)$ values through the described method. Treatment of Ties: The treatment of ties within the Mann-Kendall test entailed the midrank approach where the ranks are taken as a midpoint of the tied values. Serial Correlation: The test assumes that there should not be any serial correlation among the time series data. In order to confirm this, an autocorrelation test was run with the help of the Durbin-Watson test, showing that there was no serial correlation ($P > 0.05$). Otherwise, pre-whitening had to be done before carrying out the Mann-Kendall test. An abrupt change in the trend of temperatures was noticed using the Mann-Kendall test around 2013 (Fig. 1b). Exact Year and Sample Size: For the time series analysis of the temperature data, a span of years

from 2005 to 2021 was considered, providing a sample size of 17 years. The *Angelica sinensis* is a cold resistant plant, so the temperatures post-2016 could prove to be beneficial for the crop. Rationale and Selection of Breakpoints: The drop in temperature post-2016 from its warming trend justified making it the breakpoint for the time series. For the trend analysis, the Mann-Kendall breakpoint test was used, identifying the significant UF/UB values to find mutations in 2013 and 2016. During the aforementioned period of 17 years, the temperature of all the growth stages of *Angelica sinensis* generally showed an increasing trend, except for the emergence-to-three-leaves growth stage (Fig. 2(b)), as presented in Fig. 2. The strongest temperature increase occurred in the transplanting-to-emergence growth stage (Fig. 2(a)), with a climate tendency rate of $0.90^{\circ}\text{C decade}^{-1}$, followed by the six-leaves-to-seven-leaves growth stage (Fig. 2(d)) with a $0.62^{\circ}\text{C decade}^{-1}$ climate tendency rate, and then the seven-leaves-to-harvest growth stage (Figure 2(e)) with a $0.43^{\circ}\text{C decade}^{-1}$ climate tendency rate. On the other hand, the three-leaves-to-six-leaves growth stage (Fig. 2(c)) had the lowest temperature increase, has a $0.22^{\circ}\text{C decade}^{-1}$ climate tendency rate. It should be observed that, at the 0.05 probability level, the temperature trends of the previously described *Angelica sinensis* growth phases were not statistically significant. On the contrary, the emergence-to-three-leaves growth stage presented a cooling trend with a climate tendency rate of $-0.18^{\circ}\text{C decade}^{-1}$. The temperature variation trends of the growth stages of *Angelica sinensis* are unique. In 2018, the transplanting-to-emergence growth stage presented a significant temperature reduction trend ($P < 0.05$). In 2014, the emergence-to-three-leaves growth stage began to present a markedly significant temperature reduction trend, exceeding the 0.01 significance probability level. In addition, the three-leaves-to-six-leaves growth stage presented a significant temperature reduction trend ($P < 0.05$).

3.1.3. Inter-annual variation trend of precipitation

Variation of the precipitation during the entire growth period of *Angelica sinensis* from 2005 to 2021 is presented in Fig. 3(a). Precipitation trends over the last 17 years have been fluctuating and increasing, with a climate tendency rate of $41.6 \text{ mm decade}^{-1}$ ($P < 0.05$). Precipitation varied from 474.2 mm to 748.9 mm during the growth period, with an average of 550.2 mm . The maximum value of precipitation occurred in 2020, and the minimum value occurred in 2011. Precipitation showed a fluctuating decreasing trend during the period of 2005-2011, and it showed a fluctuating increasing trend during the period of 2012-2021. The result of the Mann-Kendall test, as presented in Fig. 3(b), shows the existence of a significant abrupt change in the trend of

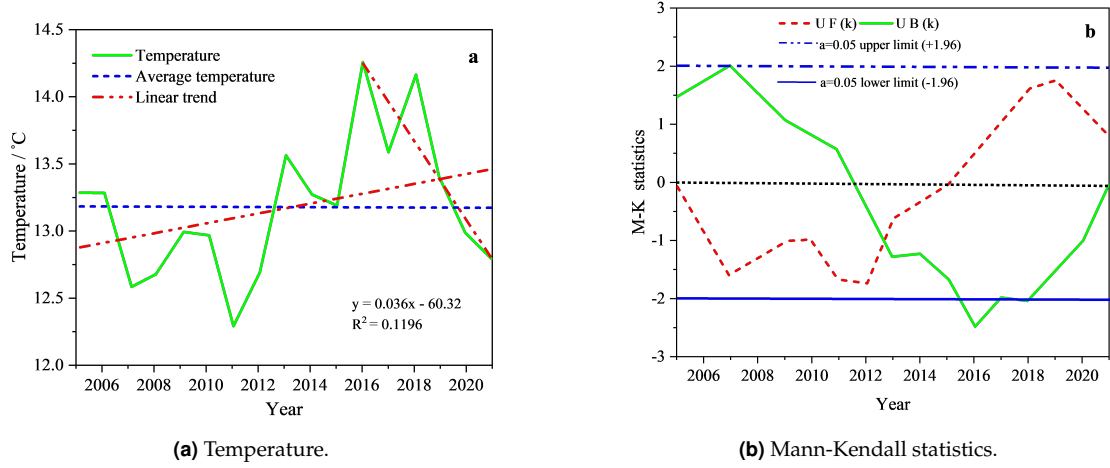


Fig. 1. Variation trends of temperature and Mann-Kendall statistics during the growing period of *Angelica sinensis*.

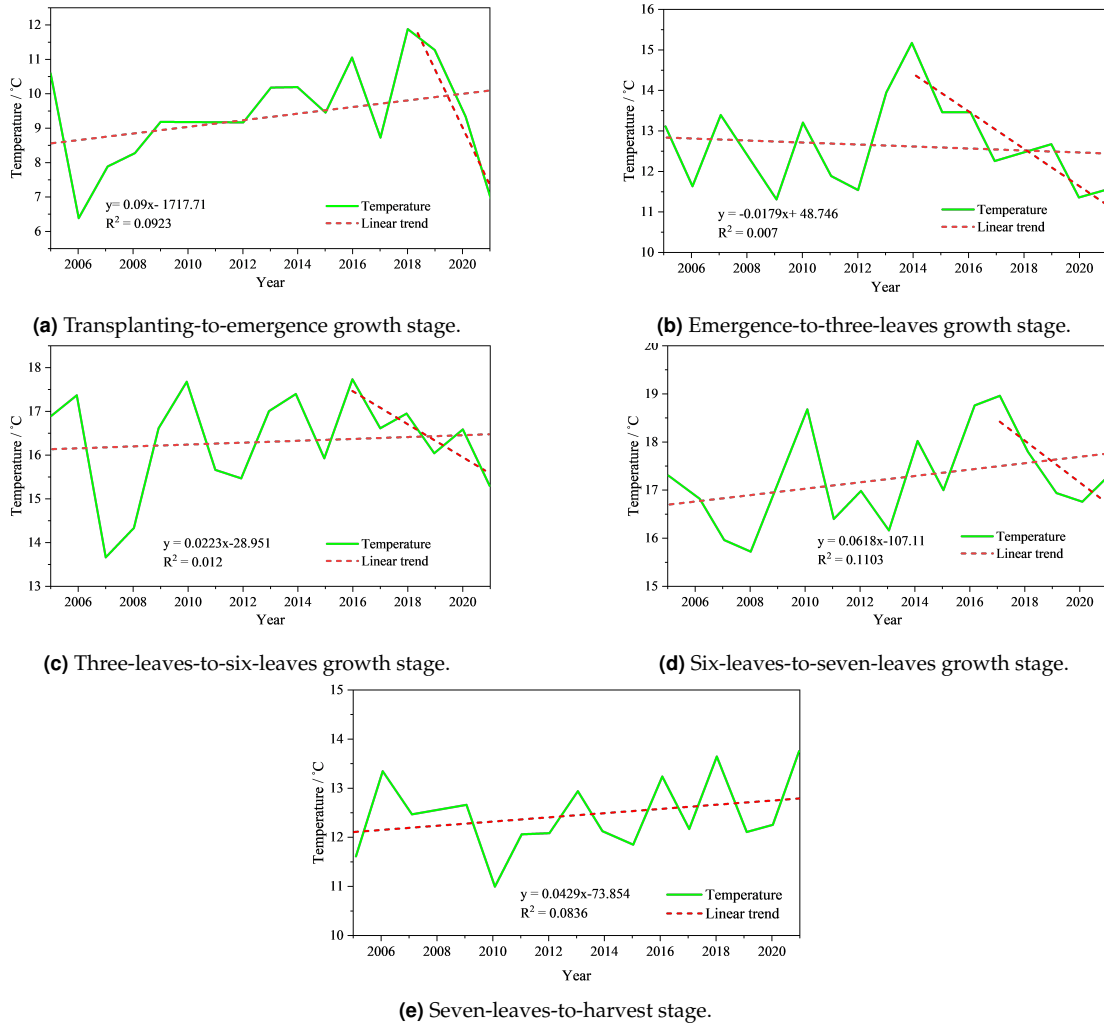


Fig. 2. Temperature variation trend of *Angelica sinensis* at different growth stages.

precipitation from low to high during the growth period of *Angelica sinensis* in 2018, and hence 2018 is the year of

abrupt change.

The trend of precipitation in all the growth stages of *Angelica sinensis* showed a slight increasing trend, except in the emergence-to-three-leaves stage (Fig. 4). The increase in the transplanting-to-emergence stage (Fig. 4(a)) was the most remarkable, indicating a climate tendency rate of 20.4 mm decade⁻¹ ($P < 0.05$), followed by the seven-leaves-to-harvest stage (Fig. 4(e)), which showed a tendency rate of 14.2 mm decade⁻¹ ($P < 0.05$). The three-leaves-to-six-leaves stage (Fig. 4(c)) and six-leaves-to-seven-leaves (Fig. 4(d)) stage showed similar increasing trends, indicating a climate tendency rate of 7.3 mm decade⁻¹ and 5.6 mm decade⁻¹ ($P < 0.05$), respectively. By contrast, the emergence-to-three-leaves stage (Fig. 4(b)) showed a fluctuating decreasing trend, indicating a climate tendency rate of -6.6 mm decade⁻¹.

3.2. Climate change's effects on *Angelica sinensis* growth and development

3.2.1. The effects of climatic change on *Angelica sinensis* growth days and yield

On the basis of the *Angelica sinensis* growth season over the period of 2005 to 2021, significant interannual variations have been identified with a noticeable long-term trend. The total length of the *Angelica sinensis* growth season varies from a minimum of 185 days in 2018 to a maximum of 219 days in 2021 (Fig. 5(a)). Over the course of the last 17 years, the *Angelica sinensis* growth season exhibits an increasing trend with a climate tendency rate of 1.0 days decade⁻¹. However, the increasing trend in the *Angelica sinensis* growth season over the last 17 years is not uniform. It increases from 2005 to 2011, decreases from 2011 to 2018, and then reverses its trend with a consistent increasing pattern over the last four years.

On the other hand, the annual yield of *Angelica sinensis* exhibits significant variations with an increasing trend over the last 17 years (Fig. 5(b)). The average annual yield of *Angelica sinensis* over the last 17 years was found to be 289.4 g/m² with a significant climate tendency rate of 44.9 g/m² decade⁻¹. The maximum annual yield of *Angelica sinensis* was observed in 2020 at 638.4 g/m², while the lowest value was observed in 2010 at 145.5 g/m².

3.2.2. The impact of temperature and precipitation changes on the yield of *Angelica sinensis*

Further analysis was conducted to quantify the exact relationship between yield and the two major climatic factors, temperature and precipitation.

Temperature response:

The relationship between the mean temperature during the growth period and the yield of *Angelica sinensis* is

non-linear. As indicated in Fig. 6(a), yield increases with temperature up to a threshold, after which it declines. The quadratic regression equation describing this relationship is:

$$y = -107.95x^2 + 2891.4x - 19039 (P > 0.05) \quad (6)$$

However, this model is not statistically significant, indicating that temperature alone cannot reliably explain yield variability. Therefore, the estimated optimal temperature of 13.4°C should be interpreted as a biological reference value rather than a statistically robust optimum, assuming other factors remain constant.

Response to Precipitation: Unlike temperature, the relationship between yield and total precipitation during the growth period is strong and statistically significant. Fig. 6(b) shows a strong positive linear relationship between yield and total precipitation from 2005 to 2020. Table 1 shows the results of the path analysis on the relationship between *Angelica sinensis* yield and meteorological factors during six different growth stages, including correlation coefficients and direct path coefficients for temperature and precipitation. The correlation coefficient, which was calculated, was 0.581, which is statistically significant ($P < 0.05$). This is also consistent with the results obtained from the path analysis, which was discussed earlier, showing that precipitation was the major climatic parameter influencing yield.

Path analysis was conducted to examine the relationship between the yield of *Angelica sinensis* and the climatic factors during the growth period. By using path analysis, the direct path coefficients of the individual climatic factors could be determined. The analysis also revealed the major climatic factors and their contributions to yield. Based on the direct path coefficients presented in Table 1, the descending order of influence of the climatic factors is determined quantitatively as follows: precipitation during Entire growth period (0.562) > precipitation during Seven-leaves-to-harvest stage (0.521) > precipitation during Three-leaves-to-six-leaves growth stage (0.550) > precipitation during Emergence-to-three-leaves growth stage (0.369) > temperature during Transplanting-to-emergence growth stage (0.282) > precipitation during Transplanting-to-emergence growth stage (-0.281). This ranking is derived directly from the magnitude of the direct path coefficients, ensuring consistency between the narrative and the values reported in Table 1.

From the study, the major climatic factors affecting the yield of *Angelica sinensis* were found to be precipitation during Entire Growth Period, precipitation during Seven-leaves-to-harvest stage, precipitation during Three-leaves-to-six-leaves growth stage, temperature dur-

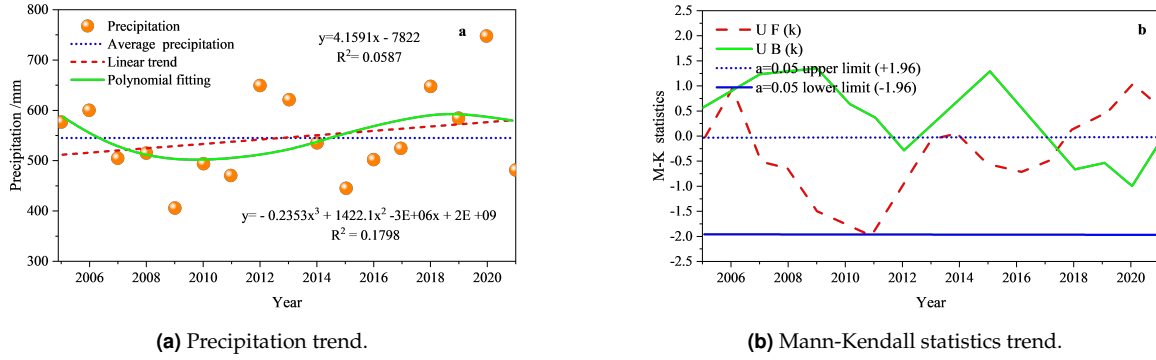


Fig. 3. Variation trend of precipitation and Mann-Kendall statistics during the *Angelica sinensis* growing stage.

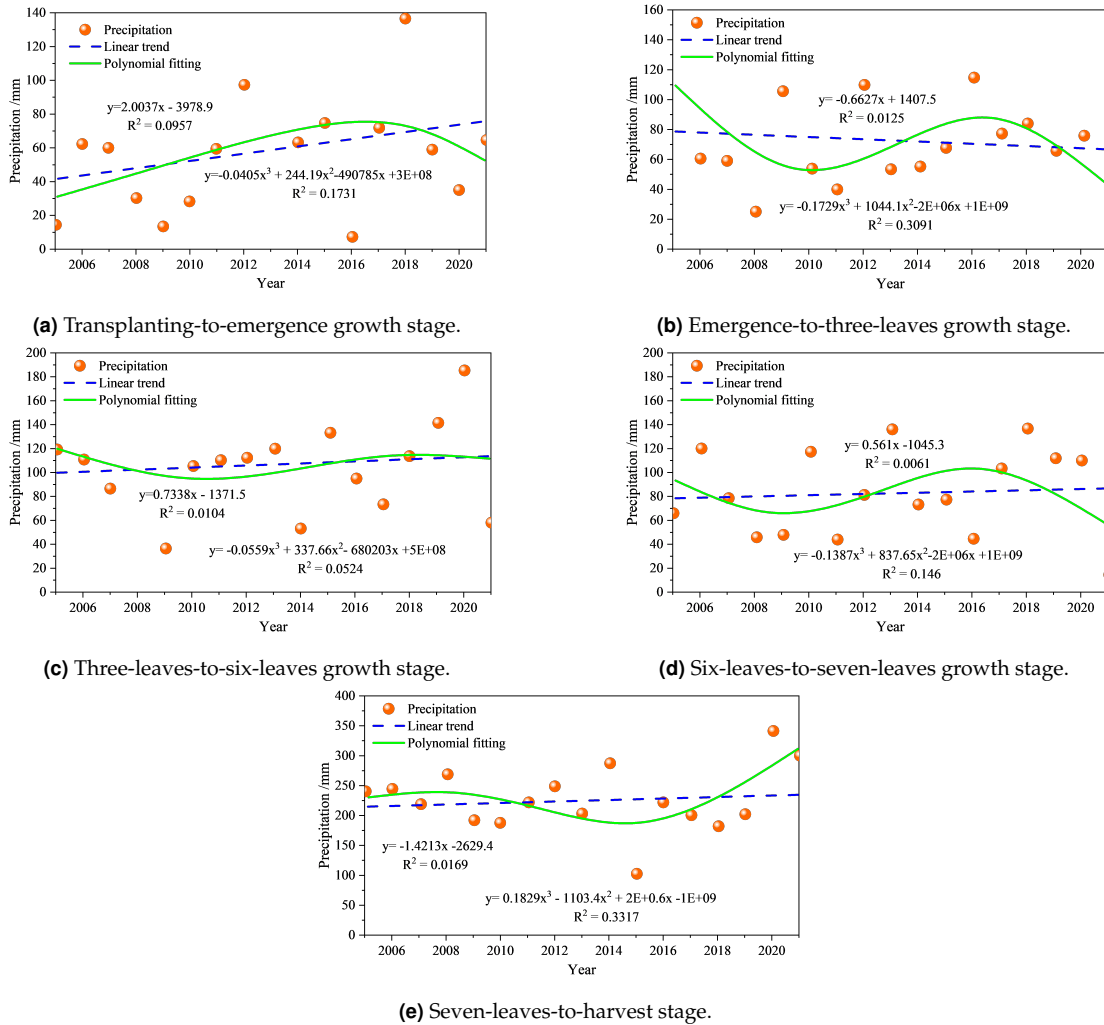


Fig. 4. Precipitation variation trend of *Angelica sinensis* at different growth stages.

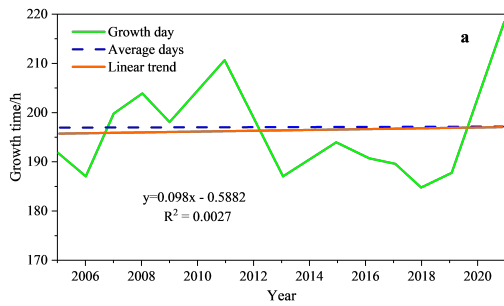
ing Transplanting-to-emergence growth stage, and precipitation during Transplanting-to-emergence growth stage. It was also found that the meteorological factors showed differential influence on the yield in different growth stages.

The analysis indicates that the climatic factor with the strongest influence on yield is precipitation, with the highest correlation coefficient recorded during entire growth stage (0.581). The second strongest correlation coefficient was recorded during Three-leaves-to-six-leaves growth

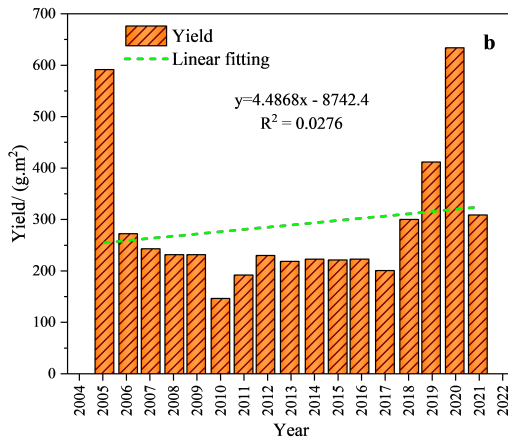
Table 1. Correlation coefficients and direct path coefficients between *Angelica sinensis* yield and meteorological factors during different growth stages.

Growth Stage	Factor	Correlation Coefficient	Direct Path Coefficient
Transplanting-to-emergence growth stage	Temperature	0.239	0.282
	Precipitation	-0.228	-0.281
Emergence-to-three-leaves growth stage	Temperature	-0.216	-0.201
	Precipitation	0.366	0.369
Three-leaves-to-six-leaves growth stage	Temperature	0.050	0.122
	Precipitation	0.502*	0.550
Six-leaves-to-seven-leaves growth stage	Temperature	-0.156	-0.122
	Precipitation	0.098	0.098
Seven-leaves-to-harvest stage	Temperature	-0.059	0.120
	Precipitation	0.046	0.521
Entire Growth Period	Temperature	0.050	-0.157
	Precipitation	0.581*	0.562

Note: * indicates significance at $P < 0.05$.



(a) Growing days trend.

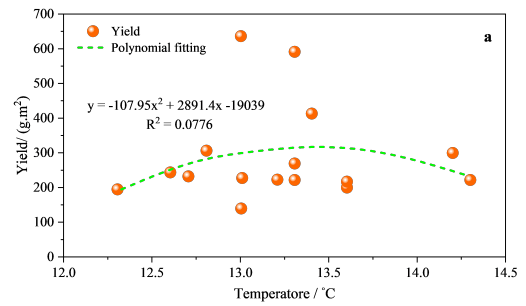


(b) Annual yield trend.

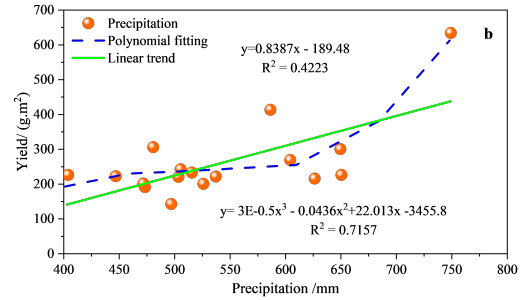
Fig. 5. Growing days and annual yield trends of *Angelica sinensis*.

stage (0.502). The results were statistically significant during the entire growth stage and Three-leaves-to-six-leaves growth stage.

The results from the direct path coefficients also showed a strong effect of precipitation on *Angelica sinensis* yield during Three-leaves-to-six-leaves growth stage (direct path coefficient = 0.550) and Seven-leaves-to-harvest stage (0.521).



(a) Temperature- yield correlation.



(b) Precipitation- yield correlation.

Fig. 6. Correlation between temperature, precipitation, and yield of *Angelica sinensis* in the growing stages.

A nuanced result is obtained during Seven-leaves-to-harvest stage, with the correlation coefficient being almost negligible (0.046). The direct path coefficient, however, shows a strong positive effect of precipitation on *Angelica sinensis* yield during seven-leaf-to-harvest growth stage (0.521).

Temperature affects the plant in a comparatively weaker and more variable manner at different growth stages. The most significant direct positive effect of temperature occurs at Transplanting-to-emergence growth stage (0.282), which highlights the need for a warm climate for successful ger-

mination and emergence. At the same time, there is a weak negative direct effect at Emergence-to-three-leaves growth stage (-0.201), which indicates that a cool climate may be more beneficial to the plant at this stage. At the stages of rapid growth, i.e., Three-leaves-to-six-leaves growth stage and Six-leaves-to-seven-leaves growth stage, the effects of temperature on the plant growth are minimal, with path coefficients being ± 0.122 , which again highlights the role of precipitation as a limiting factor at these stages. The analysis reveals that *Angelica sinensis* requires different meteorological conditions at different growth stages, with the mid-vegetative stage requiring the most water, the late reproductive stage revealing a hidden need for direct moisture, and the transplanting stage being the only stage at which temperature has a significant positive effect on the outcome.

3.3. Discussion

Climate change poses significant challenges to the cultivation of medicinal plants, especially *Angelica sinensis*, as they show significant sensitivity to changes in temperature and precipitation. *Angelica sinensis*, as a cool-season crop with specific thermal and moisture requirements, the quantitative relationships between climate factors and yields are critical in formulating strategies for adapting to climate change in the Northwestern Cool and Semi-Humid Region of China. By combining long-term trend analysis with path analysis, the study aims to investigate how variations in temperature and precipitation affect *Angelica sinensis* yields. The methodological framework of this research involves using multiple statistical tools to comprehensively evaluate the relationship between climate factors and yields. The linear trend estimation method was used to evaluate the climate tendency rate of temperature and precipitation over the 17 years from 2005 to 2021. The World Meteorological Organization's non-parametric Mann-Kendall mutation test was employed to assess sudden changes in the trend of climatic parameters. The association between yields and meteorological conditions was assessed using correlation analysis. To assess the actual impacts of particular climatic conditions at various growth stages, the path analysis was employed.

In an effort to avoid the effects of any confounding variables in this study, it is necessary to note that some of the management variables such as choice of cultivar, planting density, fertilizer use, irrigation and pest management were not controlled. These variables remained relatively constant throughout the 17 years' observation period. Cultivar and planting density were kept constant and, moreover, farming practices like irrigation and fertilizer application

were conducted following standard procedures followed in the area, reducing the effect of these variables on the crop yield. However, it cannot be ignored that the management practices might affect the correlation between climate and yield. It would thus be worthwhile if future studies included an evaluation of these variables as well.

The analyses carried out in this study have been focused on seasonal mean and totals (such as mean temperature and precipitation totals). However, no attention has been paid to extremes, such as heatwaves, heavy precipitation spells, and dry spells. While the main goal of this study was to identify climate change trends and their effect on crop yield, it should be noted that climate extremes can also greatly affect the yield of *Angelica sinensis*. Future research will need to focus specifically on the effects of these phenomena on crops.

The results offer a number of interesting implications regarding the impacts of climate change on the cultivation of *Angelica sinensis*. The temperature during the growing season fluctuated upward with a $0.37^{\circ}\text{C} \cdot \text{decade}^{-1}$ climate tendency rate and a significant anomaly in 2013. Meanwhile, a statistically significant decreasing trend in temperature at a rate of $2.89^{\circ}\text{C} \cdot \text{decade}^{-1}$ ($P < 0.05$) has existed since 2016, which may be beneficial to this cold-resistant plant species. The temperature threshold for optimal plant growth was found to be 13.4°C based on the quadratic regression model, although it failed to reach statistical significance ($P > 0.05$), indicating that temperature may not be a dominant factor influencing plant growth. In contrast, the impacts of precipitation were more significant and consistent throughout the study period. The increasing trend in growing season precipitation at a rate of $41.6 \text{ mm} \cdot \text{decade}^{-1}$ and a significant low-high shift in 2018 indicate that this plant species may be more adapted to a drier climate. The relationship between plant growth and precipitation was found to be strong and statistically significant ($0.581, P < 0.05$), although the stage-specific importance of precipitation on plant growth remains to be understood. The path analysis results revealed that the Three-leaves-to-six-leaves growth stage had the highest direct path coefficient (0.550), while Seven-leaves-to-harvest stage had a substantial direct path coefficient (0.521), although the simple correlation coefficient between plant growth and precipitation at this stage was very low (0.046). This may indicate that the impacts of late-season precipitation on plant growth may be masked by other factors and that path analysis can be a more powerful tool in revealing latent relationships between factors and plant growth. The impacts of temperature on plant growth were found to be weaker and more variable throughout the study period,

although a significant positive direct path coefficient (0.282) existed during Transplanting-to-emergence growth stage, indicating that this stage may be temperature-sensitive and that warm conditions may be necessary for successful plant establishment, while cool conditions may be more beneficial to plant growth during Emergence-to-three-leaves growth stage (-0.201).

In addition to making the discussion section more robust, the current research provides references that help prove the relationship between climate factors and the output of *Angelica sinensis*. First, temperature has always been known as one of the main climatic factors affecting the growth and development of plants. In their work, Dong et al. [14] found out that temperature variation plays an important role in biosynthesis in *A. sinensis* and causes more significant changes during low temperatures, which supports the findings of the current research. Moreover, precipitation was noted as a crucial factor determining agricultural yields. According to studies conducted by Tan et al. [10] and Yan et al. [12], bioclimatic conditions such as precipitation determine the distribution of *A. sinensis* in China. It is also noteworthy that according to the results obtained in this research, the precipitation that occurs in certain phases of the growth process, including Three-leaves-to-six-leaves growth stage, is of great significance when it comes to getting higher yield. These results are further confirmed by Gong et al. [13] as they note that the environment plays an important role in producing bioactive compounds in the plant.

Nevertheless, several limitations of the current analysis need to be noted. Firstly, this study is exploratory in nature and uses only one location (Minxian Agricultural Meteorological Observation Station). Therefore, the results obtained here might not be applicable for the other locations within the Northwestern Cool and Semi-Humid Region. Secondly, despite those 17 years is a considerable timespan in terms of analysis of trends, still some other climatic cycles might have affected the crops during the studied period, but were not taken into account due to limited data availability. Additionally, the effects of agrarian confounders, such as soil moisture, irrigation, fertilization, and planting density, were not explicitly controlled or considered in this study, which could have influenced the observed yield. No evaluation of autocorrelation was performed on the data collected over 17 years; thus, assumptions about the non-significance of autocorrelation between the data are not backed by evidence. However, at least the latter issue can be addressed in future research, as our goal was to analyze general trends and interplay of climatic factors with the yield of *Angelica sinensis*.

The multicollinearity of climatic predictors was not evaluated in the current analysis. Since our focus was on the trends related to the impact of climatic factors on the yield of the studied crop, the assumption of low collinearity was made. However, it must be admitted that further evaluation of multicollinearity might affect the results and influence path coefficients in case of incorporation of more predictors and utilization of such techniques as Variance Inflation Factor (VIF).

Lastly, such variables as soil physicochemical characteristics, microbial communities' composition, and other agricultural practices that can affect the growth and development of plants have not been analyzed. Nonetheless, several valuable recommendations for cultivating this plant can be derived based on obtained results. For instance, the results indicate that it is necessary to provide *Angelica sinensis* with enough water in the periods from 3 to 6 leaves vegetative growth and reproductive stages of development despite the presence or absence of drought symptoms. The optimum temperature of the environment should be close to 13.4°C , meaning that current cultivation sites will need to be reconsidered in accordance with changing climatic conditions. Lastly, an increasing trend of precipitation since 2012 and a pronounced shift in its level in 2018 can explain climatically favorable conditions for the cultivation of *Angelica sinensis* in recent years.

4. Conclusions

The aim of this paper is to analyze the variability of meteorological parameters during the growth period of *Angelica sinensis* in the Northwest Semi-humid and Cool Region of China and their impact on crop yield. This research employs a combination approach that uses longterm trend analysis along with path analysis to determine the major meteorological influencing factors and provide guidelines to adapt agricultural practice based on climate change.

Long-term meteorological data for 2005 to 2021 was collected from the Agricultural Meteorological Station of Minxian in Gansu Province, together with meteorological data recorded in parallel at the Minxian National Meteorological Observatory. Statistical methods used include linear trend analysis, Mann-Kendall mutation test, correlation analysis, path analysis, and quadratic regression.

- Throughout the entire growth period, temperature showed a fluctuating upward trend from 2005 to 2021, with a climate tendency rate of $0.37^{\circ}\text{C decade}^{-1}$, and a temperature mutation was observed in 2013. After 2016, temperature showed a statistically significant decrease of $-2.89^{\circ}\text{C decade}^{-1}$.

- Despite the fact that the quadratic regression model was not statistically significant, 13.4°C was found to be the ideal temperature threshold for optimizing yield, although it did not achieve statistical significance ($P > 0.05$), indicating that the temperature may not be a dominant factor influencing plant growth.
- Throughout the growing season, precipitation showed a fluctuating upward trend with a climate tendency rate of 41.6 mm decade⁻¹, and a low-to-high mutation of precipitation was observed in 2018.
- The relationship between yield as well as total precipitation in the growing season was strong and statistically significant, with a correlation coefficient of 0.581.
- Path analysis results showed that precipitation during Three-leaves-to-sixleaves growth stage had the highest direct path coefficient of 0.550, indicating that this was the critical water requirement period.
- Precipitation during Seven-leaves-to-harvest stage also showed a substantial direct path coefficient of 0.521, although the simple correlation coefficient was negligible at 0.046, indicating a latent effect.
- Temperature was observed to have a notable positive direct effect during Transplanting-to-emergence growth stage, with a path coefficient of 0.282, although a negative direct effect of -0.201 was observed during Emergence-to-three-leaves growth stage.
- The duration of the growing season was observed to increase by 1.0 day per decade, ranging from 185 days in 2018 to 219 days in 2021.
- Annual yield showed a statistically significant increase of 44.9 g/m² decade⁻¹, with an average of 289.4 g/m², a maximum of 638.4 g/m² recorded in 2020, and a minimum of 145.5 g/m² recorded in 2010.

The scope of the study needs to be expanded to include multiple observation points, along with incorporating the effects of soil physiochemical characteristics and rhizosphere microorganisms. The models developed need to predict future habitat suitability under varying climate change scenarios. Moreover, irrigation methods that comply with the requirements of the study should be explored for validating the findings from path analysis and improving water management techniques. More work is required regarding the topic of early bolting and its association with climate variables, along with agricultural practices like mulching and intercropping.

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