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Forestation and Hydrology: Lessons Learned from China

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Abstract: China's unprecedented forest-based ecological engineering programs over the past several decades present a unique opportunity to understand forest-water interactions at a large scale. This review synthesizes advances of forest hydrological studies in China in the context of dramatic forest cover recovery, hydrologic change, and a shift in land management policy. We review current monitoring networks and research tools and key ecohydrological processes influenced by massive national forestation, including increases in evapotranspiration and carbon sequestration, decline in total water yield, significant reductions in soil erosion, and trade-offs among ecosystem services. We discuss lessons learned and identify critical research gaps in understanding hydrologic responses to shifts of land management policy from international perspectives. We conclude that while enormous progress has been made in understanding forest-water relations in China, long-term watershed-scale studies are needed to fully characterize the diverse forest hydrologic processes across China's vast landmass. Continuously monitoring and assessing hydrologic recovery processes and consequences is critical to sustaining ecological restoration programs under a changing environment. **DOI: 10.1061/JHYEFF.HEENG-6795.** *© 2026 American Society of Civil Engineers.*

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Introduction

The intimate relationships between forests and water and soil conservation have long been recognized by traditional wisdom in eastern Asia, encapsulated by the popular saying *Shui Yuan Han Yang* (i.e., forests preserve/conserve/protect water). Scientifically, however, the rigorous study of forest hydrology in China began relatively late. Before the 1980s, only a few isolated experiments examined how forests influence streamflow and soils. For instance, small watershed comparisons in the Yellow River basin in the 1960s and thinning impact studies on dark coniferous forests in the upper Yangtze River basin in the 1950s found that forest cover can reduce annual surface runoff and is favorable for water retention (Liu and Zhong 1978; Ma 1993). Modern forest hydrology research in China was catalyzed in the 1980s by urgent environmental issues. Severe soil erosion, periodic devastating floods (e.g., in 1981 and 1998), and water scarcity in northern regions underscored a lack of scientific knowledge to guide watershed management (Guo et al. 2005; Ma 1993; Zhang et al. 2004). In response to these challenges and concurrent with China's economic reforms, the government launched ambitious nationwide forestation and soil conservation programs. This provided impetus and funding for systematic studies of forest-water relationships. Particularly, the past two decades have witnessed a dramatic rise in Chinese forest hydrology literature (Sun et al. 2006, 2023b; Wei et al. 2008). Now China has the world's largest area of plantation forests and the total forest cover exceeds 24% of the country's land area, owing to massive tree planting efforts since the late 20th century. These transformations make China a valuable *natural laboratory* to study the hydrological effects of large-scale land cover change.

This article reviews the lessons learned about the forestation effects on hydrological processes in China to serve as an update of previous retrospective synthesis of China's forest hydrology studies (Wei et al. 2008). We first recount the history of forest cover change in China and the parallel development of forest hydrology as a research field. We then examine major advancements in monitoring and modeling techniques that have enabled recent studies. Next, we synthesize key findings on how forestation has affected hydrological processes, including evapotranspiration, water yield, and soil erosion, and the trade-offs among different ecosystem services. Finally, we discuss remaining knowledge gaps, data limitations, and the implications of China's forest hydrology research for both domestic and global land and water resources management policies before concluding with recommendations for future research directions.

Historical Perspectives

The development of forest hydrology as a scientific field in China has been tightly linked with the national land management policies. In this section, we first summarize the country's major forestation programs since 1949 and then trace the evolution of forest hydrology research, highlighting milestones in observations, experiments, and modeling that underpin later sections.

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Table 1. The six key ecological restoration projects in China

Projects	Start date	Scope	Investment	Achievements
Three-North Shelter Forest Program	1978	North, Northeast, and Northwest	Over 120 billion CNY	Afforested 32 million ha
Yangtze River and Zhujiang River Shelter Forest Projects	1989	Yangtze River and Zhujiang River basins	~212.9 billion CNY by 2020	Afforested 21.7 million ha by 2020
Natural Forest Protection Project	1998	State-owned forests	Over 500 billion CNY	Protected 130 million ha natural forests; Completed 20 million ha forest construction
Grain for Green Project	1999	Upstream regions of major river basins	~211.3 billion CNY	Restored ~26.9 million ha land (1998-2008)
Beijing-Tianjin Sand Source Control Project	2001	Beijing, Tianjin, Hebei, Shanxi, Shaanxi, and Inner Mongolia	~55.8 billion CNY (2002-2012) ~87.8 billion CNY (2013-2022)	Afforested 9 million ha
Returning Grazing Lands to Grasslands Project	2003	North and Southwest	18.5 billion CNY by 2010	Completed 51.6 million ha fenced enclosures

Major Forestation Programs (1949–)

China's forest cover has undergone dramatic changes over the past century due to human activities and subsequent restoration efforts. Widespread deforestation and land reclamation for food in the China's long history led to severe soil erosion and degraded watersheds. Since 1949, the founding of the People's Republic of China, the national forest cover trend can be divided into three stages (Zhang and Song 2006): a transition stage (1949–1981) marked by net forest loss, a slow increase stage (1982–1993), and a rapid increase stage from 1994 onward. In the late 1970s, the government began investing heavily in ecological restoration projects to counter environmental damages (Lu et al. 2018) (Table 1). Notable among these initiatives is the Three-North Shelterbelt Program (so called the *Green Great Wall* started in 1978), which aimed to establish extensive windbreak forests across northern China to control wind erosion and mitigate dust storms (Zhu and Zheng 2019). Later, as China's economy improved, the *Grain for Green* Program (also known as the Returning Farmland to Forest Program) was launched in 1999 in the provinces of Sichuan, Shaanxi, and Gansu, offering farmers and local governments incentives to convert steep croplands back to forest or grassland (Shao et al. 2022). Between 1999 and 2008 alone, the Grain for Green Program restored an estimated 26.9 million hectares of land, including ~9.3 million ha of tree plantations on former farmland and ~17.6 million ha of forestation on barren land. In parallel, the Ministry of Water Resources implemented large soil and water conservation projects (starting in 2002) that established demonstration sites across dozens of provinces to increase vegetation cover on erodible slopes. Since 2016, China's commitment to "Ecological Civilization" as a national policy has further intensified ecological restoration efforts: the government invests roughly 10 billion CNY (~1.4 billion USD) each year in integrated restoration projects for mountains, rivers, forests, farmlands, lakes, grasslands, and deserts nationwide. Total investment in these projects from 2021 to 2030 is expected to exceed 250 billion CNY, targeting the rehabilitation of an additional 10 million hectares of lands.

As a result of these sustained efforts, China's forest cover has expanded rapidly. By 2020, planted forests alone accounted for about 0.77 million km^2 (roughly 77 million hectares), which is 31% of the world's planted forest area (Cheng et al. 2023) (Fig. 1). Over three-quarters of China's plantations are concentrated in the eastern, south-central, and southwestern regions of the country (Tong et al. 2023). Including natural forests, overall forest cover in China has risen to over 24% in recent years, a stark increase compared to the low point in 1980 when only ~12% of the country was forested. This massive forestation represents the largest land cover transformation program in the world, fundamentally altering China's terrestrial surface and hydrological responses.

Emergence of Forest Hydrology Research

The rapid advances of forest hydrology as a scientific discipline in China closely followed the nation's environmental crises and restoration programs (Fig. 2). Although traditional observations of forest-water interactions have a long history in China, organized scientific study began much later than those in the western countries. Early pioneering studies in the 1950s–1970s provided valuable yet fragmentary insights into the subject. For example, a small watershed comparison study in 1960s in the Loess Plateau found that forested catchments yielded less annual runoff than non-forested ones, highlighting forests' role in reducing streamflow and enhancing groundwater recharge (Liu and Zhong 1978). Forestry researchers in Sichuan observed increases in runoff and soil erosion after forest thinning, underscoring forests' importance in retaining water and soil (Ma 1987, 1993). These isolated studies, however, did not coalesce into a broad research field at the time.

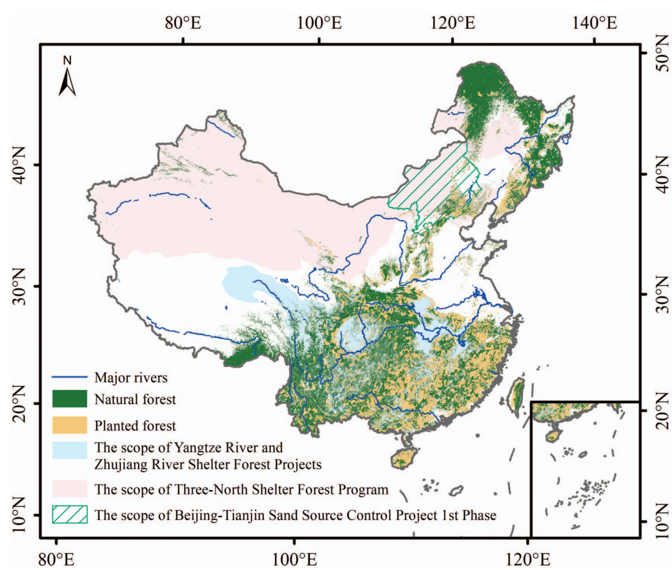

Fig. 1. (Color) Spatial distribution of planted forests and selected national ecological restoration projects in China.

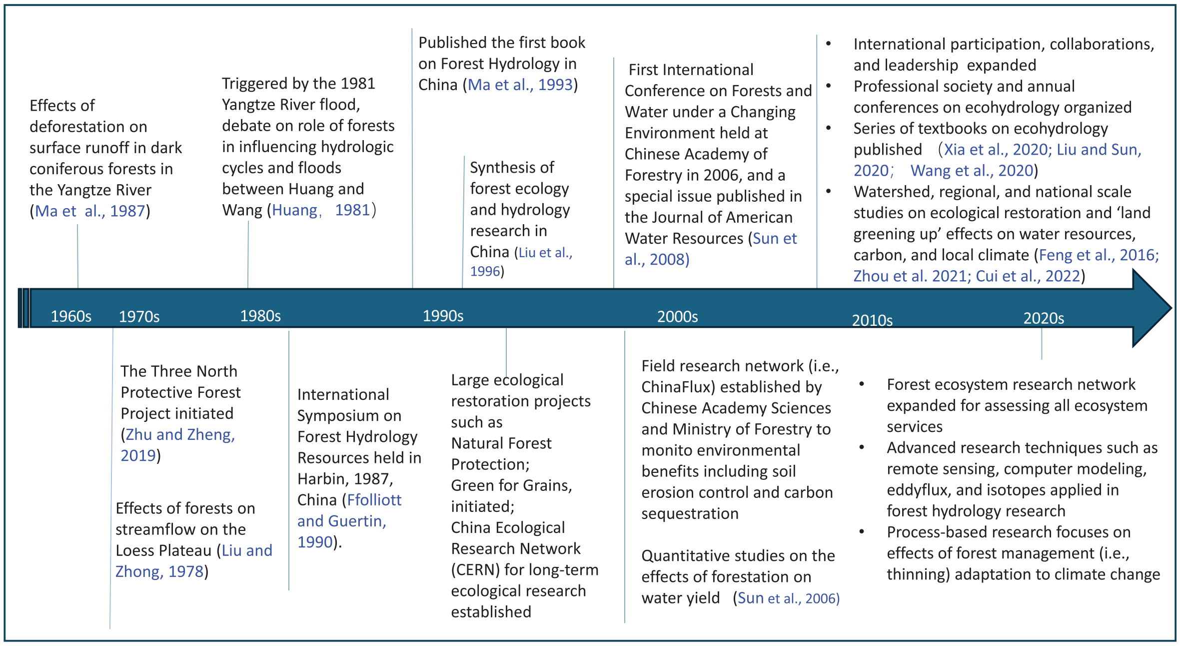

Fig. 2. (Color) Timeline of selected milestones of China's progressive forest hydrological research driven by key land management policies.

It was not until the 1980s that modern forest hydrology research in China truly gained momentum (Zhang et al. 2004). The major trigger was the urgent need for scientific guidance on watershed rehabilitation as China embarked on large-scale soil erosion control and forestation projects during its reform era (Guo et al. 2005; Wei et al. 2008). In 1980, China's forest cover had dropped to a historic low (<9%), while urgent environmental problems such as catastrophic floods, sediment-choked rivers, and reservoir siltation demanded actions. Researchers and policymakers were both concerned with several questions: Would planting trees alleviate flooding and droughts? How much forestation could curb the nation's severe soil losses? With no long-term experimental data available, reliable answers were few and sometimes controversial (Ffolliott and Guertin 1990; Huang 1981; Liu et al. 1996). The devastating Yangtze River floods of 1998 became a turning point that killed more than 2,000 people, prompting a nationwide logging ban in natural forests and a sharp increase in ecological funding. Over the next two decades, Chinese scientists launched numerous studies on forest hydrology, often adapting international research approach such as the Long Term Ecological Research (LTER) Network to domestic conditions. By the 2000s, forest hydrology had emerged as a recognized research domain in China, with dedicated programs and growing publications (Sun et al. 2008). A series of textbooks on ecohydrology were also published in recent years (Liu and Sun 2020; Wang et al. 2020; Xia et al. 2020).

The extensive forest cover changes have provided researchers with a rare opportunity to study forest-water relationships at regional to national scales far larger than traditional catchment experiments (Sun et al. 2006; Teo et al. 2022). Correspondingly, scientific output has surged. Especially since 2000, there has been exponential growth in Chinese forest hydrology literature (Wei et al. 2008), reflecting substantial advances in understanding how changes in forest cover influence hydrological processes and water balance across diverse climates (Sun et al. 2023b; Zhang et al. 2017). What started as a delayed and data-sparse field has evolved into an increasingly rich body of research, propelled by the scale of China's environmental initiatives. The historical lessons learned, both successes and ongoing debates, formed the foundation for current and future forest hydrology investigations in China.

Advances in Forest Hydrological Research

China's progress in forest hydrology research has been underpinned by parallel advancements in data collection methods and analytical tools. In recent decades, the country has dramatically improved its capacity to monitor forest hydrological processes and to simulate forest-water dynamics using computational models. These developments have expanded both the quantity and quality of information available for understanding forest hydrology.

Long-Term Ecosystem Monitoring Networks

Recognizing the need for continuous field observations, China began establishing forest ecosystem research stations as early as the late 1950s (Zhang et al. 2004). Some of the earliest stations, such as the Changbaishan Forest Ecosystem Station (Fig. 3) in northeast China, were set up to study forest ecology and later joined international programs (e.g., UNESCO's Man and the Biosphere network) in 1979. In 1988, the Chinese Academy of Sciences officially created the Chinese Ecosystem Research Network (CERN), integrating dozens of ecological field stations across the country. CERN consists of 44 long-term monitoring sites covering major ecosystem types (Fu et al. 2010; Xia et al. 2018). It is a founding member of the International Long-Term Ecological Research Network and the Global Terrestrial Observation System. Around the same time, the State Forestry Administration (now National Forestry and Grassland Administration) developed a parallel system focused on forests: the Chinese Forest Ecosystem Research Network (CFERN). CFERN has its roots in several experimental forestry stations established in the 1950s–1960s, and it expanded significantly after the 1980s (Niu et al. 2013). Currently, CFERN encompasses 73 forest ecohydrological stations spanning a wide range of climate zones and geographic regions in China. These stations are strategically distributed from tropical to boreal zones,

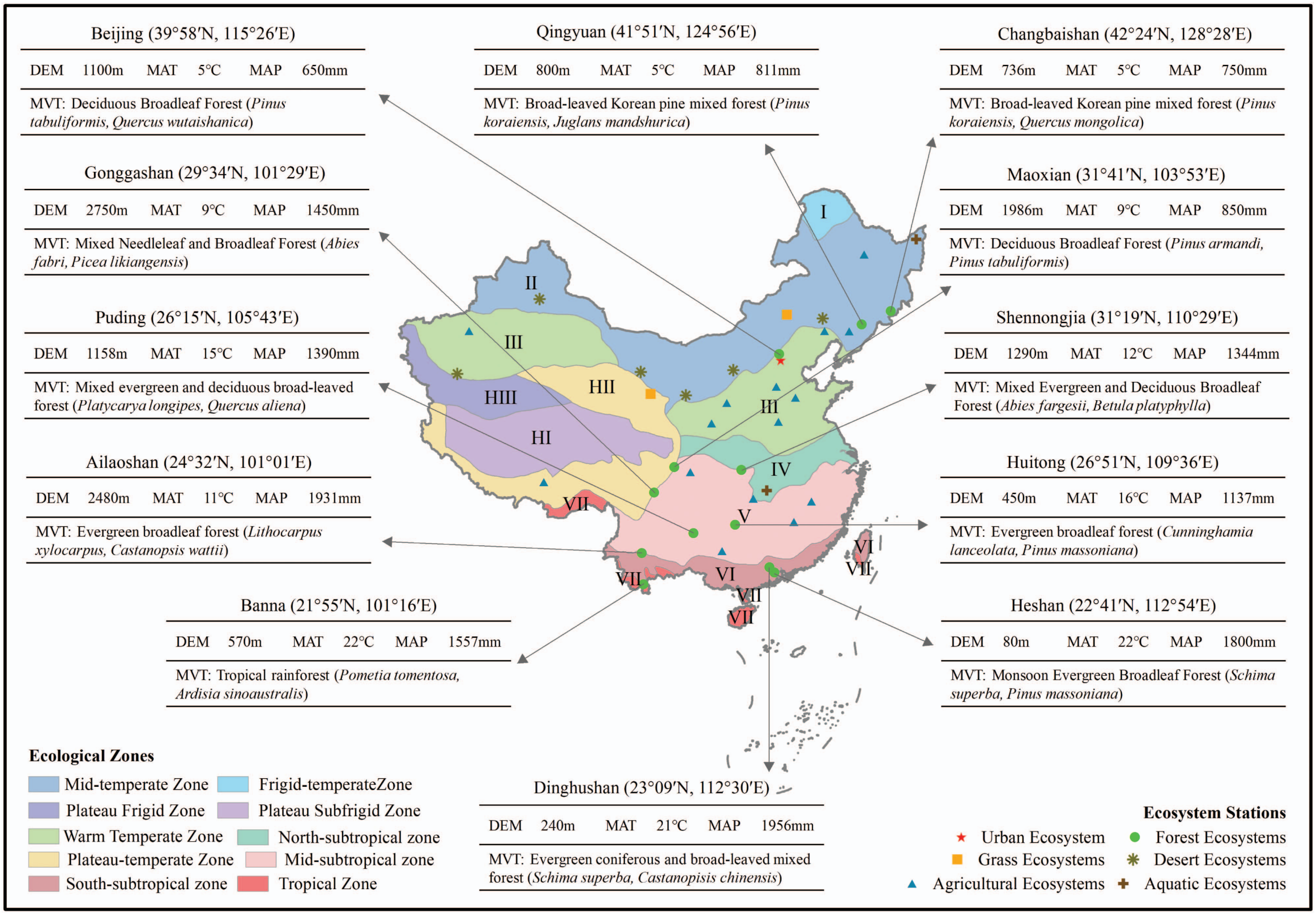

Fig. 3. (Color) Distributions of the Chinese Ecosystem Research Network (CERN) and information of elevation (DEM), mean air temperature (MAT), mean annual precipitation (MAP), and major vegetation types (MVT) for forest research stations.

capturing the heterogeneity of ecosystem types and environmental conditions. Standardized long-term measurements include hydrologic variables such as precipitation, throughfall, stemflow, soil moisture, runoff, and groundwater, as well as related meteorological and biochemical parameters (Wang et al. 2017). The primary goal of these networks is to document the ecohydrological behavior of ecosystems over time and improve understanding of regional differences (e.g., how a pine forest in arid northwest China might differ from a subtropical broadleaf forest in water-rich south China).

In addition to the permanent stations, a number of temporary or project-based research sites have been established to address specific questions. Many such sites were tied to key national forestry programs. For example, experimental plots under the Natural Forest Protection Program or the Three-North Shelterbelt project provided venues where researchers set up instruments to evaluate local effects on water yield and erosion. As a result, the observational infrastructure for forest hydrology has greatly expanded. A recent review of canopy interception studies found data from approximately 180 different forest sites across China, each with at least one year of interception measurements (Deng et al. 2024), demonstrating the breadth of field experiments now available.

Simulation Model Development and Applications

Alongside field observations, Chinese researchers have increasingly applied computational models to quantify forest-water interactions and predict outcomes under various scenarios. In the past few decades, advances in information technology, data availability, and environmental modeling have enabled the use of a wide spectrum of hydrological models in forested watersheds (Sun et al. 2007, 2023a). These models range from simple water balance equations (Wang et al. 2011) to more complex landscape distributed models (Zhang et al. 2008; Zhou et al. 2011). For example, conceptual water balance models (e.g., based on the Budyko framework) with one parameter have been widely used to estimate the long-term impacts of vegetation change on mean annual runoff at large scales (Zhou et al. 2021). Distributed hydrological models with detailed representations of soil-vegetation-atmosphere processes have been implemented for research in Chinese basins. Examples include: Soil and Water Assessment Tool for simulating land use and climate effects on watershed hydrology (Zhou et al. 2011); MIKE-Système Hydrologique Européen (MIKE-SHE), a coupled surface-subsurface model, used in northern China watersheds (Wang et al. 2012; Zhang et al. 2008); topography-based hydrological modeling system (TOPOG), a topography-based model applied in experimental forest catchments (Yu et al. 2010); Geomorphology-Based Hydrological Model for large river basins (Gao et al. 2015); Regional Hydro-Ecological Simulation System (RHESSys) for ecohydrological impacts of forestation (Peng et al. 2016); Hydrological Simulation Program-FORTRAN (HSPF) for evaluating rainfall and flow changes in rainforest watersheds (Zhou et al. 2017); and Water Supply Stress Index model China version (WaSSI-CN) for basin-scale

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water and carbon flux simulation (Song et al. 2025a, b; Zhang et al. 2021) (Fig. 4). Each model comes with different assumptions, structural complexity, parameter transferability, spatiotemporal scales, and data requirement, and researchers choose among them based on study objectives and data availability. A common practice has been to calibrate and validate these models against observed data from the monitoring networks, then use them to disentangle the effects of forest change from climate variability. Modeling studies have greatly advanced insights in cases where long-term experiments are lacking. Such tools have also allowed exploration of scenarios that cannot be tested empirically.

There is a trend toward more integrated modeling approaches that couple hydrology with ecological and climatic components. Recent models explicitly incorporate energy cycles, vegetation growth, topography, and biogeochemistry to better replicate forest hydrological processes at fine scales (Boardman et al. 2025; Gao et al. 2015; Marshall et al. 2021; Zhou et al. 2017). These sophisticated models are increasingly used to predict how changes in forest cover will interact with climate change and human water use, and to inform decision-making. The combination of expanded monitoring and advanced modeling in China has provided researchers

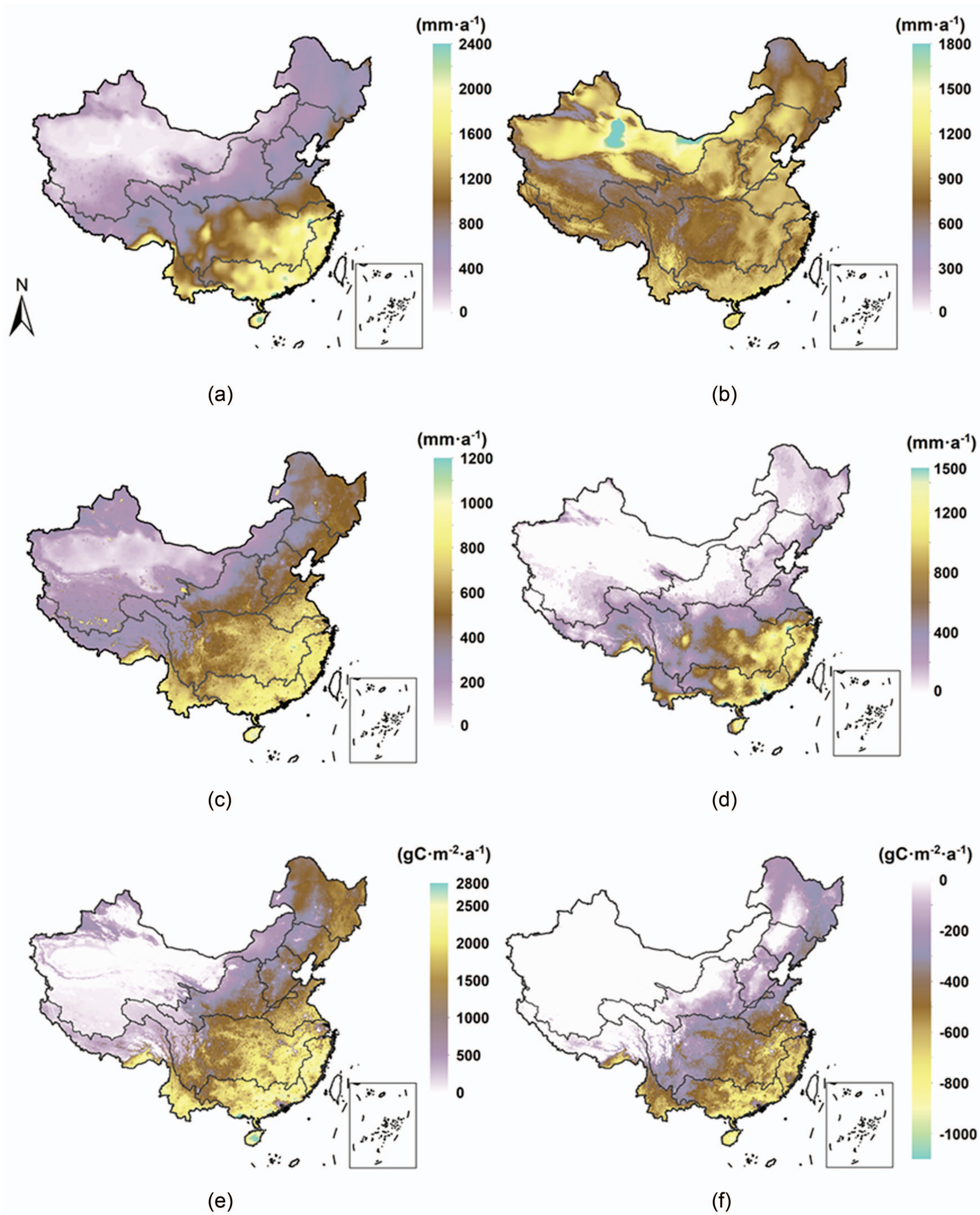

Fig. 4. (Color) Multidecadal average (a) precipitation; (b) potential evapotranspiration; (c) evapotranspiration; (d) water yield; (e) gross primary productivity; and (f) net ecosystem; exchange at 10-km resolution in China during 1982–2018 simulated by the WaSSI-CN model.

with powerful tools. High-resolution satellite data (e.g., since the 1980s) and big-data techniques (machine learning, data assimilation) further complement these efforts (Cheng et al. 2024; Shen et al. 2023; Tsai et al. 2021).

Understanding Ecohydrological Impacts of Forestation

China's ambitious forest restoration can be viewed as a grand land manipulation experiment that has yielded a wealth of knowledge about ecohydrological responses to land cover change. The expansion of forests over millions of hectares has allowed scientists to observe how various hydrological processes respond at scales much larger than traditional small watershed studies. In the past four decades, terrestrial water and carbon fluxes in China's ecosystems exhibited overall increasing trends, with significantly higher evapotranspiration (ET) and gross primary productivity and divergent changes in water yield. Vegetation greening due to forestation and ecological restoration has been identified as a major driver behind many of these trends, enhancing ET (Yang et al. 2023b; Yao et al. 2023), altering the magnitude and seasonality of water yields (Teo et al. 2022; Xue et al. 2022; Zhou et al. 2010), and reducing soil erosion and sediment loads (Chu et al. 2009; Li et al. 2018). This section summarizes the key findings from recent research on the ecohydrological impacts of forestation in China.

Forest Canopy and Floor Interception

Forest canopy and floor litter interception is an important component of total ET. Multiple datasets derived from direct measurements, modeling, and remote sensing have been used to quantify interception losses in China's forested ecosystems, revealing large variations depending on forest species, canopy structures, litter and understory characteristics, and climatic conditions (Wu et al. 2021; Zhang et al. 2022). The canopy interception rate typically falls within 11%–34% across different regions, with the average annual interception reaching 134–627 mm from north to south (Wei et al. 2005; Wen and Liu 1995). A recent meta-analysis based on data from 47 research sites reported larger variations in canopy interception rate across tree species, ranging from 12.4% of *Populus davidiana* to 47.6% of *Myricaria squamosa* (Zhang et al. 2022).

Studies on forest floor highlighted its role in enhancing soil moisture retention, mitigating surface runoff and soil erosion, and regulating water balance in forest ecosystems (Li et al. 2013; Xia et al. 2019). The high porosity enables forest floor to intercept throughfall 2–4 times their own weight (Liu 1996). Data retrieved from eight representative sites in China show that litter interception varied from 0.9 to 7.7 mm (Sun et al. 2018). Observation of forest-water retention in 1,045 sites across the country suggests that litter water-holding capacity accounted for 5.4% of the total forest-water retention, while canopy interception and soil water storage contributed 21.2% and 73.4%, respectively (Wu et al. 2021).

Total Evapotranspiration

Changes in ET directly influence water yield from catchments and are tightly coupled with carbon cycling in forests (Liu et al. 2025; Xiang et al. 2025; Yang et al. 2023b). Quantifying forest ET has therefore been a core focus in China's hydrology studies, especially to understand how forestation affects water availability. Researchers in China have employed a variety of methods to measure or estimate ET from forests (Tie et al. 2018). Traditional hydrological approaches such as the catchment water balance method infer ET as the difference between precipitation and runoff over an annual cycle, which has been applied in some long-term experimental watersheds. At smaller scales, lysimeters have been used beneath forest canopies to directly measure soil evaporation and infer ET components. Micrometeorological techniques, particularly the eddy covariance method, have seen extensively used in China since the 2000s to continuously monitor water vapor flux above forests. Other micrometeorological methods including the Bowen ratio energy balance and large-aperture scintillometers have also been tested (Liu et al. 2011, 2013; Tang and Wang 2022). In addition, vegetation physiological measurements such as the sap-flow method and stoma meter method provide insight into tree-level transpiration rates (Du et al. 2021; Wang and Ma 2002). The proliferation of flux tower sites and remote-sensing-based ET products in recent decades has greatly expanded data on forest ET across China (Li et al. 2014).

Studies indicate that forest ET rates in China exhibit strong spatial patterns and have undergone notable changes over time (Table 2). Geographically, mean annual ET rate tends to decrease with increasing latitude in China, largely mirroring the northward decline in temperature, precipitation, and growing season length (Xiao et al. 2013). Apart from climate, vegetation characteristics (species, age, leaf area index) and land management also modulate ET. Syntheses of long-term flux data have revealed an upward trend in ET over the past several decades in many regions. In fact, analyses of multisource datasets suggest that there has been a multidecadal increase in global land ET since the 1980s, and China has contributed significantly to this trend for its massive forestation programs (Chen et al. 2019). The primary driver appears to be the widespread increase in vegetative greenness (indicated by leaf area index) due to forestation and improved vegetation management. Secondary factors include a generally warming climate and increased regional precipitation and atmospheric moisture demand (Yang et al. 2023b). A recent assessment using three high-resolution ET products found that annual actual ET increased over 84.8% of China's land area from 1982 to 2017 (statistically significant in 52.8% of the area), with a nationally averaged increasing rate of about 1.27 mm per year (Yao et al. 2023). However, different regions show considerable variability and even some opposite trends, depending on local climate conditions and the extent of landscape change (Li et al. 2017; Ma et al. 2024). For example, in some cold or arid regions, ET increases may be limited despite greening, as climate remains the controlling factor. Overall, recent research highlights that forestation has generally elevated ET and substantially altered ET patterns in China. Such ET changes has important implications for regional water availability and water related ecosystem services.

Water Yield

How forest cover affects water yield (or runoff) is a long-standing question in hydrology, and it has also been a central topic in China's forest hydrology investigations (Meli et al. 2024; Sun et al. 2008; Van Meerveld et al. 2021; Wei et al. 2008). Classical paired watershed experiments (PWEs) worldwide have established that deforestation and forestation tend to increase and decrease annual water yield, respectively. Chinese studies have broadly corroborated these findings but also revealed complexities under China's diverse environmental conditions (Table 3). In general, deforestation increases annual runoff from watersheds due to reduced ET and, sometimes, soil degradation that limits infiltration and groundwater recharge (Wang et al. 2008, 2011). However, the magnitude and even direction of forestation effects can vary significantly across different basins and climates, leading to more uncertain or even controversial in China's context (Zhang et al. 2022; Zhang and Wei 2021; Zhou et al. 2010). Factors such as precipitation regime, soil properties, preexisting land use, and tree species all could influence the outcome.

No rigorous PWEs have ever been conducted in China, but available observations support the general pattern that forestation

Table 2. Summary of selected studies on evapotranspiration in China

Reference	Methodology	Time period	Key results
Xiao et al. (2013)	Eight forest eddy covariance flux sites	2003–2010	Annual ET ranges from 151 mm/yr in Changbaishan (mixed forests) to 958 mm/year in Yueyang (deciduous broadleaf forests)
Li et al. (2014)	Remote Sensing-Penman Monteith (RS-PM) model	1982–2009	Mean annual ET was 500 mm/year with a range from 484 to 521 mm/year in China, showing an increasing trend
Liu et al. (2016)	Boreal ecosystem production simulator	2000–2014	Annual ET generally increased in regions with greening trends and decreased in regions with browning trends
Li et al. (2017)	MODIS data products	2001–2013	Average annual ET in China decreased at a rate of −0.6 mm/year
Yao et al. (2023)	GLEAM, GLDAS, and NOAH datasets	1982–2017	Annual ET increased over 84.8% of China's land area, with a nationally averaged increasing rate of about 1.27 mm per year
Ma et al. (2024)	150 eddy covariance sites	2002–2020	The ET of China's terrestrial ecosystems varied from 147 to 1,125 mm, and forests ranked second (following wetlands) with a mean ET of 656 ± 180 mm
Song et al. (2025b)	WaSSI-CN model	1982–2018	Mean annual ET was 390 mm/year and significantly increased due to increasing precipitation and greening in eight out of the 10 major river basins

Table 3. Summary of selected studies on forest-water yield relationships in China

Reference	Methodology	Time period	Key results
Sun et al. (2006)	Budyko-based water balance model	1961–2000	Average water yield reduction due to forestation vary from 50 mm/year (50%) in the semiarid Loess Plateau region in northern China to 300 mm/year (30%) in the tropical southern region
Wei et al. (2008)	Meta-analysis	1960s–2000s	Little long-term data were available to assess the forest-streamflow relationship in China due to an absence of standard paired watersheds
Zhou et al. (2010)	Statistical regression models and water budget analysis	1956–2006	Forest recovery redistributes water from the wet season to the dry season and consequently in increases water yield in the dry season in humid Guangdong Province
Feng et al. (2016)	Water and carbon balance modeling and statistical analysis	1982–2010	Revegetation in the Loess Plateau is approaching water resource limits and threatening sustainability of forestation efforts
Li et al. (2018)	Coupled land-atmosphere global climate model	1982–2011	Afforestation increased precipitation in parts of North and Southeast China, and supplied enough water to cancel out enhanced ET
Zhang et al. (2022)	WRF model and water budget analysis	1982–2015	Revegetation in the Loess Plateau does not decrease water yield due to increased regional precipitation driven by vegetation-climate feedbacks
Xue et al. (2022)	Budyko-based attribution analysis	1954–2014	Forest expansion reduced water yield in dry regions but had insignificant impact in wet basins
Teo et al. (2022)	Regional climate model and Budyko-based water balance model	2041–2070	Precipitation feedback driven by large-scale reforestation can potentially increase water yield in the Loess Plateau–North China Plain, Yangtze Plain, and Southeast China

Note: WRF = weather research and forecasting model.

effects on water yield are more pronounced in water-limited regions (drier north) than in energy-limited regions (humid south) (Liu et al. 2022; Zhang et al. 2017). Forestation in the Loess Plateau has raised concerns about substantial streamflow reductions. For instance, a national-scale modeling experiment by Sun et al. (2006) projected that average annual water yield could potentially decrease by 50 mm (or around 50% of total flow) in the semiarid Loess Plateau of northern China, and by up to 300 mm (or around 30%) in the humid tropical south as a result of forestation. Studies suggest that the aggressive revegetation (part of Grain for Green) has indeed led to marked declines in runoff, potentially approaching or exceeding sustainable water resource limits for the Loess Plateau

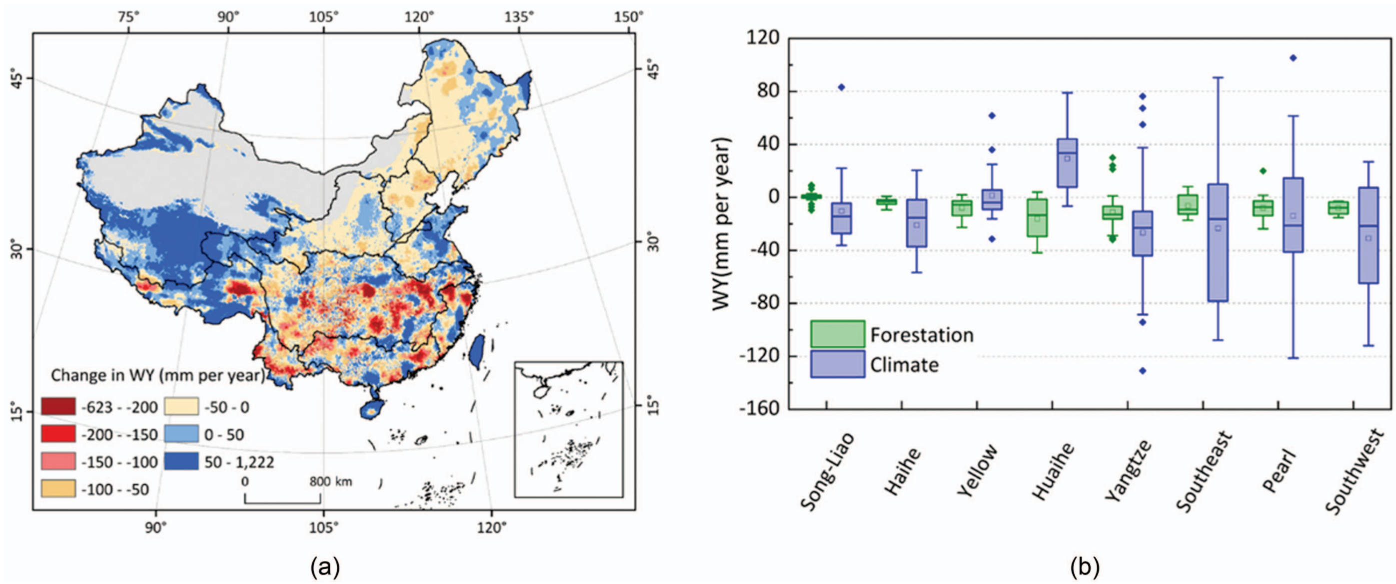

Fig. 5. (Color) WaSSI-CN modeled annual water yield change as a result of land cover and climate change from 1982–2018, a period of rapid *greening up* due to forestation in China: (a) simulation at 10-km scale; and (b) summarized contribution of climate change and landcover change by eight major large basins.

(Feng et al. 2016). Similarly, in the Great Green Wall shelterbelt reforestation region in northern China, planted pine or poplar forests in the 1970s have showed degradation and mortality largely due to water shortages to support mature stands (Zhu and Zheng 2019). In more humid environments, the impact of new forests on annual runoff is smaller or can be masked by climate variability and human water use. An empirical analysis in a recovering forest region of Guangdong (southern China) indicated that forest regrowth may regulate seasonal flow, i.e., reducing wet-season flows slightly but augmenting dry-season baseflows, thereby redistributing water yield more evenly through the year (Zhou et al. 2010). Another study comparing pairs of basins found that forestation contributed to measurable runoff declines for two dry basins, whereas the increase in forest cover did not significantly change total runoff in two wet basins (Xue et al. 2022). However, these observations are complicated by human influences such as reservoirs and urbanization and climate change in the studied basins. A recent continental modeling study by Song et al. (2025a, b) using the WaSSI-CN water model suggests both forest cover increase and climate change affect spatial patterns of water yield during 1980–2018 (Fig. 5). Overall, the Qinghai-Tibetan Plateau has become wetter while other regions have seen a decrease in water yield. These results align with the notion that forestation clearly reduces water yield in water-scarce regions, but could prompt baseflow and lowflow to various extents by improving soil infiltration and subsurface storage in humid regions (Bruijnzeel et al. 2025).

The complexity of quantifying forest-water yield relationships at larger scales also arises from other human interventions. Over decades, China's rivers have been heavily regulated by dams, water diversions, and water withdrawals. Detecting the pure *forest signal* in observed streamflow records is challenging in many human-influenced basins. Examples include the cases previously reported in Zhou et al. (2010) and Xue et al. (2022), where hydraulic engineering projects might have affected dry-season flows in the humid south since the 1950s.Wei et al. (2008) noted that the lack of standard long-term PWEs in China has impeded definitive conclusions. Still, the convergence of modeling and observational studies suggests a clear trade-off between forest expansion and water yield in many regions. An important practical implication is that forestation policies need to be tailored to regional water conditions. Researchers have argued that tree planting efforts should be emphasized in relatively wet regions (e.g., southern China) where water resources are sufficient, and limited or managed with caution in dry regions (like the Loess Plateau or North China) to avoid exacerbating water scarcity (Liu et al. 2016; Xue et al. 2022). Selection of tree species that use less water and maintaining forest-grassland mosaics are additional strategies to mitigate water losses. These considerations are increasingly recognized in Chinese ecosystem management.

Another research frontier addresses the possible feedbacks of vegetation change on regional climate, which could in turn affect water yield at a large scale (Cui et al. 2022). Recent modeling studies have explored whether large-scale forestation in China can alter precipitation patterns, which essentially asks the question "do forests make rain?" Using coupled land-atmosphere models, Li et al. (2018) found that the biophysical feedbacks from China's historical greening likely led to increased precipitation in parts of North and Southeast China, which in their model was enough to compensate for the enhanced ET in those regions. Teo et al. (2022) similarly projected that extensive forestation can slightly raise regional precipitation due to factors like increased surface roughness and moisture recycling, thereby offsetting some water loss and even increasing net water yield in certain scenarios for the North China Plain, Yangtze Plain, and Southeast China under future climate conditions. While these modeling results carry uncertainty, they suggest that the negative impact of forests on water yield could be partially alleviated by climate feedbacks, especially over long periods and large areas.

Forest and Soil Erosion

A major motivation behind China's forestation campaigns was to combat soil erosion and reduce sedimentation of rivers and reservoirs. Large portions of China (notably the Loess Plateau, southwestern karst regions, and parts of the Yangtze and Yellow River basins) suffered from severe soil loss due to deforestation and unsustainable farming on slopes (Han et al. 2024; Liu et al. 2025).

Forest hydrology research has therefore devoted considerable attention to how forestation improves soil conservation. The consensus from previous studies is that forest cover can significantly mitigate soil erosion by reducing surface runoff volume and peak flows, and by physically protecting the soil from raindrop impact (Gong et al. 2022). A forest acts as a natural buffer that reduces the detachment and transport of soil particles. The canopy and leaf litter dissipate the kinetic energy of raindrops and prevent direct splash erosion on the ground, while tree roots and accumulated organic matter help stabilize the soil, promote infiltration, and reduce overland flow. Empirical data from runoff plot studies across China confirm the strong erosion control by forests. In a comprehensive analysis of 2,823 plot-years of data from 73 sites, Guo et al. (2015) found that soil loss rates of forest, shrub, and grassland were 0–1.9, 0.3–8.1, and 4.0–1.6 t/ha per year, respectively. By contrast, on fallow land the soil loss was much higher (roughly 31–107 t/ha), and on conventionally tilled farmland it varied largely across the country from 8 t/ha to 49 t/ha per year.

At larger watershed scales, China's massive forestation has led to dramatic reductions in sediment yield in many river systems. The first national water census reported that the area affected by water erosion declined from 1.83 million km^2 in 1996 to 1.29 million km^2 in 2011, a 29% decrease attributed largely to vegetation restoration and soil conservation measures (Li et al. 2018). Nowhere is this more evident than in the Loess Plateau, once one of the world's most erosion-prone regions. Thanks to extensive planting of trees and grasses since the late 1970s, average vegetation cover in the Plateau's 12 main catchments increased from 25% in 1978 to 46% by 2010. Over roughly the same period, the Yellow River's sediment load plummeted. Between the 1980s–1990s and the 2000s, vegetation restoration caused an 26% reduction in water yield and a 21% reduction in sediment concentration in the Yellow River, and 57% (0.23 Gt per year) of the drop in sediment transport can also be attributed to the increased vegetation cover (Wang et al. 2015). Sediment discharge from the Plateau is now approaching levels not seen in centuries. Chen et al. (2015) noted it has declined to near the estimates for the Tang Dynasty (~740 AD) when the landscape was far less degraded. These outcomes validate the enormous effort China invested in forestation for erosion control. Moreover, studies also recognize that large dams and reservoirs have played a role by trapping sediment (Chu et al. 2009; Li et al. 2018). In the major rivers, especially the Yellow River, reservoir sedimentation accounts for a significant portion of the observed sediment decline in the latter 20th century. Still, vegetation restoration is the key driver behind the sustained, long-term reduction in upland erosion rates.

Trade-Offs among Ecosystem Services

While forestation has delivered multiple ecological benefits (such as water retention, carbon sequestration, biodiversity habitat, and erosion control), it has also raised concerns about trade-offs among ecosystem services (Chen et al. 2015; Feng et al. 2016; Yu et al. 2024). A prime example is the balance between the enhanced carbon sequestration and associated climate mitigation versus the reduced water yield. Satellite and field data suggest that carbon storage in planted forests increased from 675.6 ± 12.5 Tg C in 1990 to $1{,}873.1 \pm 16.2$ Tg C in 2020, representing an average annual growth rate of approximately 40 Tg C (Cheng et al. 2024). Forestation and forest recovery tie up more carbon in biomass and soils, but they also consume more water through evapotranspiration, leaving less runoff for human use or aquatic ecosystems (Lin et al. 2025). Another trade-off is between controlling soil erosion and maintaining downstream sediment delivery. While reducing erosion is beneficial upstream, an extreme reduction in sediment reaching the ocean can have unintended consequences for delta ecosystems that depend on sediment deposition (Chu et al. 2009).

In China, these trade-offs are most pronounced in fragile environments like the Loess Plateau. The simultaneous drivers of a warming climate and extensive forestation have significantly reduced water availability for people in some northern regions by increasing evaporative losses (Schwärzel et al. 2020). Soil moisture in parts of the Plateau has been depleted by the proliferation of vegetation, to the point that soil water carrying capacity being exceeded and some planted forests have experienced growth stagnation or die-back (Fu et al. 2017; Yang et al. 2023a). In other words, the very success in establishing vegetation in this dry region has in places led to water shortages for both the ecosystem and local human needs, illustrating a clear forest-water trade-off (Liu et al. 2022). Moreover, the reduction in total sediment flux due to erosion control and reservoir trapping has created new challenges for river management. For instance, the greatly diminished sediment load of the Yellow River could extend lifespan of reservoirs and enhance hydropower potential (Wu et al. 2025), yet also contributed to the shrinking of the river's delta and coastal wetlands due to insufficient sediment deposition.

Our understanding of the magnitude and mechanisms of these trade-offs is still limited. Water yield, carbon sequestration, soil conservation, and even biodiversity can sometimes conflict with one another when forest cover is increased rapidly. A forest plantation optimized for carbon might be very dense and fast-growing, but use a lot of water and provide less base flow downstream. Conversely, managing a forest for water (e.g., via thinning) might reduce its carbon uptake or erosion protection. The challenge for China is to find a sustainable balance, especially in regions like the Loess Plateau or dry parts of southwest China, where water is the critical limiting resource. Balancing the needs of ecosystems and human water demands is an ongoing policy debate. Researchers have suggested adopting region-specific forest management strategies, e.g., limit new plantings in extremely arid zones, use more drought-tolerant species or switch to grassland in those areas, and concentrate forest expansion in humid regions to maximize overall benefits (Fu et al. 2017; Liu et al. 2016; Wei et al. 2008). Integrated modeling of ecosystem services is also being advanced to quantitatively evaluate trade-offs and synergies under different land-use scenarios (Yu et al. 2024).

Discussion

Research Gaps

Despite the progress made, forest hydrology research in China still faces a number of unresolved questions, largely stemming from its late start and the complexity of large-scale forest changes in the vast country. One fundamental limitation has been the lack of long-term, controlled experimental data such as standard PWE studies (Wei et al. 2008). Lack of land for vegetation manipulation experiments due to forest protection regulations and long-term funding supports are the key reasons to prevent conducting the costly PWE studies. Consequently, basic forest hydrologic questions remain unanswered. For instance, to what extent forests reduce water yield or augment dry-season flows in different regions. While modeling and statistical analyses have attempted to fill this knowledge gap, there remains no scientific consensus (Zhang et al. 2022; Zhang and Wei 2021; Zhou et al. 2010). Scale effects present additional challenge that findings at the plot or small catchment scale do not always extrapolate neatly to regional basins (Zhang et al. 2017). Another notable issue is the

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large uncertainty in attribution analysis that attempts to distinguish effects of forest change from simultaneous climate variability and other human activities (e.g., reservoirs, irrigation, urbanization). This uncertainty is amplified by data quality issues. Long-term runoff records may have biases or inhomogeneities due to water consumption or dam construction, and remote-sensing ET products can diverge significantly in absolute values (Yao et al. 2023). Rigorous data quality control and integration of multiple data sources are needed to improve confidence in findings. Encouragingly, China's monitoring networks (e.g., CERN, CFERN) are now generating better and longer datasets, and efforts are underway to make these data more accessible and standardized. Continual support for these networks is crucial. Sustained funding and commitment to long-term ecosystem research will be needed to bring China's forest hydrological data on par with that of countries where experiments have run for decades. Establishing a few well-instrumented flagship watershed experiments in China could greatly advance understanding.

Research Informing Management

The knowledge gained so far has important implications for how forestation and forest management should be implemented going forward. First, the clear message that forestation can significantly reduce water yield in dry regions means that policymakers must weigh the water cost of planting trees against the ecological benefits. In northern China, where water scarcity is acute, this has led to a re-evaluation of planting strategies. There have been calls to prioritize planting in humid regions and adopt more water-efficient vegetation in dry regions (Chen et al. 2015; Feng et al. 2016; Yu et al. 2024). Additionally, forest management practices like thinning or selective planting can be employed to balance water savings with other goals, aiming for an optimal forest coverage that maximizes erosion control and carbon sequestration with acceptable impact on water resources. China's regional forestry plans are gradually incorporating such scientific input. Second, the huge success in reducing soil erosion through forestation suggests that maintaining forest cover in erosion-prone headwaters should remain a high priority. The benefits to downstream reservoir storage, water quality, and flood mitigation are well demonstrated. However, managers must also consider sediment flow needs downstream. Third, the documented trade-offs among ecosystem functions highlight the need for multiobjective strategies of integrated land-water management. Recent studies stress that these trade-offs must be explicitly considered in planning and evaluating forestation programs. What constitutes success for forestation is context-dependent. In some cases, a modest reduction in water yield might be acceptable for large gains in soil and carbon, but beyond a threshold it could undermine water security. Thus, a key message from China's experience is the importance of multiobjective watershed management.

International Perspective

Forest hydrological studies have a century long history (Andréassian 2004; Bosch and Hewlett 1982; Ellison et al. 2017; Farley et al. 2005). Evidence of forest-water relations, planted forests versus water yield in particular, found in China generally converges with global literature. China's unprecedented scale of forestation highlights policy-relevant insights on dry-season flow regulation, sediment reduction, and land-atmosphere feedbacks at regional to national scales. China's journey has also opened new frontiers in forest hydrology research and underscored the critical need to balance ecological restoration with hydrological sustainability at a large scale. The experiences gained have not only advanced scientific understanding but are also guiding more holistic land-use policies that consider water, soil, climate, and social outcomes. The lessons learned from China are invaluable to other countries pursuing landscape restoration as a *nature-based solution* to many merging environmental issues. Indeed, forest restoration hydrology that concerns hydrologic process evolution (Bruijnzeel et al. 2025) and water yield (Jones et al. 2022) has become an important topic in ecohydrology. These lessons will motivate collaborative networks for standardized watershed experiments, model intercomparison, multisource data assimilation, and open data sharing to improve generalization of knowledge across biomes. However, the long-term effects of such unprecedented human intervention are only emerging and have not been fully understood. The establishment of representative experimental watersheds, long-term support for international collaborative programs, and improvement in interdisciplinary studies linking hydrology with ecology and socioeconomic research will be key for addressing the challenges brought by large-scale forestation.

Summary

China's rapid and large-scale forestation over recent decades has provided both tremendous opportunities and significant challenges for ecohydrological science and water management. On one hand, the expansive regreening of the country has enabled unprecedented research into forest-water relations, leading to greater appreciation of the role of forests in regulating hydrology and water quality. Ecohydrologists have made great strides in understanding how forestation affects evapotranspiration, water yield, soil erosion, and ecosystem functions across China's diverse environments. China has demonstrated that with substantial investment and political will, degraded landscapes can be restored at a continental scale, yielding benefits like carbon sequestration and soil conservation on an enormous magnitude. On the other hand, this undertaking has revealed the complexities and trade-offs inherent in land management. The evidence gathered to date confirms that newly established forests generally enhance water retention in soils and reduce erosion, but forests do use a large amount of water. Reforestation on previous forest lands or afforestation on previously croplands or degraded lands or grasslands is likely to reduce total water yield due to increased water use, especially in arid regions. These insights are invaluable for managing forests in a way that optimizes the mix of ecosystem services. Forestation is not a panacea, and careful planning is required to avoid unintended consequences like water shortages or altered river sediment regimes. The challenges for scientists and policymakers are to fully comprehend and predict the effects of such land cover changes under varying conditions, and to develop strategies that maximize the benefits of forestation while mitigating negative impacts.

Debates on forest-water relations at different scales remain in China (and elsewhere) and uncertainty is large in quantifying the forest-water cycles at different scales, highlighting the need for more high-quality data and further research. Continued support for long-term forest hydrology research at watershed scale to regional scale through the existing ecological monitoring networks will be crucial for closing the knowledge gaps. China's experience also suggests that sustainable forest management requires coordination between forestry and water sectors that are adaptable to local conditions. Encouragingly, there is growing recognition of these needs within China's governance, and course corrections such as refining the Grain for Green Program implementation are already in progress. The opportunities lie in leveraging this knowledge to inform better practices both in China and worldwide, ensuring that forestation contributes to ecological health and water security. Future challenges lie in the continued commitment to research, international collaborations (sharing data and expertise), monitoring, and adaptive management in the face of climatic and socioeconomic changes.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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Author Contributions

Kai Duan: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Project administration; Resources; Writing – original draft. Xinyue Yang: Data curation; Validation; Visualization; Writing – review and editing. Zhiyuan Song: Data curation; Visualization. Xiaodong Liu: Writing – original draft; Writing – review and editing. Meixian Liu: Writing – original draft; Writing – review and editing. Ge Sun: Conceptualization; Investigation; Supervision; Writing – review and editing.

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