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Ecological Risks Arising for the Regional Water Resources in Inner Mongolia Due to a Large-Scale Afforestation Project

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Abstract: In recent years, a large-scale afforestation campaign has taken place in Inner Mongolia, China, to control desertification and soil erosion. However, the water consumption associated with large-scale afforestation significantly impacts the water resources in Inner Mongolia, resulting in a substantial ecological risk. This study aimed to evaluate the ecological risk of water resources caused by afforestation in the region. In this study, based on land cover data, Normalized Difference Vegetation Index (NDVI) data, and meteorological data, used trend analysis, water balance equation, and Water resources Security Index (WSI) index to analyze the ecological risks of water resources caused by afforestation in Inner Mongolia from 2000 to 2020. The results show that:(1) The afforestation area in Inner Mongolia was 5.37×10^4 km^2 in 2000-2020; (2) Afforestation in arid and semi-arid areas leads to the reduction of water resources. (3) Afforestation reduces water resources in the study area by 0.62×10^8m^3/year; (4) ~76% of afforestation regions face ecological risks of water resources. This study provides scientific suggestions for the sustainable development of regional water resources and afforestation

Keywords: afforestation; water resource; ecological risk; Inner Mongolia

1. Introduction

To protect the fragile ecosystem and economy, combat desertification, and control dust storms, the Chinese central and local governments have implemented a series of ecological engineering projects in China [1], such as the Slope Land Conversion Project, China's Natural Forest Protection Project, River Shelterbelt Project, and the Returning Farmland to Forest and Grassland [2]. Ecological engineering slowed desertification and its expansion in China, significantly contributing to the world's "greening" trend [3]. Chen et al. [3] indicated that the global green leaf area has increased by 5% since the early 2000s. China and India contributed 25% and 6.8%, respectively, to the increase in greening on land.

However, this significant land cover change resulting from afforestation very strongly affected the ecological environment, especially the water resources [4–7]. It was confirmed that forests could increase regional evapotranspiration and reduce total runoff discharge compared to the absence of forests under the same precipitation conditions. Some studies pointed out that 10-40% of annual precipitation was lost by the canopy interception [8] It was shown that the total canopy interception was calculated to be 76.6 mm in Shaanxi Province, northwest China, accounting for 18.6% of the gross

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precipitation. Moreover, in forests, the shallow roots extract soil water provided by precipitation while consuming groundwater by the deep roots during the dry period [9].Karimov et al. [10] found that shallow groundwater contribution to plant transpiration exceeds 60% in the upstream area of the Syrdarya River, in Central Asia. In the Ejina Basin, China, *Populus euphratica* obtains 53% of its water from groundwater [11]. In the dry season, the groundwater uptake accounts for 73.2% [12]. Under the effects of canopy interception and transpiration from soil and aquifer layers, the effective precipitation and groundwater recharge in forests is much lower than in other areas [13]. Keese et al. [14] used an unsaturated flow modeling study that indicated the forests significantly decrease groundwater recharge by factors of 2 to 30 relative to the recharge for non-vegetated simulations [14]. Therefore, it was concluded that large-scale tree planting in China could lead to regional water resource shortages. Xiao et al. [15] indicated that since 2000, the water consumption of plantations has increased to 40.42 billion m^3 in southwest China. This amount accounts for 10.69% of the water resources for the entire year. Cao et al. [16] used seven models and estimated that afforestation will increase net water consumption by 559-2354 m^3/ha annually compared with the amount of water potential natural vegetation would consume. Water resources are an important basis for maintaining the sustainability of ecosystem development in arid and semi-arid areas [17,18]. Due to climate change and water resources development and utilization, the spatial distribution of water resources changes [19], leading to the risk of water supply - demand in regional ecosystems [20].

Inner Mongolia is a perfect natural laboratory to study the forest's effects on regional water resources. The forest areas of Inner Mongolia showed rapid increases through several large-scale ecological restoration projects implemented since 2000. Inner Mongolia is located in environmentally fragile arid and semi-arid regions that currently face water scarcity. However, informative reports about the impacts of forest dynamics on the variation in water resources at the regional scale remain unavailable. It is urgently necessary to study the dynamic changes and ecological risks on water resources to better regulate ecological engineering policies and provide benefits for human beings.

2. Materials and Methods

2.1. Study area

Inner Mongolia is located in northern China, covering an area of 1.18 million km^2, or 12.3% of the national terrestrial area [21]. It extends from 97°E-126°E and 37°N–53°N (Figure 1). The mean temperature is approximately 0-8 °C. The average annual precipitation is only 50-450 mm and gradually increases from west to east; approximately 75% of the rainfall is concentrated between July and September [22]. The main vegetation types are forested prairies, temperate prairies, desert steppes, and deserts intergrading from east to west (Figure 1). Inner Mongolia contains the largest grassland and natural pasture in China. According to the results of the eighth forest resources inventory, the grassland area is 88 million hectares, accounting for ~74% of the total land area of Inner Mongolia and ~22% of the grassland area of the entire country. The forest land area is 45 million hectares, accounting for ~22% of the total land area of Inner Mongolia and ~14% of the forest area of the entire country. The ecology and environment of Inner Mongolia are fragile, very sensitive, and vulnerable to the water resource. Ecological restoration projects have been implemented to address land desertification and improve the environment, such as Returning Farmland to Forest, and Beijing-Tianjin Sand Control.

According to the Inner Mongolia Water Resource Bulletin, the area's total water resources in 2020 were 503.93 × 10^8 m^3, surface water resources were 354.19 × 10^8 m^3, and groundwater resources were 243.94 × 10^8 m^3. However, water resources are mainly concentrated in the northeastern part of the study region, Hulunbuir City. In contrast, the per capita water resources in the northwestern part are only one-fifth of the world average, and it is one of the most water-scarce regions in China. Water supply in Inner Mongolia includes surface water and groundwater. The surface water primarily comes from precipitation and Yellow River water diversion.

Based on our investigation and the data available, we summarized three major water resource uses in Inner Mongolia. Agricultural irrigation and industrial water consumption accounted for

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70.8% of total water consumption. Ecological and people's livelihoods accounted for 15.1% and 6.0% of the total water consumption, respectively.

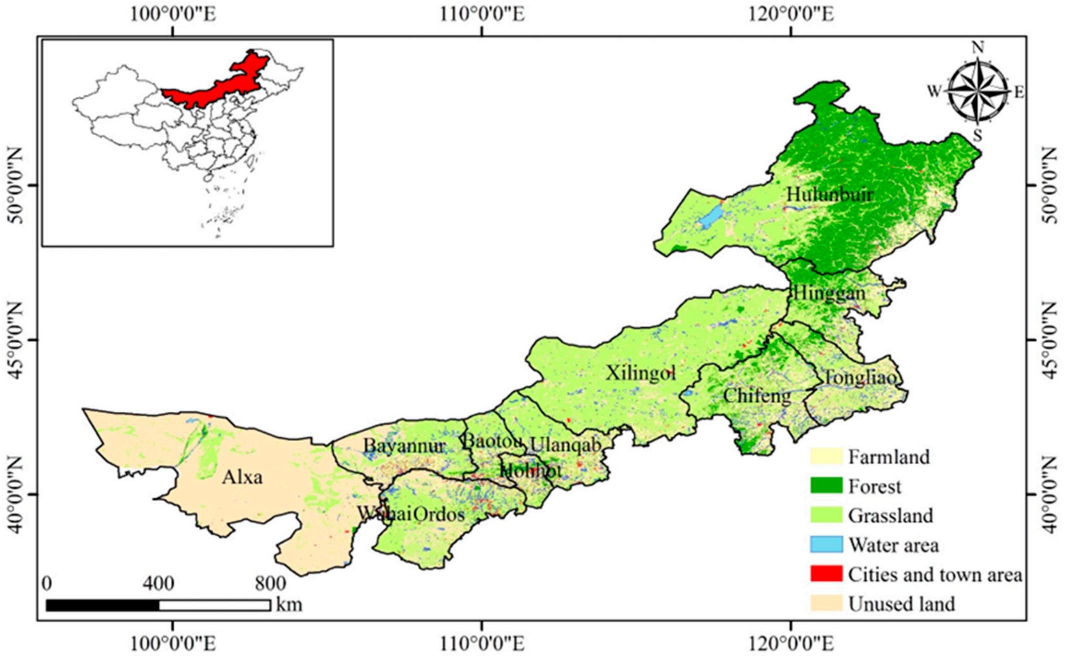

Figure 1. The location of the study area.

2.2. Data Collection

The meteorological data mainly included monthly precipitation and temperature from 2000 to 2020. The meteorological data from 37 stations were collected from the Chinese National Meteorological Information Center (http://data.cma.cn). Land use/land cover remote sensing monitoring data in China from 2000 to 2020 were collected from the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC, http://www.resdc.cn). The NDVI dataset originated from the Global Inventory Modeling and Mapping Studies (GIMMS) covering the period from 2000 to 2020 was collected from the Ecological Forecasting Lab of NASA's Ames Research Center (https://ecocast.arc.nasa.gov). The annual evapotranspiration (ET) data (MOD16 data product) from 2000 to 2020 was obtained from the Land Processes Distributed Active Archive Center (https://lpdaac.usgs.gov/). The MOD16 evapotranspiration datasets is based on the logic of the Penman-Monteith equation, which includes inputs of daily meteorological data and MODIS remote sensing data products such as vegetation property dynamics and land cover [23]. We obtained afforestation data from annually published China forestry statistical yearbooks from 2000 to 2020 (State Forestry Agency of the People's Republic of China). We obtained the water resource data from the Inner Mongolia Water Resource Bulletin (2000-2020, http://slt.nmg.gov.cn/).

2.3. Methods

2.3.1. Identifying the afforestation regions

The identification of afforestation regions is an important prerequisite to evaluate the ecological risk of water resources caused by afforestation [24,25]. Compared with natural forest land, NDVI of artificial forest land is more easily affected by human activities, and the change trend is more obvious [26]. In this study, NDVI and land cover data were used to analyze the spatial characteristics of vegetation and forest land, and afforestation areas were identified through the combination of the two, and finally sample points were used to verify the results (Figure 2). The main steps are as follows:

(1) Trend analysis was used to identify areas with significant increase in NDVI in Inner Mongolia from 2000 to 2020. Trend analysis is a linear regression analysis of time-dependent variables [27,28]. The constantly changing properties of the vegetation may be reflected in the trend of the change in NDVI for each grid by applying linear trend analysis. In this study, the trend of NDVI change in the Inner Mongolia from 2000 to 2020 was determined using a unitary linear regression model, and the slope of the trend was calculated using the least squares method:

$$Slope = \frac{n\sum_{i=1}^{n}(i \times NDVI_i) - \sum_{i=1}^{n} \times \sum_{i=1}^{n} NDVI_i}{n\sum_{i=1}^{n} i^2 - (\sum_{i=1}^{n} i)^2} \quad (1)$$

where: $Slope$ refers to the trend of vegetation change, n is the number of years studied (n = 21 in this study), i is the ordinal number of a given year, and $NDVI_i$ denotes the NDVI value for year i ; in the case of a $Slope$ > 0, this indicates the NDVI tends increasing.

A significance test is often used to assess the accuracy of the trend change. In this study, we assess the significance of trends using the F-test ($p<0.05$). The calculation's formula is as follows:

$$F = U \times \frac{n-2}{Q} \quad (2)$$

$$U = \sum_{i=1}^{n}(\hat{y}_i - \bar{y})^2 \quad (3)$$

$$Q = \sum_{i=1}^{n}(y_i - \hat{y}_i)^2 \quad (4)$$

where: U refers to the sum of squares of errors, Q is the regression square sum, y_i is the NDVI value for year i, $\hat{y}_i$ is the NDVI regression value for fear i; $\bar{y}$ is the average NDVI value in n year; and i is the ordinal number of a given year.

(2) Five periods of land cover data (2000, 2005, 2010, 2015, 2020) were used to identify forestland increased region in 2000-2020. The histogram analysis method was used to calculate the NDVI values of the forestland increased region, and the NDVI range of 20%-80% was taken as the NDVI threshold of the afforestation regions.

(3) Extract afforestation area by overlapping the results derived in the prior two steps. The NDVI increased region within the NDVI threshold of afforestation region is identified as afforestation area. Finally, the extraction results were verified by using 23 afforestation sample points obtained from field investigation in Ulanqab. The overall identification accuracy was 73.9%.

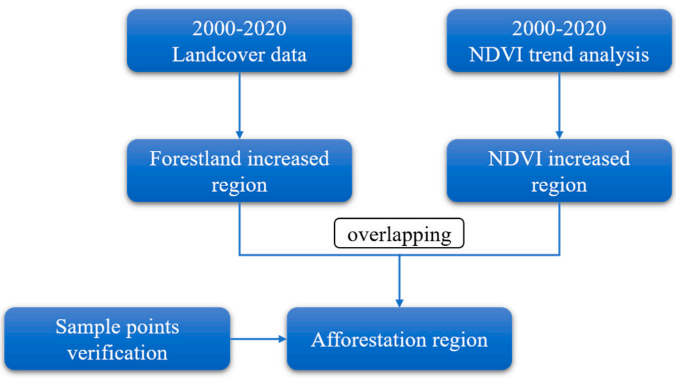

Figure 2. The workflow of identifying the afforestation regions.

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Figure 3. Field survey of afforestation sample points.

2.3.2. Water balance

To understand the influence of afforestation on water resources in Inner Mongolia, the water balance equation was used to calculate the change of water resources in afforestation regions[29], which can be described as follows:

$$Q = P - ET_a - \Delta S \quad (5)$$

where: Q refers to the water resource (mm); P is the precipitation (mm); ET_a is the actual evapotranspiration (mm); ΔS indicates to basin water resource change (mm), which is generally assumed to be zero in a long term.

In order to detect the change trend of water resources caused by afforestation during the 2000-2020, the least square linear regression model can be used.

2.3.3. Ecological risk

Water resources Security Index (WSI) was used to evaluate the ecological risk of water resources caused by afforestation, which quantified regional water security from the perspective of regional supply and demand balance [30]. The equation is as follows:

$$WSI = lg\left(\frac{P}{D}\right) \quad (6)$$

where: P refers to the water resource supply (mm), we assume that the afforestation only has precipitation supply; D is the water resource requirement (mm), the ET_a was taken as the water resource requirement of the afforestation. In the case of $WSI < -0.5$, this indicates high risk; $-0.5 \leqslant WSI < 0$, this indicates low risk; $0 \leqslant WSI < 0.5$, this indicates low security; $0.5 \leqslant WSI < 1$, this indicates high security.

3. Results

3.1. The spatial distribution of afforestation in Inner Mongolia

According to the change trend of NDVI in Inner Mongolia from 2000 to 2020, ~ 65% of the region's NDVI shows an increasing trend, vegetation coverage has improved significantly, mainly distributed in the central and eastern part of Inner Mongolia (Figure 4). Within these NDVI-increased significantly land areas, their forest cover was designated as afforestation.

The spatial distribution of afforestation showed pronounced spatial heterogeneity, and afforestation is mainly distributed in the eastern part of Inner Mongolia (Figure 5). The forest cover area in the study area increased from 20.74 × 10^4 km^2 in 2000 to 26.11 × 10^4 km^2 in 2020.The afforestation area in Inner Mongolia was 5.37 × 10^4 km^2 from 2000 to 2020. The growth rate was 0.27 × 10^4 km^2/a. The forest coverage rate increased from 17.53% to 22.07%. Hulunbuir has the largest afforestation area, with an area of 2.46 × 10^4 km^2, accounting for 45.81% of the total afforestation area.

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The afforestation area of Chifeng is second only to Hulunbuir, accounting for 10.75% of the total afforested area. The afforestation area of Wuhai and Alxa in western Inner Mongolia was relatively small, accounting for 0.24% and 1.57% respectively.

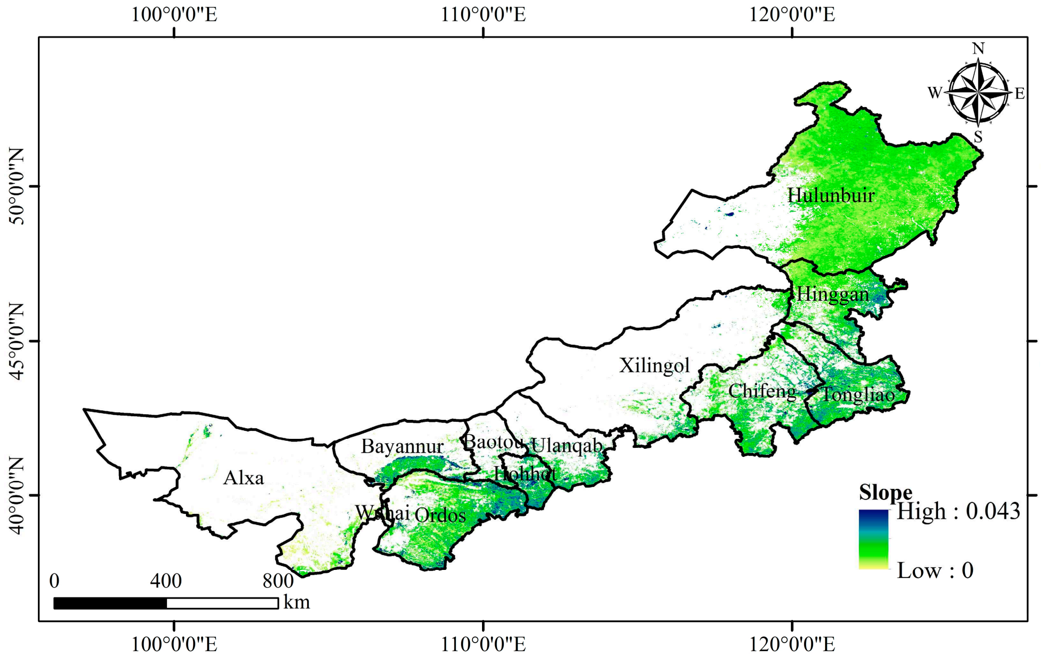

Figure 4. Regional spatial distribution characteristics of NDVI increase (2000-2020).

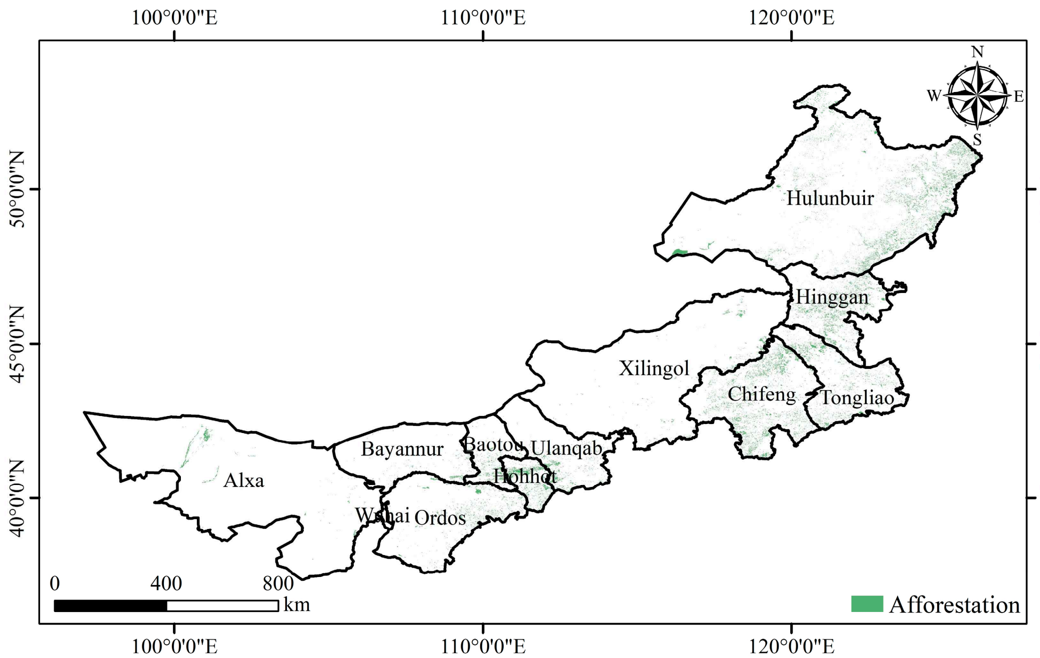

Figure 5. Afforestation in Inner Mongolia (2000-2020).

3.2. ET comparison between artificial forest land and natural forest land

The effects of afforestation on regional water resources were studied by comparing ET changes of artificial forest and natural forest. The annual ETa of the artificial forest in Inner Mongolia was 488.77mm, slightly higher than that of the natural forest (418.82mm), and the potential ET (PET) of the artificial forest was 1186.19mm, much higher than that of the natural forest (950.14mm) (Figure

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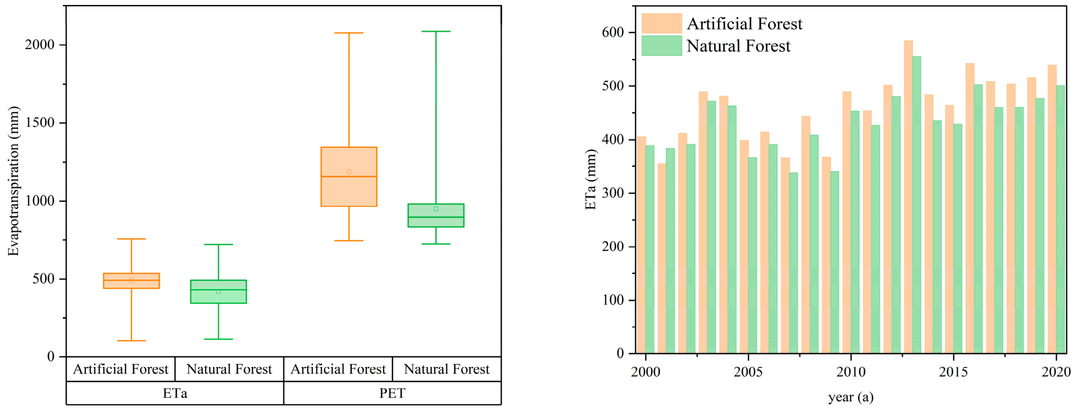
6a). Under the background of climate change warming and wetting in the Inner Mongolia Plateau [31], ET showed an obvious increasing trend from 2000 to 2020, with increasing at a rate of 7.15mm/ year in artificial forest and 5.25mm/ year in natural forest. The consumption of water resources in the artificial forest is greater than that in the natural forest.



(**a**) (**b**)

Figure 6. ET comparison between artificial forest land and natural forest land. (**a**) Comparison of ETa and PET; (**b**) Variations of ETa for artificial forest land and natural forest land (2000-2020).

3.3. Changes in water resources caused by afforestation

The water resources change caused by afforestation during 2000-2020 was calculated by the water balance equation (Figure 7). The results showed that the change of water resources in Inner Mongolia caused by afforestation showed a decreasing trend, and showed obvious spatial heterogeneity. ~43% of the afforestation regions showed an increasing trend of water resources, mainly distributed in the eastern areas with sufficient precipitation, especially Hulunbuir and Hinggan; ~57% of the afforestation regions showed a decreasing trend of water resources change, mainly distributed in the central and western regions with insufficient precipitation, especially in Alxa, Ordos, Hohhot, Baotou and Ulanqab.

From the time change trend of water resources consumption in afforestation (Figure 8), it can be seen that the water resources consumption in afforestation was between 60-90 × 10^8 m^3 from 2000 to 2020, showing an increasing trend, with a change rate of 0.62 × 10^8 m^3/ years, of which the water resources consumption in 2011 was the smallest, the minimum value was 62.40 × 10^8 m^3, and the water resources consumption in 2013 was the largest, the maximum value was 85.10 × 10^8 m^3, and the mean value of multi-years was 73.07 × 10^8 m^3.

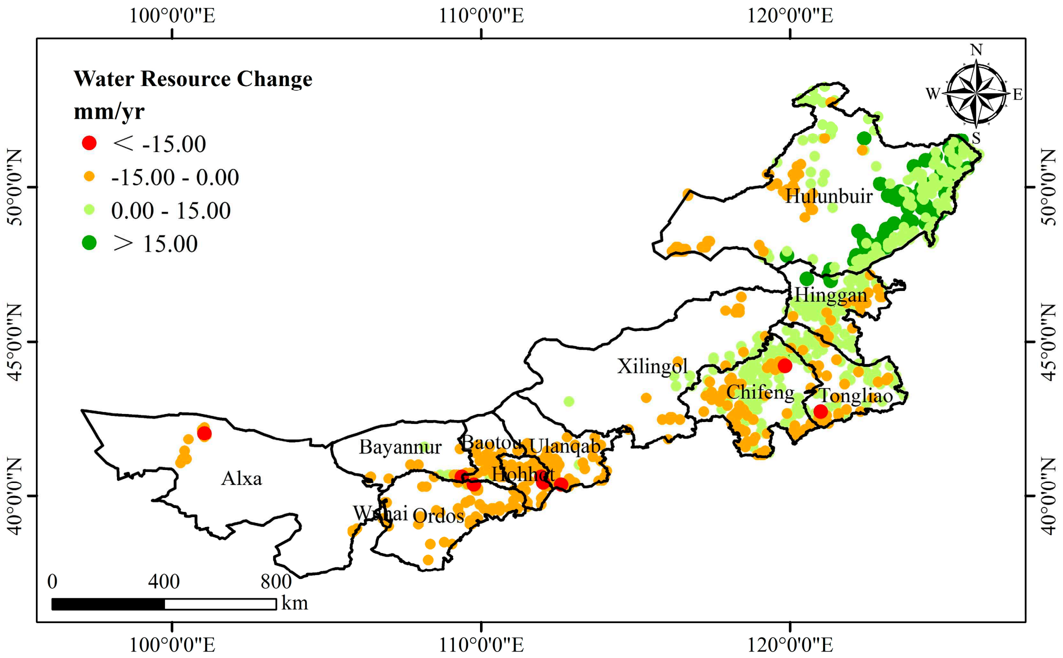


Figure 7. Variations of water resources caused by afforestation in Inner Mongolia (2000-2020).

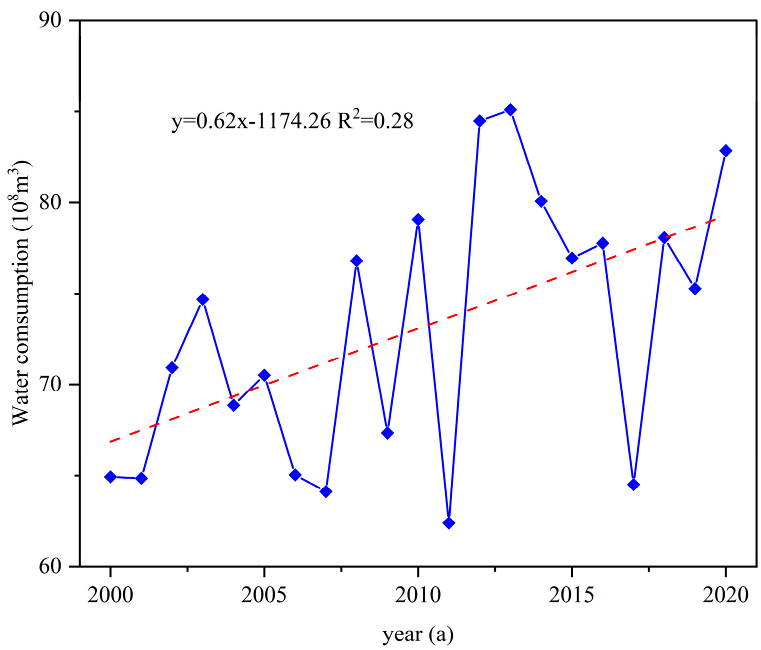


Figure 8. Variations of water consumption estimation for afforestation region (2000-2020).

3.4. Ecological risk of water resources in afforestation area

The ecological risk caused by afforestation was calculated from the perspective of water supply by WSI. Under the assumption that only precipitation supply is considered, most areas in the study area face ecological risks caused by afforestation (Figure 9). The ecological risk increased from east to west, indicative of spatial heterogeneity. ~24% of the afforestation regions are at high risk, mainly in the central and western parts of Inner Mongolia; ~bout 52% of the afforestation regions are at low risk, mainly in the eastern part of Inner Mongolia, especially Chifeng and Tongliao. ~24% of the afforestation regions are at low security, mainly in the eastern part of Hulunbuir. There is no high security of afforestation in Inner Mongolia.

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From the temporal change trend of WSI in afforestation (Figure 10), it can be seen that the WSI in afforestation has gradually changed from low risk to high risk from 2000 to 2020, showing a decreasing trend. In 2008, the WSI was the largest at -0.25. The WSI in 2013 and 2020 were the smallest, which is -0.57, and the ecological risk of water resources caused by afforestation was the largest. The ecological risk was at high risk in 2003, 2009, 2011, 2013, 2015 and 2020.

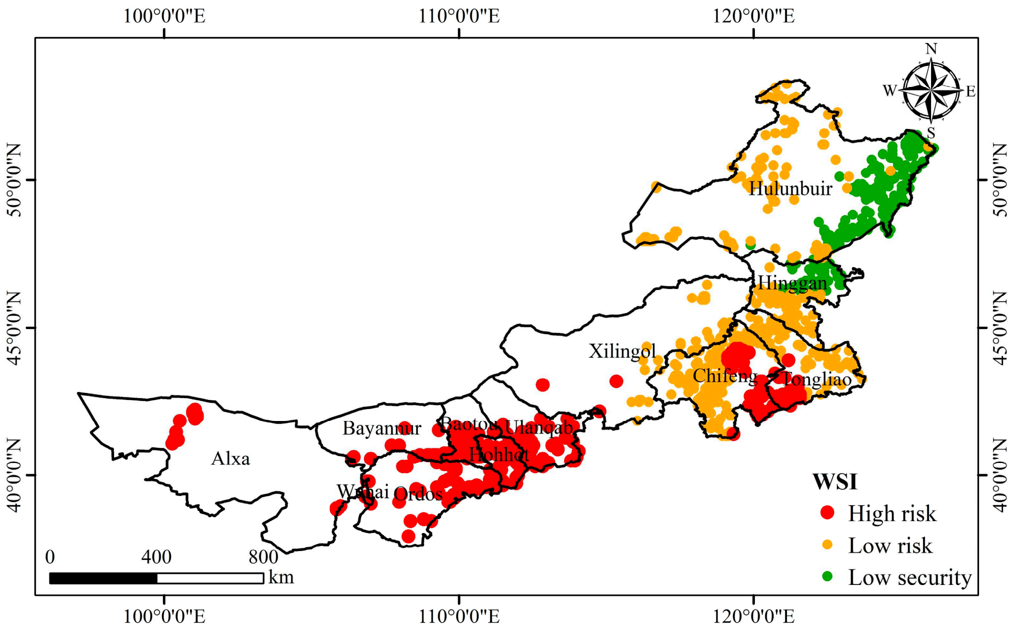

Figure 8. Ecological Risks Arising for the Afforestation in Inner Mongolia.

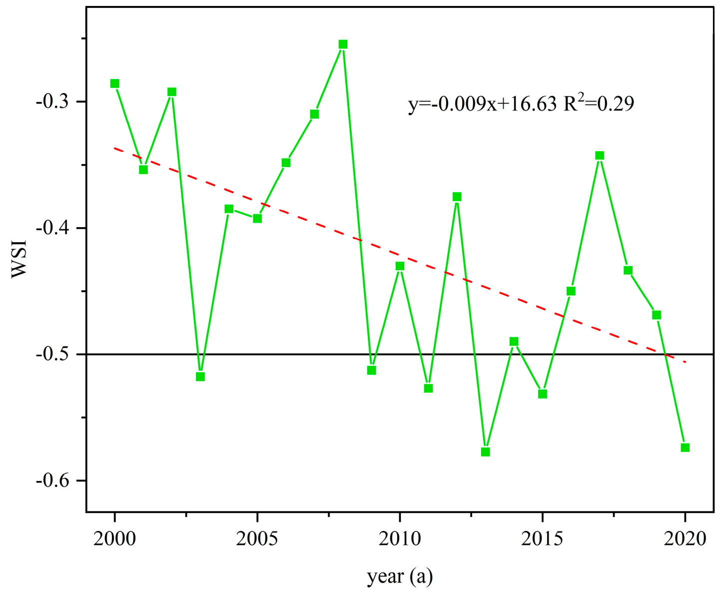

Figure 9. Variations of WSI for afforestation region (2000-2020).

4. Discussion

4.1. Identification of afforestation

Inner Mongolia is one of the key regions targeted by Chinese ecological restoration programs [21], and ecological restoration projects such as afforestation have a significant impact on regional water resources. It is an important basis for calculating and evaluating the ecological risk of water resources to accurately identify the afforestation regions. In this study, the change characteristics of land cover data and NDVI data were combined to identify the afforestation areas in Inner Mongolia. The afforestation area, growth rate and spatial distribution characteristics were consistent with previous research results [21,24,25,32], indicating that the large-scale ecological restoration project has made certain progress since 2000. Due to the large study area, the identification of forest land and shrub vegetation with low vegetation coverage is poor, and the actual afforestation area may be underestimated. In future studies, we plan to combine fieldwork, deep learning methods with high-resolution remote sensing data to extract afforestation at different time scales and analyze afforestation at different time and space scales [33–36].

4.2. Impacts of climate change on large-scale afforestation

Forest plays an important role in regulating regional climate and has significant influence on regional hydrological cycle [37]. Afforestation can not only increase the carbon sink capacity of ecosystems, reduce the impact of climate change [38], but also decline the surface temperature and reduce the occurrence of drought events [39]. The spatial heterogeneity of precipitation results in the change of afforestation activities from east to west in Inner Mongolia. From east to west, the planting of tree species has changed from trees to shrubs, and the ecological function has changed from water conservation to wind protection and sand fixation [40,41]. The suitable density of afforestation was related to climate, it was determined by the water balance of the soil-vegetation system: a part of the rain falls on the soil and evaporates into the atmosphere, and the other part of the rain penetrates the soil to replenish the groundwater and maintain the normal growth of plants [42]. When the density of afforestation exceeds the water supply capacity of the region, it means that groundwater was consumed faster, which affects the survival of vegetation and creates greater ecological risks [43,44].

4.3. The impact of large-scale afforestation on the water resources and ecological environment

Some studies show that the water consumption associated with afforestation is greater than that of natural vegetation [45]. The forests' water consumption increases significantly, resulting in regional ecological water resources imbalance [2,16,46]. In addition, afforestation in arid and semi-arid areas, where precipitation is insufficient, will have an impact on groundwater recharge [47]. The precipitation is less in western Inner Mongolia than in eastern Inner Mongolia, and the vegetation is more dependent on groundwater. Afforestation increases vegetation coverage. Water consumption through vegetation canopy interception and vegetation transpiration increase as vegetation coverage increases. The soil water mainly moves upward, decreasing the groundwater recharge and groundwater table [7,48]. It is very difficult to restore the groundwater level once the water table depth has decreased [49], which suggests that these changes may lead to permanent decreases in the ground's capacity to store water [16,50]. At the same time, other studies have shown that afforestation can alleviate groundwater depletion in areas with sufficient precipitation [43,51,52]. Next, we will study the influence of afforestation on groundwater in different climate areas of Inner Mongolia.

Large-scale afforestation increases water consumption and may exacerbate land degradation, especially by planting fast-growing and short-lived vegetation [53]. In arid and semi-arid regions with sparse precipitation and large evaporation, the stability of the ecosystem is poor due to the simple species composition and structure. A large-scale vegetation restoration destroys the original stable state of the ecosystem [5]. In this process, the planted vegetation competes with the original vegetation for water, which changes the regional eco-hydrological processes and causes more severe ecological problems [54]. The decrease in groundwater depth causes the degradation of surface vegetation and land degradation [55]. In future studies, we will pay more attention to the impact of afforestation on regional groundwater depth.

4.4. Future ecological risks to afforestation

Afforestation in China, an expensive ecological restoration policy, has yielded far fewer returns than expected, with only 5-34% survival rates in the northwestern provinces [16,50]. According to China's ecological plan for the next 15 years, in order to achieve carbon neutrality and carbon peak,

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the national forest coverage rate will reach 26% by 2035, which indicates that China will continue its afforestation program in the future. Therefore, we suggest that: (1) To avoid afforestation in arid and semi-arid areas, so as not to cause a permanent decline in regional water storage capacity; (2) Selecting suitable vegetation according to local conditions is an important prerequisite for promoting ecological restoration and sustainable development [56]; (3) The formulation of an optimized groundwater extraction plan is one of the most effective management strategies to protect and maintain the current ecological environment and ecosystem [57–59]; (4) As the climate of the Inner Mongolia Plateau is warmer and wetter, the increase of precipitation in the future may reduce the ecological risks caused by afforestation [31,60].

5. Conclusions

Base on the land cover data, NDVI data and meteorological data, this study analyzed the ecological risks of water resources caused by afforestation in Inner Mongolia from 2000 to 2020. The results show that afforestation in Inner Mongolia had a specific impact on regional water resources. Water resources are scarce in Inner Mongolia, which cannot support the sustainable growth of large-scale forestland. Large-scale afforestation increases total water consumption, leading to regional water resource consumption and becoming a potential source of ecological risks in the region. Developing optimized afforestation schemes and improving water resource utilization efficiency are crucial to avoid potential ecological risks.

Author Contributions: Conceptualization, methodology, formal analysis, writing—original draft preparation, P.C.; writing—review and editing, project administration, funding acquisition, R.M. and J.S.; investigation, data curation, visualization, L.S., L.Z. and J.W. All authors have read and agreed to the published version of the manuscript.

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