Impact of Climate Change on the First Plucking Date and Quality of Huiming Tea in Jingning

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Abstract Based on the observation data of daily average temperature, daily rainfall and sunshine duration from 2005 to 2024 from the national basic meteorological station and regional meteorological station in Jingning, as well as the data of tea yield and growth period, the first picking date and quality of Huiming tea in Jingning were evaluated by the analysis of physical and chemical indicators and climate quality index of Huiming tea. The results show that in the past two decades, the first picking date of Huiming tea showed a significant advancing trend. Climate warming led to an increase in ≥0 ℃ active accumulated temperature, thus advancing the first picking date. The climate quality index of tea was "very excellent" in most years, and the physical and chemical indicators were at the special grade. Tea yield was significantly correlated with multiple meteorological factors, especially closely related to sunshine duration in early February and ≥5 ℃ active accumulated temperature from February to April.

Key words Huiming tea; Climate change; Tea quality

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Jingning She Autonomous County in Zhejiang Province is located in the mid-subtropical climate zone. It has distinct four seasons, abundant heat, a warm and humid climate, plentiful rainfall, and a long frost-free period. Its ecological environment quality has ranked among the top five in China for many years. Both the air and water quality meet the national first-class standards. It is warm in winter and cool in summer, so it is known as the "Shangri - La of East China", and it is very suitable for the cultivation of tea trees. Huiming tea produced in Jingning is a local specialty variety as well as a product with a geographical indication of China. By the end of 2023, the total planting area of tea in the county was 5 073.33 hm^2, with the total output of 3 809 t and output value of 674 million yuan. In the county, there were over 40 000 people engaged in tea industry.

Global climate change has affected the growth and development of various types of plants to varying degrees. Research on tea growth, especially during the germination period and the critical growth period, has received increasing attention[2-7]. To implement Xi Jinping's thought on ecological civilization, it is necessary to firmly establish and practice the concept that Lucid waters and lush mountains are invaluable assets, further explore the green ecological resources of Huiming tea in Jingning, and promote the high-quality development of tea industry. In this paper, based on the meteorological data of the national basic meteorological station in Jingning from 2014 to 2024, the weighted index summation method[1] was used to construct a tea climate quality index model to evaluate the climate quality of Huiming tea in Jingning[8-12]. At the same time, the correlation between meteorological factors and tea yield was analyzed to identify the key growth periods affecting the formation of the quality of Huiming tea in Jingning. The aim is to avoid or mitigate the adverse effects of various meteorological disasters on the quality of Huiming tea during these critical growth periods, and provide meteorological data support for Jingning to expand the scale of Huiming tea industry, promote the improvement of industrial efficiency, and achieve the development of Huiming tea industry in Jingning.

1 Data sources and research methods

1.1 Data sources The meteorological data used in this study are from the national meteorological observation station in Jingning She Autonomous County (station number 58648, 119.6558° E, 27.9919° N, altitude 245.6 m) from 2005 to 2024, including the data of temperature, precipitation, relative humidity, sunshine duration, *etc.* The data of daily average temperature, daily precipitation, *etc.* from 2014 to 2024 at Huiming Temple meteorological observation station (station number K9242, 119.6503° E, 27.9489° N, altitude 630.0 m) in Jingning.

The study area of Huiming tea is the production area of Huiming Temple tea in Hexi Sub-district (the core production area of Huiming tea in Jingning She Autonomous County). The tea variety is Huiming Wuniuzao tea. The straight-line distance from Huiming Temple meteorological observation station in Jingning is 400 m. The data of the first picking date and growth period of Huiming tea are sourced from the Jingning Bureau of Agriculture and Rural Affairs and Jingning Tea Association. The fresh tea used for the analysis of tea quality from 2024 to 2025 is all from Jingning Jinjiang Huiming Tea Industry Co., Ltd. The inspection

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institution for the quality of Huiming tea is the Hangzhou Tea Research Institute of the All China Federation of Supply and Marketing Cooperatives.

1.2 Research methods Trend analysis: linear regression and Mann – Kendall test were used to identify the changing trends of climate and the first picking date.

Correlation analysis: Pearson/Spearman correlation analysis was used to analyze the relationship between the first picking date and key climatic factors.

Assessment of climate quality: based on the *Certification Specifications of Tea Climate Quality in Zhejiang*, as well as meteorological conditions and biochemical indicators and sensory score of tea, the climate quality of tea was graded (very excellent, excellent, good, and average).

2 Results and analysis

2.1 Growth period of Huiming Tea in Jingning in the past two decades (2006 – 2025) As shown in Table 1, the growth period of Huiming tea in Jingning in the past two decades can be divided into 13 stages. The buds of Huiming tea usually began to differentiate on February 10. The single bud with the best quality was picked since around March 5, and the picking period could last until one bud and four leaves (around April 15). The entire picking period lasted for about 40 – 45 d.

Table 1 Division of the growth period of Huiming tea in Jingning

Growth period of Huiming tea	Time
Bud differentiation	February 10 – February 15
Germination	February 20 – March 1
Unfolding period of fish leaves	March 5 – March 10
One bud and one leaf	March 15 – March 20
One bud and two leaves	March 25 – March 30
One bud and three leaves	March 30 – April 5
One bud and four leaves	April 10 – April 15
Formation of flower buds	Early June – middle July
Budding period	Late July – early August
Flowering period	Middle August – middle September
Fruit ripening period	Late October – early November
Seed picking period	Middle November – late November
Year-end break period	Late November – early February

2.2 First packing date of Huiming tea Wuniuzao in Jingning and ≥0 ℃ active accumulated temperature from January 1 to the first packing date in the past ten years (2016 – 2025) In the past decade (2016 – 2025), the first picking date for Huiming tea Wuniuzao in Jingning was the earliest on February 10, 2020, followed by February 12, 2019, and the latest date was March 1, 2016 (Table 2). The longest difference between the earliest and the latest picking dates was 21 d. From January 1 to the first packing date, ≥0 ℃ active accumulated temperature ranged from 291.6 to 415.9 ℃ · d in the past ten years. The increase in the accumulated temperature was significantly correlated with the advancing of the first picking date.

Table 2 First picking date of Huiming Tea Wuniuzao in Jingning and ≥0 ℃ active accumulated temperature from January 1 to the first picking date during 2016 – 2025

Year	First picking date	≥0 ℃ active accumulated temperature from January 1 to the first picking date//℃ · d
2016	March 1	364.6
2017	February 20	415.9
2018	February 26	320.6
2019	February 12	291.6
2020	February 10	302.6
2021	February 13	331.8
2022	February 28	317.2
2023	February 19	357.1
2024	February 19	376.6
2025	February 28	350.6

2.3 Meteorological conditions such as temperature (accumulated temperature), precipitation and sunshine in the production area of tea in Jingning from 2005 to 2024

2.3.1 Temperature. Over the past 20 years, the annual average temperature in the production area of tea in Jingning generally showed a significant upward trend (Fig. 1). The climate tendency rate during this period was approximately 0.58 ℃/10 a. That is, the annual average temperature in the production area of tea in Jingning rose by approximately 0.58 ℃ every ten years over the past two decades. The warming rate far exceeded the global average, highlighting the severity of regional climate change. Especially in the past five years, it has steadily entered the "19 ℃ era". This change was the core climatic driving factor that led to the advancing of the first picking date and the adjustment of the growth period of Huiming tea.

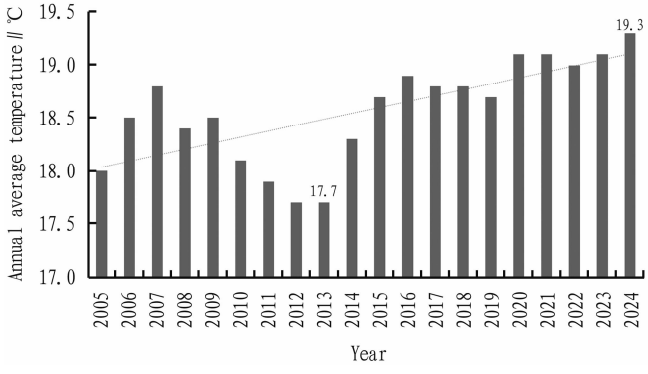

Fig. 1 Annual average temperature in the production area of tea in Jingning during 2005 – 2024

Temperature is the core climatic factor influencing the growth and development of tea trees. The above-mentioned changes have had a profound impact on the production of Huiming tea in Jingning. ① Advanced phenological period: due to continuous warming and increased accumulated temperature, the overwintering dormancy period of tea trees has been shortened, and the sprouting period and first picking date in spring have been significantly advanced. This is in complete agreement with the phenomenon that the first picking date was advanced from early March to mid-to-late February.

② Changes in quality formation: the increase in temperature during winter and early spring is conducive to the synthesis of nitrogen-containing compounds such as amino acids in tea trees, which may have a positive effect on the enhancement of the freshness (taste) of tea. However, rapid temperature rise in spring will shorten the time for the accumulation of the best internal substances in tea, may lead to an imbalance in the ratio of tea polyphenols to amino acids, and poses a potential risk to the quality. ③ Changes in disaster risks: the intensification of warm winters, although reducing the probability of extreme low-temperature frost damage, will lead to insufficient dormancy of tea trees, and make them more vulnerable to the harm of "cold spell in later spring" and late frost in spring. Because the tea buds that sprout prematurely have weaker resistance to low temperatures, and once they encounter cold air, the losses will be even more severe. ④ Adjustment of growth cycle: the increase in the annual average temperature may extend the effective growth period of tea trees throughout the year, posing new requirements for the yield and quality management of summer and autumn tea.

2.3.2 Accumulated temperature. ≥0 ℃ active accumulated temperature is a fundamental indicator for measuring the annual total heat conditions and agricultural production potential of a region. It represents the sum of all temperatures ≥0 ℃ in a year, and reflects the overall level of light and heat resources in a region. The data of accumulated temperature in the production area of tea in Jingning over the past 20 years reveal that the annual total heat resources in this region were very abundant, and showed a stable high-level fluctuation with a increasing trend. Over the past 20 years, the average of ≥0 ℃ active accumulated temperature in the production area of tea in Jingning reached as high as 6 592.8 ℃ · d. This extremely high value confirms the climatic characteristics of "abundant heat and long frost-free period" in the region, and it provides extremely favorable heat conditions for the growth of tea trees. Tea trees have a long annual growth cycle and a long effective photosynthesis period, which are important guarantees for high-yield and high-quality tea. Compared with the ≥10 ℃ accumulated temperature fluctuating obviously, the change of ≥0 ℃ accumulated temperature was relatively stable, but the upward trend was still clearly visible. The accumulated temperature generally showed an upward trend on the whole. Especially from 2020 to 2023, the accumulated temperature remained above 6 800 ℃ · d for four consecutive years, reaching a peak in 2021 (6 836.3 ℃ · d). This indicates that the total annual heat resources in the production area of tea in Jingning have recently reached a new and higher equilibrium state.

The analysis of the data in the production area of tea in Jingning over the past 20 years (2005 – 2024) reveals that the heat resources in this region were abundant, fluctuated greatly among these years, and increased significantly in recent years. Over the past 20 years, the average of ≥10 ℃ active accumulated temperature in the production area of tea in Jingning was up to 5 426.5 ℃ · d. This value is far higher than the accumulated temperature required for the growth of tea trees. It demonstrates that the region has extremely abundant heat resources, and is highly suitable for tea cultivation and production. This is also an important natural foundation for the outstanding quality of Huiming tea. However, the annual fluctuations of the accumulated temperature was very significant. As shown in Fig. 3, the maximum 6 041.8 ℃ · d appeared in 2024, while the minimum 4 698.5 ℃ · d can be found in 2010, so the range was as high as 1 343.3 ℃ · d. This huge fluctuation indicates that although there was abundant heat throughout the year, there are significant differences in the effective heat energy that tea trees can obtain in different years, which directly led to annual variations in the first picking date, growth process and annual yield of tea. From the perspective of time series, the changes of accumulated temperature can roughly be divided into two stages. During the fluctuation period (2005 – 2017), the accumulated temperature fluctuated widely between 4 698.5 and 5 792.1 ℃ · d, and there were several distinct low values in some years (such as 2010 and 2015) and high values in several years (such as 2018). In the high-value period (2018 – 2024), the accumulated temperature was at a higher level since 2018. Except for 2020, the accumulated temperature was above 5 450 ℃ · d in all other years. It is particularly worth noting that the accumulated temperature in 2024 (6 041.8 ℃ · d) set the highest record in the past 20 years, indicating that regional climate warming was leading to an accelerated increase in heat resources.

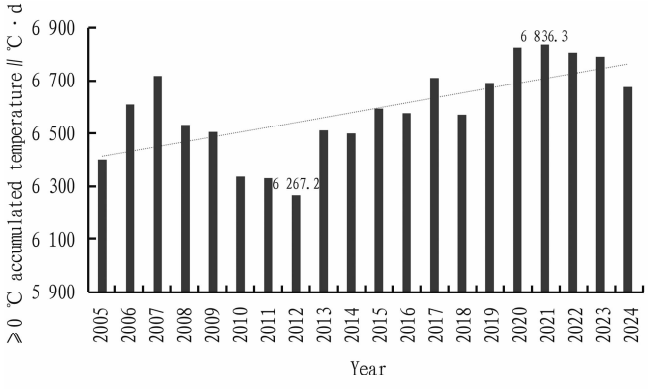

Fig. 2 ≥0 ℃ active accumulated temperature in the production area of tea in Jingning from 2005 to 2024

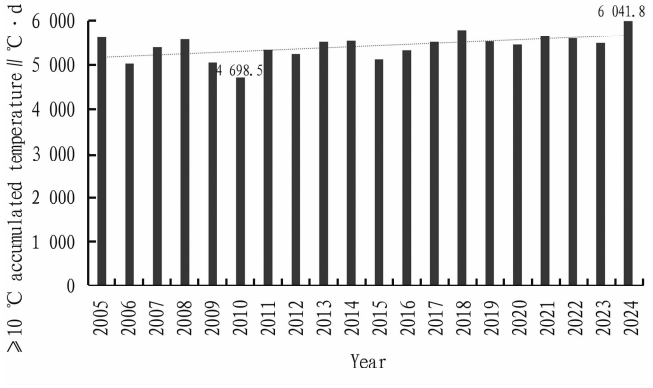

Fig. 3 ≥10 ℃ active accumulated temperature in the production area of tea in Jingning during 2005 – 2024

2.3.3 Precipitation. Precipitation is another key climatic factor affecting the growth and development of tea trees, and is directly related to soil moisture, humidity in tea gardens, water content in tea, and the efficiency of photosynthesis. From Fig. 4, it is seen

that although the region has abundant rainfall throughout the year, the annual fluctuations were extremely intense, and the phenomenon of uneven drought and flood was significant, which poses an important challenge to the stable production of tea. Over the past 20 years, the annual average precipitation reached 1 668.3 mm, fully meeting the biological characteristic of tea trees' preference for dampness, which is an important natural endowment for this region to become a high-quality production area of tea. However, the annual variation in precipitation was remarkable. The highest value occurred in 2010 (up to 2 190.1 mm), while the lowest value was in 2011 (only 1 232.5 mm), so the range was as high as 957.6 mm (Fig.4). The former was almost 1.8 times that of the latter. This huge instability is one of the main meteorological reasons affecting the annual fluctuations in tea production and quality. From the perspective of time series, precipitation did not show a distinct linear trend like temperature, but its phased fluctuations and extreme events were more prominent. During the rainy periods such as 2009 – 2010 and 2014 – 2016, the annual precipitation remained above 1 800 mm, and even exceeded 2 100 mm in 2010. In the periods with less rainfall, such as 2007 – 2008, 2011, 2017 – 2018 and 2023, the precipitation was all below 1 500 mm. It was less than 1 320 mm in 2011 and 2023, and the two years were meteorological drought years. There was "a sudden transition from flood to drought". For instance, there was a direct switch from the rainy year 2010 (2 190.1 mm) to the extremely dry year 2011 (1 232.5 mm), and such a drastic interannual change posed a huge stress on both the soil of tea gardens and tea trees themselves.

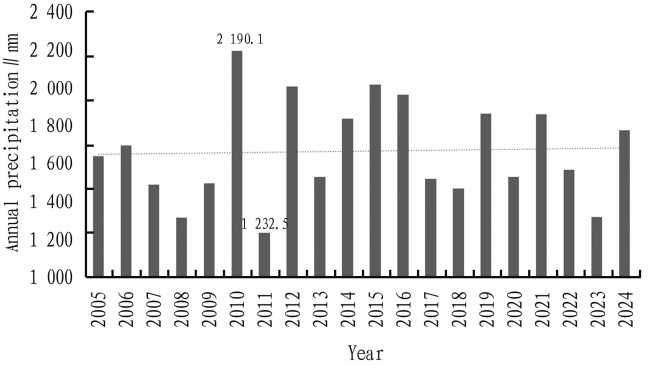

Fig.4 Annual precipitation in the production area of tea in Jingning from 2005 to 2024

2.3.4 Sunshine duration. Sunshine is the energy source for tea trees to carry out photosynthesis and accumulate organic matter, and directly affects the yield of tea and carbon and nitrogen metabolism (namely the balance of tea polyphenols and amino acids), so it is an indispensable factor for the unique quality of tea. In the production area of tea in Jingning over the past 20 years, sunshine resources were generally abundant, but there were significant fluctuations and phased characteristics from year to year. These changes interwove with temperature and precipitation factors, jointly shaping the final quality and output of Huiming tea.

Over the past 20 years, the annual average sunshine duration in the production area of tea in Jingning was 1 575.7 h. This value indicates that the region has relatively abundant light resources, which can meet the photosynthetic requirements for the normal growth and development of tea trees. However, similar to precipitation, the annual fluctuations in sunshine duration were extremely intense. It peaked 1 780.3 h in 2013, but decreased to the lowest value in 2015 (1 305.4 h), and the range was as high as 474.9 h. This means that the former was 40% higher than that of the latter. This huge instability was an important root cause of annual differences in tea quality.

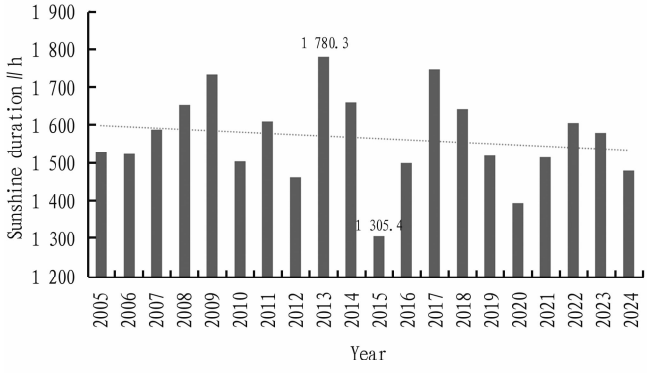

Fig.5 Total sunshine duration in the production area of tea in Jingning from 2005 to 2024

2.4 Evaluation of climate quality of Huiming Tea in Jingning Based on the meteorological data from the national basic meteorological station in Jingning from 2016 to 2025, the climate quality index of Huiming tea in Jingning during the critical period of quality formation was calculated (Table 3). It can be seen that the climate quality was "very excellent" in 8 years, and the number accounted for 80% of the total years; it was "excellent" in 20% years (2 years).

Table 3 Climate quality index and grade of Huiming tea in Jingning from 2016 to 2025

Year	Climate quality index	Grade
2016	2.0	Excellent
2017	2.0	Excellent
2018	2.8	Very excellent
2019	2.8	Very excellent
2020	2.6	Very excellent
2021	2.6	Very excellent
2022	2.8	Very excellent
2023	2.8	Very excellent
2024	2.8	Very excellent
2025	2.8	Very excellent

2.5 Physical and chemical indicators of Huiming tea in Jingning The sensory organ of samples submitted for inspection during 2024 – 2025 met the sensory requirements stipulated in the *Geographical Indication Product Huiming Tea* (DB3311/T 241 – 2023). In the physical and chemical indicators of samples submitted for inspection from 2024 to 2025, the average of moisture content was 4.37 g/100 g, and that of powder content was 0.17%; total ash content averaged 4.3 g/100 g, and the content of water

extract averaged 45.1%. The physical and chemical indicators in all three years were at the special grade. According to the climate quality evaluation index of Huiming tea in Jingning from 2021 to 2023, the climate quality was very excellent in all three years. Based on the analysis of meteorological conditions of Huiming tea in the early stage and the evaluation results of the climate quality of Huiming tea in Jingning, the climate quality of Huiming tea in Jingning was "very excellent".

Table 4 Physical and chemical indicators of Huiming tea in Jingning from 2024 to 2025

Indicator	Grade		2024	2025
	Special grade and grade 1	Grades 2 and 3		
Moisture//g/100 g	≤6.5	≤7.0	4.38	4.11
Powder (mass fraction)//%	≤1.0	≤1.0	0.20	0.20
Total ash//(g/100 g) (calculated as dry matter)	≤6.5	≤7.0	5.10	3.50
Water extract (mass fraction)//%	≥38.0	≥34.0	46.40	46.30

2.6 Relationship between the output of Huiming tea in Jingning and meteorological factors The correlation between tea yield and meteorological elements in Jingning County from 2014 to 2023 was analyzed. The results of F test reveal that sunshine duration in the 4th ten-day period (during February 1 – 10), ≥5 ℃ active accumulated temperature from February to April, precipitation in the 4th ten-day period (from February 1 to 10), precipitation in the 10th ten-day period (from April 1 to 10), annual rainfall, ≥5 ℃ active accumulated temperature from January to April, average temperature in the 11th ten-day period (from April 11 to April 20), and rainfall from September to November all passed the test of $a=0.01$, and their correlation coefficients were −0.739, 0.708, 0.682, −0.662, −0.624, 0.623, 0.622, and −0.619, respectively, indicating that there was a close relationship between these meteorological factors and tea yield.

3 Conclusions and discussion

3.1 Conclusions

(1) The climate quality index of Huiming tea in Jingning during the critical period of quality formation from 2014 to 2024 ranged from 2 to 2.8. It was above 2.5 in 9 years, and the climate quality was "very excellent", while it was excellent in two years.

(2) From 2021 to 2023, moisture content averaged 4.37 g/100 g, and that of powder content was 0.17%; the average of total ash content was 4.3 g/100 g, and the content of water extract averaged 45.1%. The physical and chemical indicators in the three years were at the special grade.

(3) The yield of Huiming tea was significantly correlated with sunshine duration in the 4th ten-day period, ≥5 ℃ active accumulated temperature from February to April, precipitation in the 4th ten-day period, precipitation in the 10th ten-day period (from April 1 to 10), annual rainfall, ≥5 ℃ active accumulated temperature from January to April, average temperature in the 11th ten-day period, and rainfall from September to November.

3.2 Discussion

(1) The mountainous area in Jingning features has characteristics of relatively low temperatures, high humidity, frequent clouds and fog, and a large temperature difference between day and night, which promotes the formation of excellent tea quality. Relatively low temperatures are conducive to the accumulation of high concentrations of soluble nitrogen compounds and the generation of amino acids and aroma substances. High humidity, frequent clouds and fog not only inhibits the synthesis of cellulose and keeps leaf buds tender, but also promotes the increase of scattered radiation, enhances the diffusion effect, and facilitates the formation of aromatic substances. A large temperature difference between day and night helps accumulate photosynthetic products and increase the content of proteins, amino acids and vitamins. The soil in these mountainous areas is mainly composed of mountain yellow-brown soil and brown soil. The thickness of soil layer and fertility level are relatively high. At the same time, they are far from towns and roads, and have fresh air. The atmosphere and water quality have not been polluted, which is conducive to the improvement of tea quality. These mountainous areas are most suitable for establishing large-scale high-quality tea bases, which can fully demonstrate the unique conditions of tea tree quality and less environmental pollution, and promote the development of famous and high-quality green tea industry.

(2) In terms of the correlation between meteorological factors and tea yield, the content of functional components in Huiming tea in Jingning is the highest within one or two weeks around late February. This is the critical period for the formation of the quality of Huiming tea in Jingning. The quality of Huiming tea in Jingning is related to the meteorological conditions during bud differentiation, bud growth and maturation period, especially the meteorological conditions during the maturation period of tea as well as before and after picking. Special attention should be paid to monitoring the temperature, precipitation and sunshine during this periods. The warming of winter (warm winter) and the increase in accumulated temperature during the growing season are conducive to the survival of overwintering insect eggs and pathogens, which may lead to an earlier outbreak period, prolonged damage period and aggravated damage of tea garden pests and diseases. It is necessary to minimize the adverse effects of various meteorological disasters on the critical growth periods of tea.

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ses and rotten potatoes caused by excessive precipitation. From the sowing stage to the emergence stage and from the emergence stage to the branching stage of potatoes, because of the relatively low water demand, the natural precipitation in Shangdu County can basically meet their growth and development needs, and the average of precipitation suitability coefficient is all above 0.5. The average of precipitation suitability coefficient during the branching-inflorescence period is 0.44, indicating insufficient precipitation. The average of precipitation suitability coefficient from the inflorescence to flowering period and from flowering to maturity period is only 0.45 and 0.38, respectively, indicating that the precipitation in Shangdu County during these growth stages is insufficient and uneven. Natural precipitation can not meet the normal water requirement of potatoes, and water deficiency has become the key factor causing fluctuations in potato yield[3].

Based on the above analysis, it can be known that the climate conditions of light, heat and water in Shangdu County are relatively suitable for potato cultivation. To further promote the development of potato industry, it is necessary to pay attention to the adverse effects of meteorological disasters such as low temperatures during the seedling stage and drought during the tuber growth period of potatoes. Shangdu County has less precipitation and large evaporation. Drought, one of the common disastrous weather phenomena, occurs frequently. Potatoes are mainly grown in dry land. Less precipitation has a significant impact on potatoes. Therefore, it is necessary to conduct the forecasting and warning of meteorological disasters such as frost damage and drought during the growth period of potatoes, strengthen meteorological service guidance during the key growth period of potatoes, cultivate excellent varieties with strong stress resistance, sow seeds in a timely manner, and irrigate in a timely and reasonable manner during the occurrence of drought. When a disaster occurs, timely preventive and remedial measures should be taken to minimize losses as much as possible.

3 Conclusion

Shangdu County has suitable climatic conditions for potato cultivation. Based on the local agricultural climate resources, it is necessary to constantly explore meteorological service products for agriculture, establish special service plans, improve the meteorological disaster prevention system, increase the research and promotion of meteorological science and technology, actively produce green and pollution-free potatoes, and promote the healthy development of potato industry.

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