Assessment of Climatic Effects of Shelterbelt Construction Based on Ground-Based Observational Data

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Abstract

Forests, particularly shelterbelts, play a critical role in addressing climate change through temperature regulation, humidity control, and windbreak effects. China' s Three-North Shelter Forest Program has been under construction for nearly 50 years, and its remarkable ecological benefits have been widely recognized. However, research on its climate effects remains insufficient. This study analyzes the impact of shelterbelt construction on meteorological factors such as temperature and precipitation based on ground-observed meteorological data. The results indicate that shelterbelt construction reduced surrounding temperatures by 0.25$±0.55°*Candincreasedprecipitationby*57.68±$43.64 mm. Temperature is driven by two competing biophysical effects—evaporative cooling and radiative warming—which are closely related to climatic background conditions, and temperature responses vary across different months. These changes in meteorological data not only fully demonstrate the important purpose of shelterbelts in windbreak and sand fixation but also represent a positive climate effect highly beneficial for vegetation restoration. This research contributes to deepening the understanding of the comprehensive benefits of the Three-North Shelter Forest Program and provides practical and effective data support for the scientific planning and construction of future shelterbelts.

Full Text

Assessment of the Climatic Effects of Shelter Forest Construction Based on Ground Observation Data

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Abstract

Forests, especially shelter forests, play a crucial role in addressing climate change through temperature regulation, humidity control, and wind prevention effects. China' s Three-North Shelter Forest System has been under construction for nearly 50 years, and its remarkable ecological effects have been widely recognized. However, current research on its climatic effects remains insufficient. Based on meteorological data obtained from ground observations, this paper analyzes the impact of shelter forest construction on meteorological factors such as temperature and precipitation. The research results show that shelter forest construction has reduced surrounding temperature by 0.25 ± 0.55 °C and increased precipitation by 57.68 ± 43.64 mm. Temperature is driven by two competing biophysical effects—evaporative cooling and radiative warming—that are closely related to the climatic background, with temperature responses varying across different months. These changes in meteorological data not only fully reflect the important purpose of shelter forests in wind prevention and sand fixation but also represent a positive climatic effect that is extremely beneficial to vegetation restoration. This study helps deepen understanding of the comprehensive benefits of the Three-North Shelter Forest System and provides practical and effective data support for the scientific planning and construction of shelter forests in the future.

Keywords: Three-North Shelter Forest; Climatic Effect; Air Temperature; Precipitation; Wind Speed; Ground Observation Data

Introduction

Global forests cover 31% of the Earth' s land surface (FAO, 2020) and represent one of the most important terrestrial ecosystems. Through photosynthesis, forests reduce atmospheric CO_2 concentrations and mitigate climate change, serving as a crucial pathway for achieving carbon neutrality and peak carbon emissions targets. In addition, forests exert significant climatic effects. Dynamic changes in forest vegetation alter climatic factors such as temperature, precipitation, and wind speed by influencing biophysical processes of land-atmosphere energy and material cycling. Satellite-based global studies indicate that forests have localized warming effects (boreal forests) or cooling effects (tropical and temperate forests) (Li, Y., et al., 2015), and that tropical forest gain and loss have asymmetric impacts on land surface temperature (Zhang, Y., et al., 2024). Meanwhile, the temperature effects induced by vegetation are associated with ecosystem type and geographic distribution (Zhao Dongsheng et al., 2023), suggesting that temperature effects vary complexly across different ecosystems. At the continental scale, forests drive atmospheric moisture transport from oceans to land (Makarieva, A.M., et al., 2013), ultimately influencing precipitation formation. Regional studies have found that deforestation reduces local precipitation (Akkermans, T., et al., 2014; Zemp, D., et al., 2017). Other research indicates that deforestation effects on precipitation exhibit a critical threshold: when forest loss remains below this threshold, it may positively influence precipitation, but once the loss exceeds 30–50%, the relationship reverses (Lawrence, D., et al., 2015; Leite-Filho, A.T., et al., 2021). Compared to the intricate relationships between forests and temperature or precipitation, the relationship between forests and wind speed appears more straightforward. Tall forests with high surface roughness effectively block and divert strong winds, reducing wind speed. Forest biogeophysical feedbacks can either enhance or diminish negative climate forcings induced by human activities (Gordon B. Bonan, 2008). Therefore, understanding the climatic effects of forests is essential for elucidating their relationship with climate change.

To address ecological problems such as land desertification and soil erosion, many countries have established shelter forests with various objectives. As early as 1934, the Roosevelt administration in the United States launched the "Great Plains Shelterbelt Project" to reduce wind speed and maintain soil moisture (Snow, Meagan, 2019). Subsequently, in 1948, the Soviet government planned "Stalin' s Plan for the Transformation of Nature," a massive shelterbelt project across the Russian steppes to develop agricultural production and enhance resistance to wind and sand (Zhu Yongjie, 2016). To prevent further northward expansion of the Sahara Desert, five North African governments jointly initiated the "Great Green Wall" project in 1970 (Goffner, D., et al., 2019). China' s Three-North Shelter Forest System Construction Project (hereinafter referred to as the Three-North Shelter Forest) also began during this period (1978). After more than 40 years of construction, China has become the world leader in shelter forest construction scale (Zhu Jiaojun, 2013). These afforestation/reforestation projects have increased global forest area over the past century and generated positive impacts on ecological environment improvement and climate regulation. The climatic effects of shelter forests manifest as improvements in regional microclimate, specifically through temperature regulation, increased air humidity, and wind speed reduction (Hu Haibo et al., 2001). Integrated assessment model and Earth system model studies project that global afforestation/reforestation area will reach 935 million hectares by 2100, reducing end-of-century temperature by 0.2 °C (Moustakis, Y., 2024). The temperature effect of afforestation is asymmetric, typically increasing nighttime land surface temperature (Yuan G., et al., 2022), which in arid regions often offsets daytime cooling effects (Peng, S., et al., 2014). Afforestation impacts on precipitation vary regionally. European reforestation has increased summer precipitation by an average of $7.6 \pm 6.7\%$, potentially offsetting a substantial portion of climate change-induced precipitation decline (Meier, R., et al., 2021). Similarly, increased forest cover in China' s Loess Plateau (Tian, L., et al., 2022) and North China Plain (Yue Li, et al., 2018) has brought about precipitation increases, creating new opportunities for local ecology and agricultural development. Increased forest cover also affects wind speed. Greening across the Eurasian continent has enhanced land surface roughness, explaining 25–60% of the observed decline in surface wind speed in the northern mid-latitude continental regions (Vautard, R., et al., 2010). Furthermore, European studies demonstrate that afforestation reduces cyclone frequency and decreases cyclone intensity and extreme precipitation (Belusic

D., 2019). As wind speed decreases due to afforestation, positive effects become more apparent. Reduced wind speed further lowers soil wind erosion modulus, providing the theoretical basis for the wind prevention and sand fixation effects of the Three-North Shelter Forest (Huang Lin et al., 2018).

Methods for assessing the climatic effects of shelter forests are diverse and can be broadly categorized into observation-based approaches and model simulation approaches. Observation-based methods include meteorological station observations (Wang Pengtao et al., 2014; Meier, R., et al., 2021) and satellite remote sensing observations (Li, Y., et al., 2015; Zhang, Y., et al., 2024). Model simulation approaches include regional climate models (Ge, J., et al., 2020), land surface process models (Buechel, M., et al., 2023), and Earth system models (Moustakis, Y., 2024). Model-based methods offer strong spatiotemporal scalability, are suitable for scenario analysis, and can isolate the influence of individual variables. However, their data authenticity may be weaker compared to observation-based methods, and they struggle to reflect actual conditions intuitively. Given these considerations, this study primarily relies on ground observation data to analyze the impacts of shelter forest construction on meteorological elements including temperature, precipitation, and wind speed, aiming to provide insights for shelter forest construction in climate change mitigation and support sustainable ecological development.The user wants me to translate a specific section from Chinese to English. This is the "## 1. Study Area Overview" section from an academic paper.

Let me analyze the requirements: 1. Translate ONLY this section 2. The section contains Chinese characters that are author names and technical content 3. Author names should be romanized using pinyin 4. Journal names: Use English title if available, otherwise translate the meaning 5. Institution names: Use official English names when known 6. Technical terms: Use standard English equivalents 7. DO NOT leave any Chinese characters 8. Return ONLY the translated section with the same structure

Looking at the text:

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## 1. Study Area Overview

The Three-North Shelter Forest project spans a total planning period of 73 years, covering 1
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Let me check each name: - 朱教君: Zhu Jiaojun (standard pinyin) - 纪平: Ji Ping (standard pinyin) - 张雄一: Zhang Xiongyi (standard pinyin) - 王耀: Wang Yao

(standard pinyin)

The "等" means "et al." in academic citations.

So the translated section should be:

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## 1. Study Area Overview

The Three-North Shelter Forest project spans a total planning period of 73 years, covering 1
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Wait, let me double-check the names. In Chinese academic papers, author names are typically given with surname first. So: - 朱教君: Zhu Jiaojun (Zhu is surname, Jiaojun is given name) - 纪平: Ji Ping (Ji is surname, Ping is given name) - 张雄一: Zhang Xiongyi (Zhang is surname, Xiongyi is given name) - 王耀: Wang Yao (Wang is surname, Yao is given name)

The format should## 2.1 Data Sources and Preprocessing

The land use data required for this study were obtained from the GLASS-GLC (Global Land Surface Satellite - Global Land Cover) data product, which includes annual dynamic land cover data at 5 km spatial resolution for the period 1982-2015 (Liu, H., et al., 2024). The imagery data were subsequently clipped to the Three-North Shelter Forest region.

Meteorological data were sourced from the Global Surface Summary of the Day product produced by the U.S. National Centers for Environmental Information. This dataset, initiated in 1929, includes over 9,000 meteorological stations worldwide (https://www.ncei.noaa.gov/data/global-summary-of-the-day/). Six meteorological elements were selected: mean temperature, minimum temperature, maximum temperature, precipitation, mean wind speed, and maximum sustained wind speed. Original data units were converted to the International System of Units, including temperature (°F to °C), precipitation (inches to mm), and wind speed (knots to m/s). Additional data screening was applied: data from a station were used only if it had records for more than 300 days in a given year. For precipitation data, daily precipitation exceeding 350 mm (approximately 60% of the daily extreme precipitation in northern China) was removed. Furthermore, if more than 180 days of data were missing in a year, that year' s data were excluded. Finally, daily-scale meteorological data were aggregated to monthly scale for analysis.

2.2 Three-North Shelter Forest Construction Judgment

Land use data were selected for the start and end years and decadal intervals, comprising five scenes (1982, 1990, 2000, 2010, and 2015). These images were mosaicked to facilitate identification and differentiation of afforestation areas and their temporal dynamics (Figure 1 [Figure 1: see original paper]). Figure 1 shows the Three-North Shelter Forest region, with 1982 representing the forest cover for that year, and 1990, 2000, 2010, and 2015 showing new forest cover added compared to the previous period.

2.3 Meteorological Station Selection

The Three-North Shelter Forest region encompasses numerous meteorological stations. Based on station location (within 200 km of each other) and attributes (elevation difference within 600 m), we selected meteorological stations surrounded by newly added forest (afforestation stations) and control stations. Ultimately, 7 pairs comprising 14 meteorological stations were selected (Table 1), encompassing 287,304 daily-scale meteorological records across 790 station-years. Among these, precipitation data meeting the preprocessing criteria totaled 197,416 records from 543 station-years.

Table 1 Attributes of meteorological stations. Station ID, Station name, Latitude, Longitude, Elevation (m)

2.4 Climate Effect Analysis

Considering that afforestation impacts develop gradually, this study used 2000 as the temporal midpoint to divide the data from the 7 pairs of 14 meteorological stations into pre- and post-afforestation periods for comparative analysis. Data for three variable groups (temperature, precipitation, wind speed) at two temporal scales (annual and monthly) were analyzed, with their differences representing the climatic effects of afforestation.

$$CE_{\Delta} = |CE_{\text{post-afforestation, afforestation station}} - CE_{\text{post-afforestation, control station}}| - |CE_{\text{pre-afforestation, afforestation stat}}$$

where CE_{Δ} represents the climatic effect, and $CE_{a,b}$ denotes the climatic factor for region b during period a.

3.1 Impact of Shelter Forest on Temperature

The annual temperature variation trends in the afforestation and control areas are consistent, both showing distinct seasonal dynamics (Figure 2a [Figure 2: see original paper]). Winter temperatures are lowest, ranging from -10 °C to -20 °C, while summer temperatures are highest, ranging from 10 °C to 20 °C. Notably, temperatures in the afforestation area from November to March of the following year are significantly higher than those in the control area. Monthly temperature differences before and after shelter forest construction reveal varying responses across months, with most months showing an overall cooling effect (Figure 2b [Figure 2: see original paper]). Specifically, November to January exhibit warming, while the remaining months show cooling. The maximum warming occurs in January (0.81 °C), while the maximum cooling occurs from March to May (-0.51 °C, -0.46 °C, and -0.50 °C, respectively).

Figure 2 shows monthly temperature dynamics in afforestation and control areas (a) and monthly temperature differences before and after shelter forest construction (b). The cloud-rain plots display data points from box plots, probability density distributions, and statistical information (horizontal lines represent medians, boxes show interquartile ranges, whiskers indicate maximum and minimum values, and black dots are outliers).

Interannual temperature variations between afforestation and control areas range from 2–6 °C, with control area temperatures slightly higher than those in the afforestation area. Using 2000 as the temporal midpoint, post-2000 temperatures in the afforestation area gradually approached those of the control area, even exceeding them slightly during 2017–2019. Overall, comparative analysis of the 7 afforestation/control pairs indicates that mean annual temperature decreased by 0.25 ± 0.55 °C after shelter forest construction, demonstrating that shelter forest establishment reduces ambient temperature.

Figure 3 [Figure 3: see original paper] shows the annual temperature dynamics in afforestation and control areas.

3.2 Impact of Shelter Forest on Precipitation

Precipitation in both afforestation and control areas exhibits distinct seasonal dynamics, though its monthly coefficient of variation far exceeds that of temperature (Figure 4a [Figure 4: see original paper]). Annual precipitation is highly concentrated, primarily occurring from May to September. Monthly precipitation differences before and after shelter forest construction show relatively consistent responses across months, with increased precipitation in all months except July (-10.73 mm) (Figure 4b [Figure 4: see original paper]). The maximum precipitation increase occurs in August (31.82 mm), while increases from November to March remain below 1 mm.

Figure 4 shows monthly precipitation dynamics in afforestation and control areas (a) and monthly precipitation differences before and after shelter forest construction (b). Cloud-rain plots display data points from box plots, probability density distributions, and statistical information (horizontal lines represent medians, boxes show interquartile ranges, whiskers indicate maximum and minimum values, and black dots are outliers).

Cumulative precipitation shows considerable variation between afforestation and control areas, with precipitation generally higher in the afforestation area (Figure 5 [Figure 5: see original paper]). Using 2000 as the temporal midpoint, the precipitation difference between afforestation and control areas first increased and then gradually decreased after 2000. Overall, comparative analysis of the 7 afforestation/control pairs indicates that cumulative annual precipitation increased by 57.68 ± 43.64 mm after shelter forest construction, demonstrating that shelter forest establishment enhances local precipitation.

Figure 5 [Figure 5: see original paper] shows annual precipitation dynamics in afforestation and control areas.

3.3 Impact of Shelter Forest on Wind Speed

Wind speeds in both afforestation and control areas range from 1 to 3 m/s, with seasonal dynamics showing a "bimodal" pattern (Figure 6a [Figure 6: see original paper]). Mean monthly wind speed peaks in April during spring and reaches its minimum in August during the growing season, with wind speeds in the afforestation area lower than those in the control area. Monthly wind speed differences before and after shelter forest construction show consistent responses across all months, with wind speed increasing in every month (Figure 6b [Figure 6: see original paper]). Specifically, the maximum wind speed increase occurs in April (1.03 m/s).

Figure 6 shows monthly wind speed dynamics in afforestation and control areas (a) and monthly wind speed differences before and after shelter forest construction (b). Cloud-rain plots display data points from box plots, probability density distributions, and statistical information (horizontal lines represent medians, boxes show interquartile ranges, whiskers indicate maximum and minimum values, and black dots are outliers).

Wind speeds in afforestation and control areas gradually converged, with the largest differences occurring in the 1990s (Figure 7 [Figure 7: see original paper]). Since 1960, both regions experienced a long-term declining wind speed trend, which moderated after 2000 as wind speeds began to increase gradually. Using 2000 as the temporal midpoint, wind speeds in the afforestation and control areas became increasingly similar thereafter. Overall, comparative analysis of the 7 afforestation/control pairs indicates that mean annual wind speed increased by 0.55 ± 0.74 m/s after shelter forest construction. The finding that wind speed increased in the afforestation area relative to the control area contradicts previous research.

Figure 7 [Figure 7: see original paper] shows annual wind speed dynamics in afforestation and control areas.

4.1 Temperature Effect of Shelter Forests

Generally, vegetation greening projects such as shelter forest construction enhance surface transpiration, thereby producing a cooling effect. Vegetation greening can alter biogeophysical processes through evaporative cooling (Piao, S., et al., 2020), mitigating $4.6 \pm 3.2\%$ of global warming (Li, Y., et al., 2023) and offsetting 4.7–5.8% of observed extreme high temperatures (Wu J., et al., 2024). Climate model-based studies indicate that large-scale greening in China has reduced summer mean land surface temperature by 0.11 °C (Yu, L., et al., 2020). Research has shown that evaporative cooling, a non-radiative effect, dominates local land surface temperature changes caused by afforestation in China (Ge J., et al., 2019). Studies using fused satellite datasets have demonstrated that changes in evapotranspiration due to greening lowered near-surface air temperature by 0.08 °C during 2001–2018 (Gao, Y., et al., 2023), which aligns with our findings. Conversely, tropical forest studies show that forest degradation increased tropical land surface temperature by $0.022 \pm 0.014\,°C$ (Zhu, L., et al., 2023). Moreover, the temperature effects of forest cover gain and loss are asymmetric (Su, Y., et al., 2023).

However, vegetation greening projects such as shelter forest construction can also reduce surface albedo, increasing radiation absorption and producing a warming effect. Earth system model-based studies reveal that changes in leaf area index over the past three decades have caused a declining surface albedo trend ($-1.3 \pm 0.6 \times 10^{-4}$ per decade) and imposed a positive climate forcing of $0.03 \pm 0.01\,\mathrm{W\,m^{-2}}$ per decade on land (Zeng, Z., et al., 2017). In high-latitude regions, afforestation effects on surface albedo are more pronounced than in tropical areas (James Weber et al., 2024) and may even produce net warming due to albedo reduction (Betts, R, 2000). Particularly in winter, vegetation albedo is lower than that of snow- and ice-covered ground, intensifying the warming effect (Laguë, M. M., & Swann, A. L. S, 2016).

Temperature effects triggered by vegetation change have long been a focal point in global change research. Previous studies have primarily focused on using remote sensing data to investigate impacts on

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