Mapping rainfall interception for assessing ecological restoration sustainability in China

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Abstract
Ecological restoration (ER) programs play an important role in local and global climate change and carbon management policy interventions. Water resource is a key criterion for assessing the sustainability of ERs. Herein, we explored the spatiotemporal patterns of rainfall interception (RI, an important component of ecosystem water budgets), and its drivers after ER implementation in China. Further, we assessed whether ERs are sustainable by analyzing the trends of RI and water supply. As expected, we found that ERs caused an increase in RI in China from 2001 to 2018 (0.64 mm yr−1, p < 0.01). Changes in the normalized difference vegetation index and leaf area index contributed to a higher change in RI compared with other drivers. The decrease in RI was mainly recorded in the Qinghai–Tibet Plateau in Southwest, northern North, and southern Central and Southern China. Conversely, an increasing trend of RI was recorded in the Loess Plateau in Northwest, Northeast, and East China. Moreover, ERs are not always unsustainable in China, especially in Northeast, East, Central and Southern, and high-latitude regions of northern North China. Even in the Loess Plateau, which was criticized by previous studies, the unsustainability occurred only in the semi-humid region. Future ERs should be prioritized in southern parts of Eastern, Central, and Southern China, and must be appropriately considered in the Northeast and high-latitude regions in North China. It should be alert to the pressures of ERs on water supply, and its demand remains vigilant in the Qinghai–Tibet Plateau and semihumid areas of the Loess Plateau. This study provides new ideas for accurately evaluating the impact of ERs on water security and the sustainability of ERs.

1. Introduction
To mitigate global warming, cope with the devastating environmental crisis, and strengthen the ecosystem carbon-sink base support, ecological restoration (ER) programs pertaining to afforestation and forest restoration measures are being promoted and implemented by increasing number of institutions and governments around the world. However, this has also raised reflections on potentially conflicting demands for water between ecosystems and humans [1]. Water resources undoubtedly play a vital role in the spatial layout of ERs [2], and the changes in hydrological cycle processes and ecosystem water supply services are the key to assessing whether ERs are sustainable. Whether ERs weaken the water supply services of ecosystems remains a controversial issue. Although more scholars claim that the increased vegetation cover due to ERs can have a (limited) negative impact on regional water supply [3, 4], the results from paired watershed trials suggest otherwise [5, 6]. At a regional scale, most previous studies focused on the changes in the key hydrological cycle components (e.g. runoff and evapotranspiration) after...
ER implementation, as the medium for exploring whether ERs are sustainable [1, 7]. Assuming that precipitation does not change owing to the vegetation greening, large-scale afforestation activities may decrease regional runoff and increase evapotranspiration [8]. However, the decrease in runoff could be a consequence of an increase in water withdrawal owing to rapid socio-economic development [9, 10]. The increase in evapotranspiration could be an inevitable consequence of the increase in transpiration, which is triggered by large-scale revegetation; transpiration accounts for 60%–90% of terrestrial evapotranspiration [11, 12]. Moreover, precipitation variation due to vegetation changes, which may cancel out the enhanced evapotranspiration, should not be ignored [13]. Therefore, previous studies may have overestimated or underestimated the positive or negative effects of ERs on regional water security issues, thus failing to accurately identify the sustainability of ERs.

Rainfall interception (RI) is defined as the process of redistributing the total amount of rainfall falling on vegetation surfaces (figure 1(a)). The amount of RI is often non-negligible [7], which may account for at least 25% of annual precipitation [14, 15]. Unlike evapotranspiration and runoff, variations in RI are only influenced by the changes in climate and vegetation resulting from the implementation of ERs.
[14, 16]. Water supply change is an essential indicator for assessing the sustainability of ERs, as it is the final result of changes in the hydrological cycle induced by ERs [5, 7]. Examining the spatial relationship between RI and water supply in the context of ERs implementation is essential to scientifically assessing the impact of ERs on regional water security and the sustainability of ERs. The vegetation cover is bound to increase after ER implementation. If the regional environment degrades (e.g. reduced precipitation) due to ER implementation, RI may decrease or increase. Assuming that RI and water supply are correlated, and the increase in RI is accompanied by a decrease in regional water supply or the decrease in RI is accompanied by an increase in regional water supply, the vegetation restoration policy may fail, indicating the unsustainability of ERs. Conversely, if the increase in RI is accompanied by an increase in regional water supply, the implementation of ERs enhances the ecosystem water supply service function, indicating the sustainability of ERs (figure 1(b)). However, to the best of our knowledge, no study has currently explored the sustainability of ERs from this regard.

Accurate quantification of RI is essential to further elucidating the impact of change in vegetation on the change in hydrological cycle components, such as runoff and soil moisture. With the development of remote-sensing technology, experts and institutions have recently performed studies on the estimation of RI at a regional scale. The technique of RI estimation at the regional scale based on multisource remote-sensing data, represented by the RS-Gash model, has been well-established, widely validated, and used in the watershed or global scale [17–21]. However, the investigation of the spatial heterogeneity of the factors driving RI changes based on high-resolution RI data needs to be strengthened.

China launched a series of ERs, which led to the greening of the world. Some studies have examined the changes in key hydrological processes in particular geographic regions in China as a result of ER implementation to determine whether the ‘forest–water balance’ is disturbed [1, 22–24], but controversy remains. Furthermore, some studies have investigated the changes in hydrological cycle components, such as runoff, soil moisture, and evapotranspiration, which resulted from ERs [25, 26]. However, the knowledge of how RI, an essential component of the ecosystem water budget, will change with respect to the implementation of ERs in China should be enhanced.

Therefore, China was examined in this study. The spatiotemporal pattern of RI in China during the implementation of the ERs (2001–2018) and drivers influencing RI were explored. Herein, the sustainability of ERs in China is discussed on the basis of the relationship between RI and water supply during the study period, and recommendations are provided for the future spatial layout of ERs. This study aims to answer the following:

(a) How will RI change at the national scale under ERs implementation and climate change? The change in RI is driven by the vegetation factor or the meteorological factor?
(b) Are the ERs in China sustainable in terms of water security? If not, how should the spatial arrangement of the ERs be adjusted in the future?

2. Materials and methods

2.1. Datasets and processing

Table S1 shows the primary datasets used in this study. The original 16 day normalized difference vegetation index (NDVI) and 8 day leaf area index (LAI) composite data were summarized as monthly data using maximum value composite approach [27]. Monthly gridded meteorological data from 2001 to 2018 were interpolated by ANUSPLIN software with a spatial resolution of 1 km [28]. Figure S1 shows the locations of the meteorological stations involved in the interpolation. All data were processed to a spatial resolution of 1 km using the nearest-neighbor resampling method, and they were projected into the same coordinate system (WGS_1984_Albers). Considering data availability and model self-assumptions, it was assumed that land-cover types do not change during the year and monthly data are the same for each day within the corresponding month.

2.2. Geoclimatic region

In this study, we divided mainland China into six geoclimatic regions, i.e. Northeastern China (NEC), North China (NC), Northwestern China (NWC), East China (EC), Southwest China (SWC), and Central and Southern China (CSC), based on the characteristics of the climate, geography, and economic development, as shown in figure 2. However, Hong Kong, Macao, and Taiwan were excluded from the study area because of the data collection limitations.

2.3. Methods

2.3.1. RI and water supply

RI was estimated using the RS-Gash model (see supplementary methods), which has been proven its usability at the watershed and global scale [17–21]. The base data input to the model include meteorological data (i.e. temperature, wind speed, atmospheric pressure, and relative humidity), daily rainfall and rainfall intensity, and NDVI and LAI. The detailed model description are given in previous studies [17, 18, 21]. Vegetation cover fraction was derived using the dimidiate pixel model [29] based on the NDVI dataset. Meteorological data were used to estimate the mean evaporation rate per unit vegetation cover from saturated vegetation surfaces using
Figure 2. Six geoclimatic regions (a) and climatic humid conditions zoning (b) in China.

the Dalton equation [21]. RI was estimated on a daily scale, and the results were subsequently accumulated as annual scales to explore RI’s spatial and temporal distribution characteristics. Notably, RI is defined as no data if the land-cover type is unvegetated (e.g. urban and built-up lands, barren land, and water bodies).

According to the water-balance equation [1], water supply is simplified to be the difference between the annual precipitation and annual evapotranspiration (equation (1)). This is a permitted method by many previous studies [30–32]. We calculated yearly water supply for each grid from 2001 to 2018:

\[
Ws = PRE - ET = \Delta R + \Delta RW + \Delta SW + \Delta GW
\] (1)

where Ws is the water supply, PRE is the precipitation, ET is the evapotranspiration, and \(\Delta R\), \(\Delta RW\), \(\Delta SW\), and \(\Delta GW\) are annual changes in runoff, river–reservoir water storage, soil water storage, and groundwater storage, respectively.

2.3.2. Trend and correlation analysis of variables

Nonparametric Mann–Kendall (MK) test and Theil–Sen median slope analysis (Sen) were used to analyze the trend changes in variables. These tests are widely used for assessing meteorological and hydrological data series trends [33, 34]. Based on the absolute value of the Z parameter of the MK test, a predefined rule was used: the trend is defined as significant if \(|Z| > 1.96\), i.e. \(p \leq 0.05\), marginally significant if \(1.64 \leq |Z| < 1.96\), i.e. \(0.05 < p \leq 0.1\), and nonsignificant if \(|Z| < 1.64\), i.e. \(p > 0.1\). Furthermore, Pearson correlation analysis was employed to examine the correlation between water supply and RI.

2.3.3. Calculation of contribution

Differential equations were used to estimate the contribution of changes in the driving factors (i.e. LAI, NDVI, precipitation, relative humidity, temperature, and wind speed) to the RI variations. Referring to [35], the long-term trend of RI is separated into the following:

\[
\frac{dRI}{dt} = \sum_{i=1}^{n} \frac{\partial RI}{\partial x_i} \times \frac{dx_i}{dt} = \sum_{i=1}^{n} C_i
\] (2)

where \(x_i\) is the \(i\)th driving factor, \(\frac{dRI}{dt}\) and \(\frac{dx_i}{dt}\) are the long-term trend of RI and \(x_i\), respectively; \(\frac{\partial RI}{\partial x_i}\) is the slope of the linear regression curve between RI and \(x_i\); \(C_i\) is the contribution of \(x_i\) to the responsible variable. Subsequently, \(C_i\) was expressed as the relative contribution (CRi) that visualizes the positive and negative contributions of the factors (equation (3)):

\[
CR_i = \frac{C_i}{\sum_{i=1}^{n} |C_i|}
\] (3)

2.4. Validation program

Here, the estimated RI was resampled to the same resolution as that of the RI data in the Global Land Evaporation Amsterdam Model (GLEAM) dataset, and it was compared pixel by pixel to examine the accuracy. Given the length of the time series of GLEAM data, the validation program is only used for data from 2003 to 2018. The Nash–Sutcliffe efficiency coefficient, normalized root-mean-square error, and mean absolute error (MAE) were used to assess the accuracy of the estimated RI (table S2). The results show that the estimated results agree well with the RI data of GLEAM (figure S2).
Furthermore, the Web of Science (www.webofscience.com) and China National Knowledge Infrastructure (www.cnki.net) databases were searched using the terms ‘rainfall interception’, ‘interception loss’, or ‘canopy interception’. Articles were ignored if the study area was not within China, the location of the research sites was unclear, the actual measurements were not indicated, the measurements were not obtained under natural conditions, or the study period was not between 2001 and 2018. From the over 5500 bibliographic references found, 26 scientific articles published during January 2001 to December 2020 were retained for comparative validation (table S3). The results confirm that the estimated results are generally consistent with the filed measurements (figure S3).

3. Results

3.1. Spatiotemporal dynamics of RI

Figure S4 shows that except for SW, where the RI showed a nonsignificant increasing trend, all the other five geoclimatic regions and the entire China region (0.64 mm yr\(^{-1}\), \(p < 0.01\)) had a significant upward trend. Figures 3 and S5 show that RI was dominated by an increasing trend in all the six geoclimatic regions. NEC, EC, and CSC were primarily dominated by a significant increase in RI (55.0\%, 63.4\%, and 44.3\%), whereas NC, NWC, and SWC were dominated by a nonsignificant increase in RI (35.0\%, 35.0\%, and 34.4\%). Spatially, the decreasing trend of RI occurred mainly in northern NEC, northwestern and southern NWC, most areas of SWC, and north, central, and southern CSC. However, the increasing trend of RI was observed mainly in eastern NWC, most areas of NEC and EC, southern and northeastern NC, and northern CSC.

3.2. Driving factors of RI

The contribution of NDVI to RI is highly similar to that of LAI to RI in terms of spatial patterns, whereas the contribution of LAI is slightly higher than NDVI in NEC (figure 4). The high positive contributions of NDVI and LAI to RI are concentrated in most of the NEC, southern NC, eastern NWC, northern EC and CSC, and southeastern SWC regions. However, the negative contribution is concentrated in northern NC, southwestern NWC, central and western SWC, and southern CSC. The positive contribution of precipitation to RI is mainly distributed in NEC, NC, and NWC, whereas the positive contribution is sporadically distributed in SWC, northwestern NWC, and northern EC. Relative humidity, temperature, and wind speed negatively contributed in northern NC, southern and western SWC, and northern CSC. The high positive contribution of wind speed to RI is concentrated in the western NEC, southeastern NC, southeastern NWC, northern EC, and central, northern, and southern CSC regions. On average, the contributions of almost all drivers are positive in all the six geoclimatic regions, except for the relative humidity in NC, NWC, and SWC and temperature and wind speed in NC and SWC. LAI had the largest contribution to RI in NEC, whereas NDVI had the largest

![Figure 3. Spatial variation of annual RI in the six geoclimatic regions of China from 2001 to 2018.](image-url)
contribution to RI in NC, NWC, EC, SWC, and CSC (figure 5). The absolute contribution of wind speed in EC is higher than that of LAI.

3.3. Relationship between water supply and RI
There is mostly a weak positive or negative correlation between RI and water supply. The majority of the correlations do not pass the significance test (figure 6). Strong negative correlations are mainly concentrated in eastern NWC, southern NC, and western SWC, whereas strong positive correlations are observed in most of the NEC, northern and northeastern NC, central NWC, central and southern EC, and southern CSC regions. Strong positive correlations account for 71.8% of those that passed the significance test ($p < 0.05$), mainly in NEC, NC, and EC, while strong negative correlations account for 9.1%, mainly in NWC and SWC.
4. Discussion

4.1. Spatiotemporal variation of RI and its driving factors

All of China is dominated by a significant increase in RI from 2001 to 2018 (figure 3). This dominance is primarily attributed to the large-scale afforestation activities implemented since the 1980s [36]. In particular, the Loess Plateau region, located in eastern NWC, has benefited from the world-renowned Grain to Green Program implemented in 1999 [37]. This program has led to tremendous improvements in vegetation and the environment [38], and LAI and NDVI were greatly enhanced (figure S8). Thus, the increase in RI in the region was high (figure 3). Moreover, the regions located in southern CSC are the main battlefields for the Forest Industrial Base Development Program [39]. This implies that large areas in these regions undergo forest plantation to address the supply and demand of timber and forest products in China, and that rotational logging is the main measure for forest management. Although the afforestation species in CSC are mainly fast-growing forests and annual maximum NDVI and LAI do not exhibit large-scale decreasing trends (figure S8), there is no indication that NDVI and LAI are increasing continuously and steadily. Nevertheless, the impact of rotational logging on regional climate may still be significant [40]. Therefore, although there was an increasing trend of precipitation in these regions owing to the influence of monsoon and cyclones (figure S7), the RI still showed a decreasing trend.

The ERs implemented in arid regions and climate wetting appear to increase RI (e.g. in NWC). However, climate warming and reduced relative humidity due to increased wind speeds probably decreased RI in northern NC (figures 3 and 4). Thus, the negative impact of poor climate change on RI in the arid regions may overpower the positive impact of the increase in vegetation cover due to human activities on RI, thus leading to the decreasing trend of RI in these regions. However, increasing trends of RI are observed in the vicinity of Otindag Sandland, Inner Mongolia. This increase implies the effectiveness of generations of efforts to improve the regional environment, although the affected area is still limited.
Notably, an extensive decreasing trend of RI is observed in SWC (figure 3). This decrease is due to wind speed, which serves as the primary negative driving factor (figures 4 and 5). Previous research claims that China’s ‘surface quiescence’ may have ended in 2014, and subsequently the surface wind speed entered a significant enhancement phase [41]. An increase in wind speed results in more precipitation dripping from the canopy, leading to less precipitation diverted to RI. Conversely, the continued decrease of wind speed in coastal areas causes wind speed to be a factor driving the increase in RI.

Moreover, wildfires may contribute to the vegetation destruction in southern SWC and central SWC. The ecosystems in these regions are commonly reported to be fire-prone [42–44]. Climate warming coupled with human activities such as over-grazing and mining may lead to severe vegetation degradation and desertification in local areas [45]. All of the above-mentioned possibilities are reflected by the decrease in NDVI and LAI, and the deterioration of environmental drivers in SWC (figure S8), leading to a decrease in RI. It is clear that the government has implemented a series of ecological conservation and restoration programs and policies in the region to promote regional vegetation recovery [25]. Nevertheless, the effect of current conservation and restoration measures is limited in local areas. In the future, ecological conservation and restoration efforts should be increased by balancing ERs and human development, and incorporating the characteristics of ecosystems and climate change.

### 4.2. Sustainability assessment of ERs

There was a significant negative correlation between RI and water supply in the Loess Plateau region in eastern NWC and southern NC (figure 6). This implied that the ER in the region may be unsustainable. This is consistent with previous studies [1, 46–48]. Certainly, it is unnecessary to veto the ER of the Loess Plateau because such unsustainability is concentrated in its southern region. This claim supported the opinion that the ER of the Loess Plateau should not be further promoted in the semi-humid regions, but rather in the arid and semi-arid regions, especially in the desert [49]. Additionally, unsustainable ERs are found near the Qinghai–Tibet Plateau located in western SWC. A previous study suggested that the Chinese government should protect the natural vegetation in the Qinghai–Tibet Plateau instead of planting more trees because large-scale afforestation accelerated the water consumption in this region [25]. This increase in water consumption and climate warming could lead to water shortages in the region. Furthermore, land degradation in the Qinghai–Tibet Plateau due to natural and anthropogenic factors should be monitored [50, 51]. This degradation may be a reason for the decreasing RI and water supply in the region, although the decreased precipitation must inevitably be responsible for the decrease.

To cope with climate change and keep its promise of achieving carbon peaking and neutrality before 2030 and 2060, respectively, the Chinese government has recently released a series of government documents and reports to plan ERs [52, 53]. Such measures should be implemented while considering their sustainability from the perspective of water resources. Considering the ability of the correlation between RI and water supply to assess the sustainability of ERs and the current increasing disparity between water supply and demand situations in China (figure S9), we suggest that the future ERs in China should be prioritized in the southern part of both CSC and EC. These regions have abundant water resources and low water-use intensity. Moreover, it is necessary to continue implementing ERs in these regions to resolve a series of environmental issues including poor forest quality, single species of afforestation, and degraded ecological functions in some regions [54]. Assuming that the sustainability of ERs remains unchanged, future ERs implemented in these regions could still increase the water supply. Subsequently, water stress in the Bohai Economic Rim and Yangtze River Delta urban agglomerations could be relieved by large water conservancy projects such as the South-to-North Diversion Project. Moreover, we suggest that ERs can continue to be implemented in NEC and high-latitude regions in NC, where most of the cities are characterized by heavy industries and traditional agriculture. The contradictory relationship between regional water-resource supply and demand has been moderated because of government measures such as the comprehensive promotion of water-saving society, vigorous water-saving irrigation projects, and improvement of water-resource reuse rate. ERs can be implemented in the future to increase sustainable water supply and total water resources, and achieve self-sufficiency in water resources. For the fragile ecosystems typified by the Loess and Qinghai–Tibet Plateaus, the government should not unilaterally keep pursuing greening areas and coverage, but rather should emphasize the ecosystem self-repair process and sustainability of artificial ERs, including the sustainability of water resources and greening. For the semi-humid regions of the Loess Plateau, scientific forest nurturing and management should be conducted to decrease or retard the increase in the water security problems caused by high-density afforestation in the early stage, thus alleviating the pressure on the water yield in the Yellow River due to the high water consumption in regions such as Ningxia, Shanxi, and Shaanxi. For ERs in the Qinghai–Tibet Plateau and northern NC, it is necessary to give importance to the ecological protection.
and restoration of grassland, implement measures of grassland grazing prohibition and rotation, fully promote the balance of grass storage, perform artificial grass planting, improve natural grassland, and avoid a series of catastrophic results due to the reduction of total water resources.

4.3. Limitations and uncertainties
Recent studies suggested that through land-atmosphere interactions and atmospheric transport, ER could enhance local precipitation or affect climate or water supply over wider regions [55–57]. However, these effects are complex and not considered in our calculations. Furthermore, we examined China’s ER sustainability only by quantitatively describing RI versus water supply using only water as a medium. Other benefits from RI changes after ER implementation have not been considered, such as reduction of soil erosion, improvement of potential economic benefits, and enhancement of human wellbeing. Further research should construct a comprehensive ER sustainability assessment framework with interdisciplinary fusion, and among this, RI should not be neglected.

The choice of precipitation dataset and the interpolated meteorological data may introduce uncertainty in the estimated results. The China Meteorological Forcing Dataset (CMFD) selected in this study has proven its validity in mainland China [58]. We compared the uncertainty between different precipitation products using the generalized three-cornered hat method (see supplementary methods) based on annual data [59]. The standardized uncertainty and signal-to-noise ratio of CMFD are both less than the remaining datasets, ranging from 0 to 0.2 and 0.2 to 0.4, respectively (figure S10). Moreover, we compared the meteorological data from stations not involved in interpolation with the interpolated data at the annual scale. The multi-year MAE of temperature ranged from 0.28 to 0.39 °C, that of relative humidity ranged from 0.99% to 2.47%, that of atmospheric pressure ranged from 0.44 to 0.52 kPa, and that of wind speed ranged from 0.27 to 0.4 m s⁻¹ (figures S11–S14). The multi-year RMSE for each climate factor approached zero. Furthermore, we used the same principle as that used in the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model to calculate the water supply in the grid cells, which was equal to the annual precipitation minus evapotranspiration. However, unlike the InVEST model, we did not recalculate the evapotranspiration and directly used an existing dataset, i.e. MOD16A2 (V 006). This dataset has been validated and widely used [33, 60, 61]. Thus, the impact of the self-limitation of the InVEST model on the quantitative study of water supply was avoided to some extent, such as inadequate regionalization corrections for parameter w (the plant water utilization coefficient, dimensionless), which is often set as a constant [62].

5. Conclusion
This study indicated that, overall, an increasing trend of RI in China was observed from 2001 to 2018. The decreasing trend of annual RI was widely concentrated in NC and SWC, and slightly distributed in EC and CSC, whereas the increasing trend was mainly concentrated in NEC and NWC. Vegetation factors (NDVI and LAI) dominated the change in RI in the six geoclimatic regions. The spatial correlation between RI and water supply indicated that ERs are not always unsustainable in China, especially in NEC, EC, CSC, and the high-latitude regions of northern NC. As confirmed by previous studies, large-scale afforestation activities conducted on the Loess Plateau exerted additional pressure on water supply in its semi-humid region, and these were considered unsustainable ER policies. Our study recommends that future ER implementation should be prioritized in CSC and southern EC, and these ERs can continue to be considered in NEC and the high-latitude regions in NC. However, expanding investment in ERs for achieving large afforestation area is not recommended until the security of water supply and demand is addressed in the semi-humid areas of the Loess Plateau. Constant vigilance is required to determine the negative impact of ERs and climate change on the water supply in the Qinghai–Tibet Plateau to avoid irreversible catastrophic consequences from the large-scale decrease in water supply in the region. Future emphasis should be given to the assessment of the role of RI on the sustainability of ERs.

Data availability statement
The data that support the findings of this study are available upon reasonable request from the authors.

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