Response of Radial Growth of Mongolian Pine to Climate Factors in Mu Us Sandy Land, Inner Mongolia

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Abstract. The Mu Us sandy land is located on the northwestern edge of the East Asian monsoon region in China, and its environment is fragile and sensitive to climate change. To explore the response of the radial growth of Mongolian pine (*Pinus sylvestris* var. *mongolica*), the main afforestation tree species in this area, to climate change, a traditional method of tree-ring climatology was adopted to analyze the correlation of radial growth to climatic factors in the region from 1959 to 2019 based on annual ring widths of Mongolian pine. The results showed that water and heat conditions in May of the current year were the main climatic factors restricting the growth of this tree species in the Mu Us sandy land, mainly manifested as a negative correlation with the average temperature and maximum temperature in May of the current year, while a positive correlation with precipitation in this month. In addition, the average temperature and minimum temperature in March of the current year are also restricted to tree growth. Mongolian pine is one of the excellent tree species suitable for desertification control and afforestation in the Mu Us sandy land. Under the background of the changing climate, becoming warmer and drier, the effect of drought stress on the radial growth of Mongolian pine will become more and more prominent. If the temperature continues to increase in the future, the radial growth and carbon sequestration of Mongolian pine in Mu Us sandy land will be severely affected.

Keywords: Tree-ring width, Climate change, Drought stress, Climate response.

1. Introduction

Land desertification in arid and semi-arid areas has gradually evolved into a major ecological and environmental problem confronting the world today, which is a serious threat to human survival and sustainable development [1]. Drought stress caused by global warming is the biggest driver of tree growth decline and death in arid and semi-arid areas, which inevitably has a significant impact on regional and global forest productivity and carbon fixation [2]. Mu Us sandy land is one of the four major sandy lands in China, mainly located in the south of Ordos City in the Inner Mongolia Autonomous Region, the north of Yulin City in Shaanxi Province, and the northeast of Yanchi County in Ningxia Hui Autonomous Region, with a total area of 42,200 km2, of which about 2/3 are distributed in Ordos City in Inner Mongolia [3]. The ecological environment of Mu Us sandy land is still fragile and it is one of the most serious areas of desertification in the north of China.

Historically, the Mu Us Sandy Land had a warm and humid climate and vast pastures. Since then, due to the comprehensive impact of human activities, overgrazing, climate warming, and other factors, the pasture has suffered severe damage, resulting in the degradation and death of the pasture and subsequently soil erosion and dust storms [4]. Since the founding of the People's Republic of China, the ecological environment of Mu Us sandy Land has attracted extensive attention from all walks of life. Since 1959, the country has taken a series of environmental control measures, such as vigorously building windbreak forest belts, diverting water for sluicing sand, diverting flood for warping land, etc., which have effectively controlled the desertification of Mu Us sandy land [5, 6].

Mongolian pine (*Pinus sylvestris* var. *mongolica*), which is naturally distributed mainly in Hulunbuir sand and the northern forest region of the Greater Khingan Mountains, has the advantages of strong adaptability, cold resistance, drought resistance, and rapid growth [7, 8]. Therefore, the species has been considered one of the main silvicultural tree species in the arid and semi-arid areas in the north of our country, and it has an important position in the construction of "three-north" shelter forest artificial forest [7]. In recent years, tree rings have been widely used to understand the relationship between tree growth and environmental change and reconstruct paleoclimate [9-11], which mainly depends on their characteristics such as accurate dating, high resolution, wide sample distribution, and long-time series.

Mongolian pine has become one of the commonly used tree species in tree-ring climatology because of the obvious boundary between tree rings [12-14]. Although abundant results have been achieved in previous tree-ring climatology studies of Mongolian pine in the Greater Khingan Mountains of Inner Mongolia, the objects of these studies are mostly natural Mongolian pine forests [9, 12, 15], and only a few studies involved sandy land plantations of Mongolian pine and the research sites were mainly concentrated in Hulunbuir [16]. However, there is still no report on tree growth-climate change response based on Mongolian pine plantations in the Mu Us sandy land, which seriously hinders people's understanding of the adaptability of Mongolian pine in sandy land under different climate conditions in the introduced areas. Especially under the background of climate warming in recent years, it is urgent to supplement the research in this area.

Therefore, it is of great significance to investigate the response of radial growth of Mongolian pine to climate change in Mu Us sandy land, Inner Mongolia, and to assess the adaptation degree of introduction and cultivation of Mongolian pine to climate warming and drying in arid and semi-arid areas of northern China. Therefore, this study took Mongolian pine plantations in Mu Us sandy land as the main research object and discussed the response of Mongolian pine ring width chronology to climate change according to the traditional tree-ring climatology method. The purpose of this paper is to reveal the dynamic changes of the Mongolian pine plantation community in Mu Us sandy land under the background of global warming. This not only provides a certain scientific basis for the continued development of tree planting and sand fixation models in this area in the future but also provides a reference basis for the scientific management of Mongolian pine plantations.

2. Study area description

The Mu Us sandy land in Inner Mongolia is mainly distributed in Etuoke Banner, Etuoke Front Banner, part of Ejin Horo Banner, and Uxin Banner in Ordos City, with the geographical coordinates between latitude 37°37'-39°35'N and longitude 107°18'-110°12'E. The climate is characterized by a semi-arid continental climate zone in the northern temperate zone, with an arid climate, less precipitation, and greater evaporation. Taking the multi-year climate data of Ejin Horo Banner Weather Station as an example, the annual average temperature here is 6.8℃ with the coldest in January (-10.8℃) and the hottest in July (22.1℃). The average annual precipitation is 356.1 mm, which is mainly concentrated in July and August, accounting for more than 52% of the annual precipitation.

3. Materials and methods

3.1. Sample collection

From August to October 2020, a temporary survey plot was set up in Ejin Horo Banner on the northeast edge of Mu Us sandy land in Ordos City, Inner Mongolia Autonomous Region to carry out field investigation. The geographical coordinates of the sample points were 39°19 '8.44 "N, 109°48' 6.05" E, and the altitude was 1390 m (Figure 1). The zonal vegetation in this area is semi-arid grassland. *Artemisia ordosica*, *Salix matsudana* and *Salix psammophila* are the main natural vegetation in the plot and surrounding areas. According to the traditional method of tree-ring

climatology [19], a sample plot was set to collect the tree-ring cores of Mongolian pine. To reduce the damage of drilling and sampling cores to trees, we collect one core on an individual tree at a time, and healthy and older trees were selected as far as possible. A complete ring sample core was drilled at the position of diameter at breast height (DBH) with a growth cone. At the same time, DBH and growth status were recorded in detail as well. A total of 65 ring sample cores were drilled.



Figure 1. Sample sites and meteorological stations in the study area

3.2. Establishment of tree-ring chronology

The sampled core was brought back to the laboratory, and the sample core was pasted on the special wooden groove with white latex. After 24 hours, the sample core was polished step by step with 320 and 600 mesh sandpaper until the annual ring boundary was visible under the microscope. Subsequently, LINTAB^{Tm} 6.0 (accuracy: 0.01 mm) was used to measure the ring width. The COFECHA program [17] was used to test the dating and measurement results of the tree ring sequence of Mongolian pine. The cores with short tree age, poor correlation with the main sequence, and difficulty in dating were excluded, and the retained cores were used to establish tree ring chronology. Finally, 59 cores were successfully cross-dated. The ARSTAN program [18] was used to establish the chronology. Two-thirds of the age was used as a step spline function to remove the genetic factors of trees and the growth trend caused by interference competition (referred to as detrending), and the detrending sequence was synthesized by the double averaging method. In this paper, standard chronologies with higher statistical eigenvalues, better chronology quality, and only more low-frequency changes were selected for tree-ring climatology analysis (Figure 2).

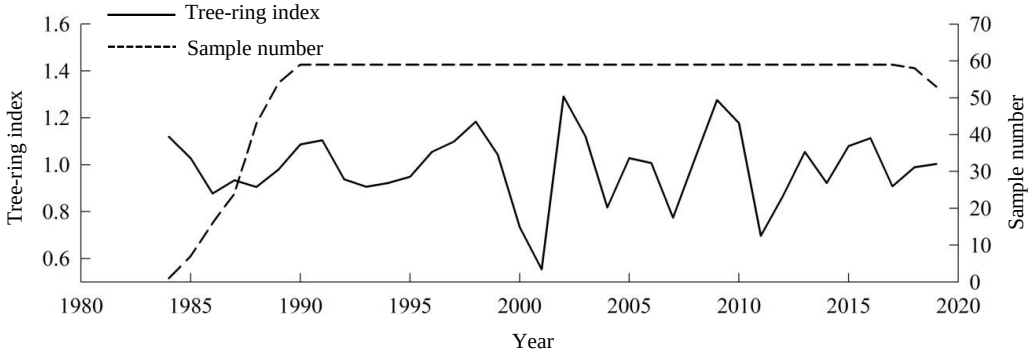


Figure 2. Tree-ring width chronology of Mongolian pine in the Mu Us sandy land

3.3. Statistical analysis of climatic data and data

The meteorological data were obtained from the meteorological station of Ejin Horo Banner, which was closest to the sampling point (Figure 3, geographical location: 39°34′N, 109°44′E, H: 1329.3m), and the recorded period was 1959-2019. The meteorological elements are monthly mean temperature (T_m), monthly total precipitation (P_m), monthly mean maximum temperature (T_{max}), and monthly mean minimum temperature (T_{min}). In the past 61 years, the average temperature and precipitation showed a relatively obvious increasing trend, and the climatic trend rates of the two were 0.34 °C·10 a^{-1} and 4.95 mm·10 a^{-1}, respectively (Figure 4). In this study, climate indicators for 17 months (last May to September) were selected for correlation analysis. Correlation analysis was performed by the program DENDROCLIM 2002 [19]. In addition, the NCEP reanalysis data were used to map the atmospheric precipitable water in the extreme years of tree ring width chronology.

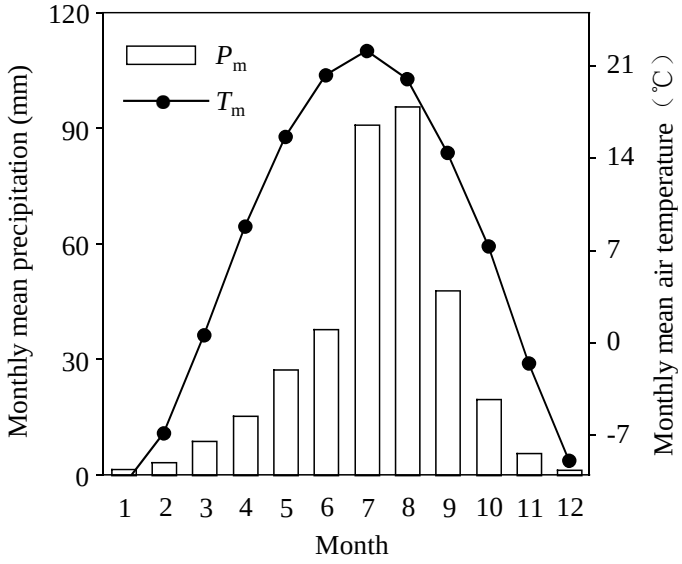


Figure 3. Monthly change of air temperature and precipitation in the study area

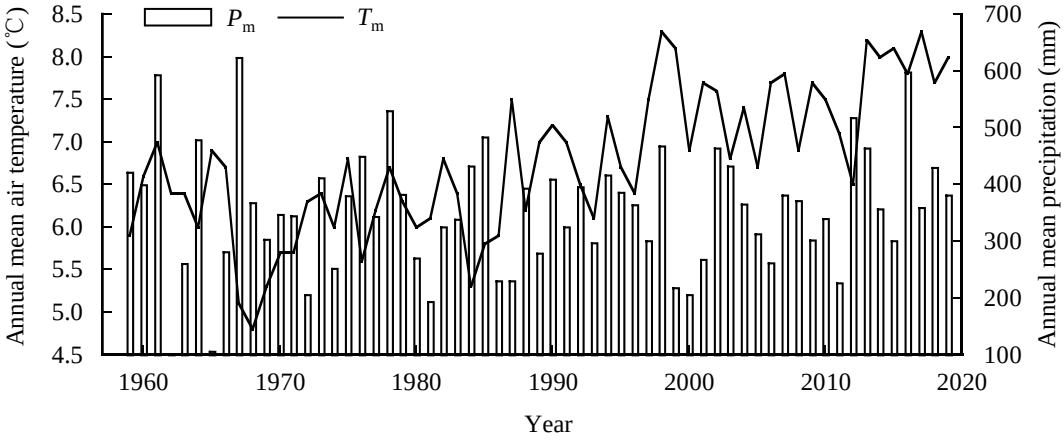


Figure 4. Annual mean air temperature and precipitation in the study area from 1959 to 2019

4. Results

4.1. Statistical characteristics of tree-ring chronology

The statistical parameters of standard chronology and different chronology of Mongolian pine in Mu Us sandy land, Inner Mongolia are shown in Table 1. The time span of the tree-ring chronology is 36 years (1984-2019), while the common interval length of the effective chronology is 31 years

(1987-2017). Table 1 shows that the average sensitivity, standard deviation, inter-tree correlation coefficient, signal-to-noise ratio, and variance explanation of the first principal component of the standard chronology are higher than those of the difference chronology. The sample population representativeness of the two chronologies was 0.776 and 0.697, respectively. Although neither of them exceeded the acceptable critical threshold of sample population representativeness (EPS) of 0.85, they still had certain representativeness. In conclusion, both the standard chronology and the difference chronology are sensitive to climate change, and the standard chronology is better than the difference chronology in most statistical characteristics, indicating that the standard chronology is more sensitive to climate change than the difference chronology, and is more suitable for tree-ring climatology research.

Table 1. Statistics of tree-ring width chronology and common interval analysis

Statistic characteristics	Standard chronology	Residual chronology
Common interval	1984-2019	1984-2019
Mean	0.9884	0.9961
Mean sensitivity	0.1613	0.1225
Standard deviation	0.1546	0.1209
First-order autocorrelation	0.0701	0.0730
Inter-tree correlation	0.302	0.224
Signal-to-noise ratio	3.461	2.304
Expressed population signal	0.776	0.697
Variation in first eigenvector (%)	40.67	33.39

4.2. Relationship between tree-ring chronology and climatic factors

Figure 5 showed that the radial growth of Mongolian pine was significantly negatively correlated with the average and maximum temperature in May ($P < 0.05$), positively correlated with the average and minimum temperature in March ($P < 0.05$), and positively correlated with the precipitation in July and May of the previous year ($P < 0.05$). In addition, the atmospheric precipitable water in May of the same year in Mu Us Sandy land was plotted by using the high- and low-value years of the tree ring width index of Mongolian pine. The results showed that there was more precipitable water near the study area in the year with a high chronology value, while the year with a low chronology value corresponds to less precipitable water, which further confirms the conclusion obtained from correlation and response function analysis (Figure 6). In conclusion, the water and heat conditions in May of that year were the main climatic factors affecting the radial growth of Mongolian pine trees in Mu Us sandy land, Inner Mongolia.

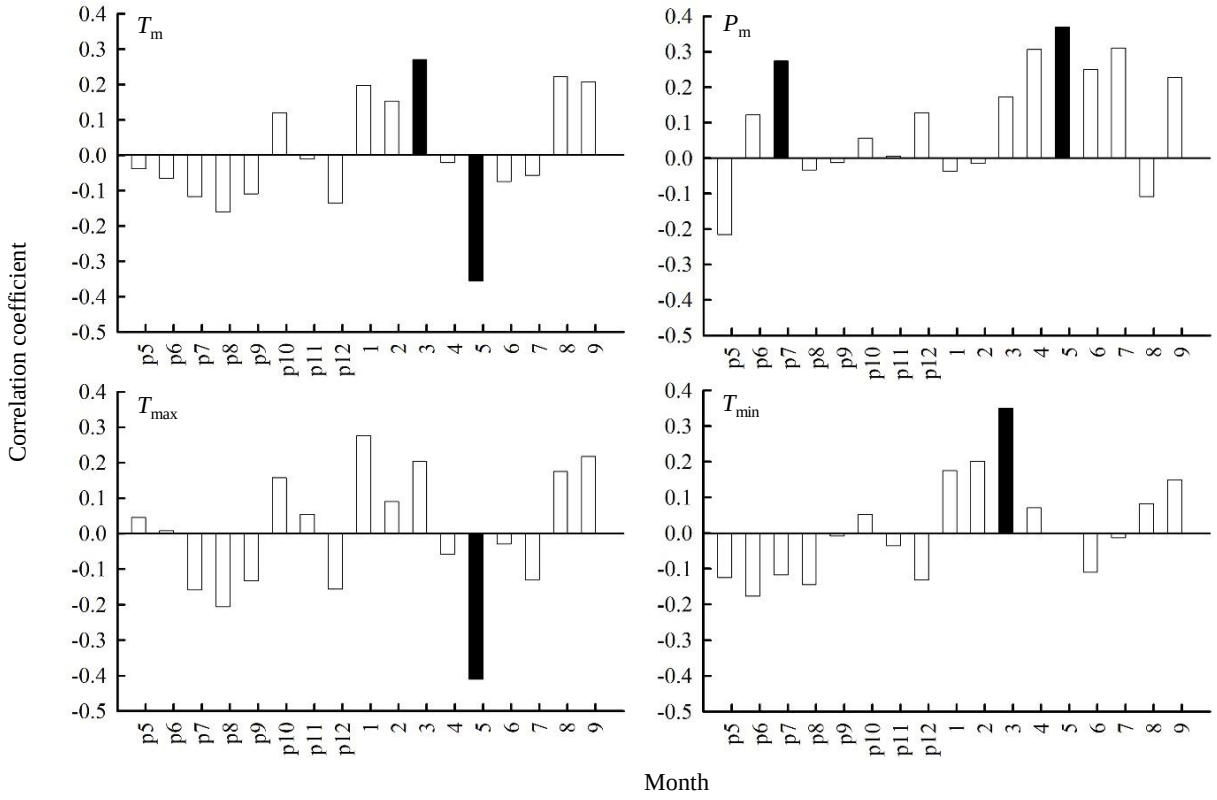


Figure 5. Correlation analysis of instrumental climate data with tree-ring chronology of Mongolian pine forest in Mu Us Sandy Land, Inner Mongolia

p: Previous year. Black pillar: $P < 0.05$. The same below

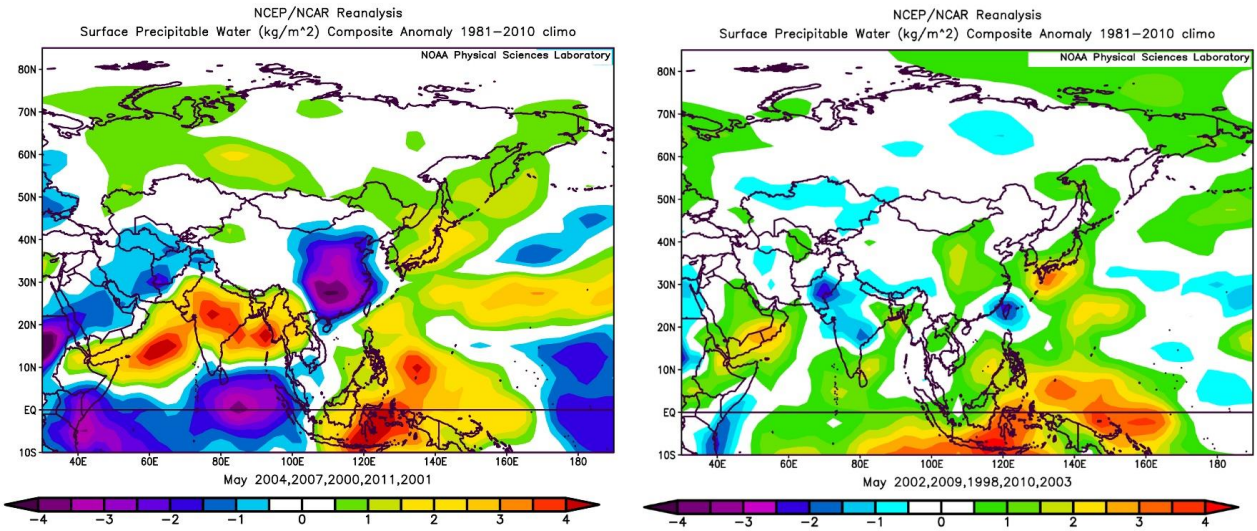


Figure 6. Surface precipitable water maps of high-value years (a) and low-value years (b) of tree-ring width chronology

5. Discussion

5.1. Response of tree growth to climatic factors

The radial growth of Mongolian pine was significantly negatively correlated with the average and maximum temperature in May, and positively correlated with the precipitation in May, which further confirmed that the drought stress in May was the main limiting factor for the growth of Mongolian

pine in Mu Us sandy land. This is consistent with the research results of Huang et al. [20, 21] on the response of tree ring width of Cypress and poplar to climate factors in Mu Us sandy land, and relevant studies have also supported this growth mechanism. For example, Zhang et al. [12] found that the temperature increase from April to August would have adverse effects on the radial growth of Mongolian pine in the Mangui region of the Greater Khingan Mountains. Therefore, the effects of drought stress on tree growth and physiological characteristics are prevalent in arid and semiarid areas in China [22]. Similar research conclusions have also been reported in Lesser Hinggan Mountains [23], Dongling Mountains [24], Funiu Mountains [25], and northwest Yunnan [26]. The Mu Us Sandy Land is located in the transition zone from semi-arid to arid, and the annual average precipitation is less than 400 mm, which is relatively dry. The growing season in this area is from May to September every year, and May is just the beginning of the growing season of Mongolian pine. In addition, the Mu Us Sandy Land is located at the edge of the Asian monsoon, which is strongly influenced by the East Asian monsoon. The rainy season mainly occurs from June to August, accounting for about 63% of the annual total precipitation, and is also the three months with the highest annual temperature. However, the temperature in May rises quickly and is slightly lower than that in June to August, while the average precipitation in May is only 27 mm, and strong wind often occurs, which is the season with the largest evaporation [27]. In general, higher temperatures combined with lower precipitation during the growing season, i.e., a dry and hot environment, can increase tree transpiration and soil water evaporation, resulting in soil water deficit and increase vapor pressure difference, resulting in insufficient water supply for photosynthesis, and limiting plant nutrient uptake, transport, and organic dry matter accumulation. In addition, continuous high temperatures will accelerate the lignification of plant roots and reduce the rate of water absorption, thereby affecting plant growth and leading to the formation of narrow rings in trees [28]. The significant positive correlation between tree growth and precipitation in May of the same year has clear physiological significance. More precipitation in the early growing season of the same year can directly increase soil water availability, thus compensating for soil water loss due to excessive evaporation, which is conducive to the formation of a wide ring. Therefore, it can be inferred that soil water availability in the early growing season of the current year may be the main limiting factor for the radial growth of Mongolian pine. Tree growth is not only affected by climatic factors in the growing season, but also by climatic factors in spring, autumn, and winter [28]. In this study, we found that the radial growth of Mongolian pine was positively correlated with the average and maximum temperature in March of the same year. The physiological explanation may be that warm early spring temperatures are conducive to breaking winter dormancy, raising soil and leaf temperatures, promoting rapid root and stem growth, and inducing earlier snowmelt. In turn, it can promote the prolongation of the growing season, advance the beginning time of cambium activity and increase the supply of photosynthetic substances, which is easy to form a wide ring.

5.2. Tree growth response to climate warming

The continuous increase in temperature and decreasing precipitation are the main reasons for the current warming and drying in the northern regions of our country [29]. With the continuous warming of the global climate, the climate warming and drying of Mu Us sandy land in semi-arid agro-pastoral ecotone areas in northern China became increasingly serious [4]. Luo et al. [27] studied the meteorological data of Uxin Banner meteorological station in the recent 47 years, and pointed out that the annual average temperature in Mu Us sandy land showed a trend of fluctuation and the maximum temperature increase in winter. Xu and Yan [30] analyzed the climate data of 8 meteorological stations in Mu Us sandy land in the past 30 years and found that the temperature in this area showed an obvious trend of warming and drying in the past 30 years, accompanied by a significant decrease in precipitation with the increase of temperature.

In general, the climate characteristics of Mu Us sandy land showed a warming and drying trend, and this trend will last for a long time. At present, there are many studies on the influence of climate warming and drying on the growth of Mongolian pine. For example, Zhang et al.[12] found that the

average temperature from April to August was the main limiting factor for the radial growth of Mongolian pine in the Greater Khingan Mountains, and the strengthening of the regional warming and drying trend would cause the growth of Mongolian pine to decline. Cao et al. [16] pointed out that the carbon sequestration capacity of Mongolian pine is affected by both temperature and precipitation, and the continuous warming in the Hulunbuir region in the future will lead to the reduction of the carbon sequestration capacity of Mongolian pine. Liu et al. [13] pointed out that Mongolian pine is prone to summer drought stress in the Bashang region of Hebei Province. With the increasing trend of warming and drying in this area, the resistance of Mongolian pine to drought events will decrease and even its healthy growth will face huge risks and challenges. According to the study of Li et al. [31], radial growth of Mongolian pine in Liaoning Province is mostly positively correlated with monthly rainfall and monthly average relative humidity, further indicating that regional water factors have a significant effect on the growth of Mongolian pine plantations. Therefore, drought stress caused by climate warming and drying has a very serious impact on the radial growth of Mongolian pine trees in the above areas. Similar research results have been reported in semi-arid inland Asia [22] and boreal forests in southern Asia [32].

In addition, Li et al.[33] studied the difference in response of natural Mongolian pine growth to climate change in the south and north of the Greater Khingan Mountains and found that drought stress aggravated by high temperature was the main reason for the growth decline of Mongolian pine in the south. If the warming continues, the distribution area of Mongolian pine may move north in the future. Zhang et al.[32] analyzed the climate growth response of 23 Mongolian pine populations distributed in most areas of northeast China and concluded that the early stage of the growing season of water supply is vital for the growth of Mongolian pine. The future temperature increase will cause the naturally distributed sandy Mongolian pine forests in northeast China to face the danger of shrinking or even disappearing. Therefore, the national government needs to strengthen the artificial management of Mongolian pine in the sandy land in the south of northeast of our country and set up a protected area when necessary, to protect the important origin base of Mongolian pine in the sandy land.

6. Conclusion

At regional and global scales, drought stress caused by climate warming has had an important impact on tree growth and cannot avoid affecting the carbon sequestration capacity of trees. Based on this study Mongolian pine in Mu Us sandy land in Inner Mongolia tree-ring width data. It was found that the water and heat conditions in May of that year were the main limiting factors for the growth of Mongolian pine in Mu Us sandy land. The results showed that there was a negative correlation between the average temperature and the maximum temperature in May of the same year and a positive correlation with the precipitation in May of the same year. In addition, the average temperature and the minimum temperature in March of the same year also had some restrictive effects on tree growth. The spatial correlation analysis revealed that the tree-ring width chronology of Mongolian pine could indicate the changes in average temperature, maximum temperature, and precipitation in May of the same year in a large range in Mu Us sandy land, which further indicated that the tree-ring samples collected this time were of good quality and had a greater spatial representation of regional environmental changes. The results of wavelet analysis and multi-power spectrum analysis showed that there were significant quasi-periods of 3.4, 5.0, and 6.1 years for tree growth in Mu Us sandy land, which may be related to the change of ENSO to some extent. In conclusion, under the background of climate warming and drying trend, the effect of drought stress on the radial growth of Mongolian pine is more and more obvious. If global temperature continues to increase in the future, the radial growth and carbon sequestration capacity of Mongolian pine in Mu Us sandy land will be adversely affected.

Acknowledgments

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