ECOLOGY

Time and space catch up with restoration programs that ignore ecosystem service trade-offs

Ruonan Li[1,2], Hua Zheng[1,2]*, Patrick O'Connor[3], Huashan Xu[4], Yunkai Li[5], Fei Lu[1,2,6], Brian E. Robinson[7], Zhiyun Ouyang[1,2], Yue Hai[1,8], Gretchen C. Daily[9]

In response to extreme societal consequences of ecosystem degradation and climate change, attention to ecological restoration is increasing globally. In China, investments in restoration exceeded USD 378.5 billion over the past decade. However, restoration programs are experiments that can cause marked unintended consequences, with trade-offs across space and time that have undergone little empirical examination. We quantified the long-term effects of large-scale afforestation for soil erosion and sandstorm prevention in semiarid China. We found that soil erosion was notably reduced by afforestation but surface runoff declined significantly, after a time lag of 18 years, limiting overall benefit. While forest area also increased, forest quality declined, interacting with reduced surface water runoff. Crucially, increased forest water consumption accelerated downstream groundwater depletion, thus intensifying conflicts over water use. The time lags and spatial trade-offs revealed by this case study provide critical lessons for large-scale restoration programs globally.

INTRODUCTION

The rapid pursuit of economic development has led to a succession of environmental problems, such as water and soil erosion, desertification, and ecosystem degradation (1, 2). Most of these environmental problems relate to impacts on ecosystems and ecosystem services (ESs) (3, 4). In response to these issues, ecological restoration programs (ERPs) have been widely implemented to improve important ESs and manage ecological concerns (5–7). In China, for example, more than USD 378.5 billion (in 2015 USD) has been invested in ERPs from 1979 to 2015, with total annual investment increasing steadily with China's growing economy (8). Today, one-third of global vegetated lands are currently greening, especially in forested regions (9), and over 30 countries have committed more than 100 million hectares to forest landscape restoration through the Bonn Challenge (10).

These large-scale programs, which aim to improve important ESs (e.g., carbon sequestration, soil conservation, sandstorm prevention, and flood mitigation), have received worldwide attention. They contribute in multiple ways toward achieving the United Nations Sustainable Development Goals (8). However, adverse outcomes have also occurred during ecological restoration, such as heightened conflicts over water use (11–16), heralding future risks to large-scale sustainable interventions (8). It is vital that the overall effectiveness of restoration is assessed on these larger, regional scales. This assessment should consider not only potential economic benefits (as has typically been done) but also risks and costs to human communities

and potential community responses thereto, to ensure successful adaptation of restoration priorities and approaches (9).

Typical ERPs tend to focus on improvement of specific ESs, with some achieving remarkable results (1, 2, 17). For example, analysis of the outcomes of 89 specific ERPs worldwide showed a win-win increase in both biodiversity and ES provision (44 and 25%, respectively) (18). Delivery of ESs following the implementation of ERPs, restoration may differentially affect the well-being of different stakeholders at multiple spatial scales (2, 19). For instance, the Three-North Shelter Forest Program, which is the largest such program in China, and the Beijing-Tianjin Sandstorm Source Control Project have led to desired reductions in local land desertification and soil erosion as well as decreases in airborne sand and dust regionally (20). These different outcomes at local and regional scales were desired. However, trade-offs often occur when multiple ESs (e.g., carbon sequestration and water resource provision) are competitively used by specific-scale stakeholders (21). Emerging studies have suggested that these ERPs, when not properly implemented, result in unintended ecological and water security concerns (22, 23).

Furthermore, the overall effectiveness of ES restoration is influenced by temporal variation in ecosystem structure and function (1, 24). The long-term effectiveness and sustainability of ERPs can be understood only by considering the direct and indirect effects of restoration on affected ESs at multiple spatial scales, as well as through their long-term temporal dynamics (25). These extensive, complex, and cumulative impacts of ERPs on multiple ESs remain underrecognized (8). This lack of biophysical and social science–based data and analysis hinders the understanding of forest-related ESs and the ability to design implement and evaluate the effectiveness of ERPs in land-system sustainability (2, 23).

To reveal the complexities of ERPs in informing sustainable land use management, we analyzed the spatiotemporal trade-offs involved in two large-scale ERPs in China. We focused on the sandstorm prevention and water resource provision of the Three-North Shelter Forest Program and the Beijing-Tianjin Sandstorm Source Control Project in the mountainous area of the Haihe River Basin (HRB) (Fig. 1A and sections S1 and S2). We used the revised wind erosion equation (RWEQ) to quantify the sandstorm prevention service.

[1]State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China. [2]University of Chinese Academy of Sciences, Beijing 100049, China. [3]Centre for Global Food and Resources, University of Adelaide, South Australia 5005, Australia. [4]Daning Management Office of the Beijing South-to-North Water Diversion, Beijing 102442, China. [5]College of Water Resource & Civil Engineering, China Agricultural University, Beijing 100083, China. [6]Beijing-Tianjin-Hebei National Observation and Research Station for Eco-Environmental Change and Integrated Management, Beijing 100085, China. [7]Department of Geography, McGill University, Montreal, QC H3A 0B9, Canada. [8]School of Geography and Environmental Science, Guizhou Normal University, Guiyang 550001, China. [9]Department of Biology, Natural Capital Project, Woods Institute for the Environment, Stanford University, Stanford, CA 94305, USA.
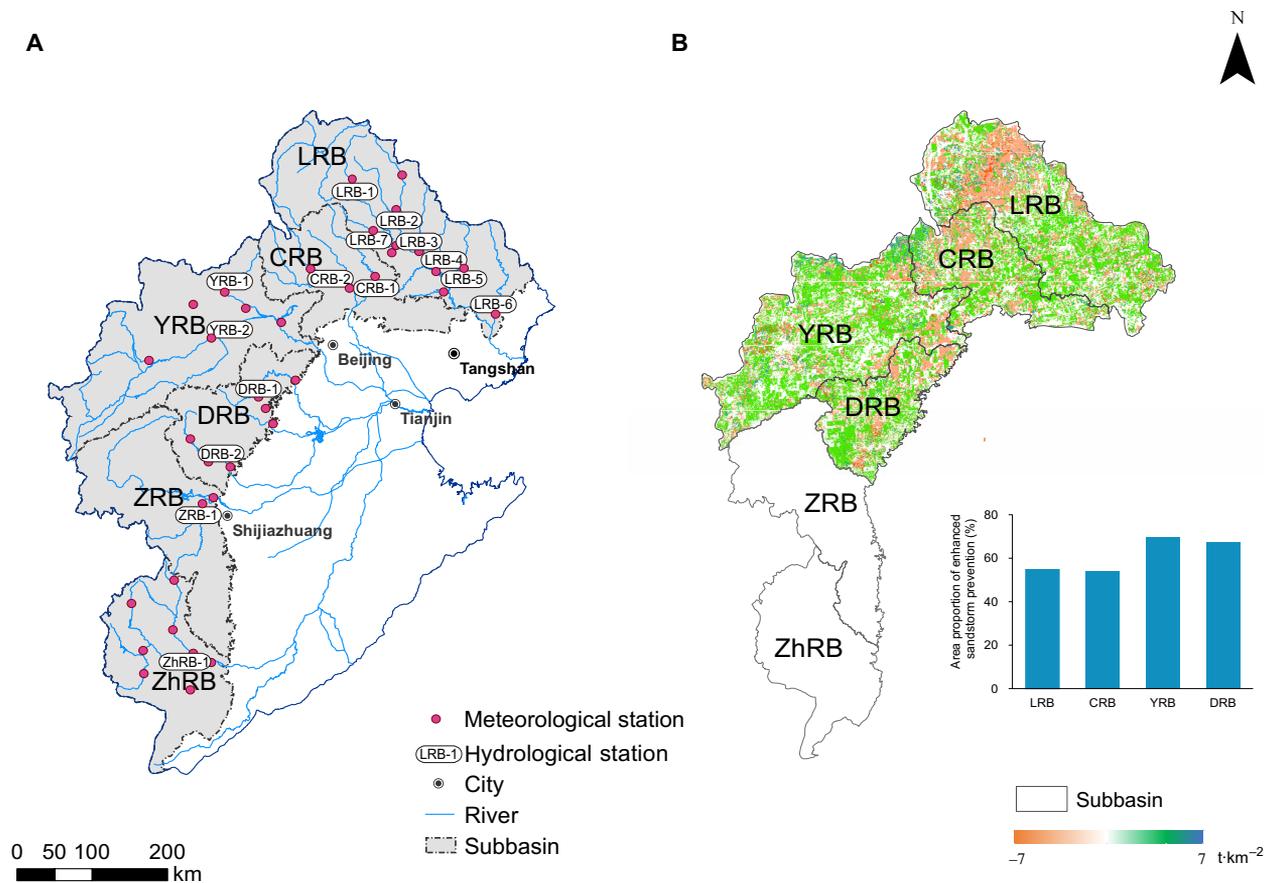*Corresponding author. Email: zhenghua@rcees.ac.cn

Fig. 1. Study area and improvements in sandstorm prevention from 1980 to 2015. (**A**) Study area of HRB with distribution of subbasins and hydrological stations in mountainous area. (**B**) Map showing biophysical change of sandstorm prevention and histogram illustrating proportion of area with enhanced sandstorm prevention for afforested subbasins. ZRB, Ziya River Basin; ZhRB, Zhang River Basin. The shades of green and red represent the intensity of increased and decreased sand erosion, respectively.

To identify the abrupt change point in surface runoff, we used a Pettitt test and double-mass curve and applied a Mann-Kendall trend analysis of hydrological and environmental factors. We also investigated the major driving force contributions of the ERPs and clarified the interrelationships among these effects to guide ERP design and management.

RESULTS

Sandstorm prevention service changes

The primary targets of the ERPs implemented in the HRB were to prevent sandstorms and to retain soil (section S2), which are critical outcomes for maintaining ESs in semiarid regions (*1*). Results showed that the area of enhanced sandstorm prevention increased from 1980 to 2015 in the afforested subbasins, accounting for 61.45% of the total area. Among the subbasins covered by the ERPs, the two subbasins with the largest increases increase in sandstorm prevention area were the Yongding River Basin (YRB) and Daqing River Basin (DRB), showing increases in the sandstorm prevention areas of 69.74 and 67.48%, respectively. Compared to 1980, sandstorm prevention increased in the afforested regions, except for areas northwest of the Luan River Basin (LRB) and Chaobai River Basin (CRB) in 2015 (Fig. 1B). That is, soil erosion increased in the northern part of the HRB, mitigating the effectiveness of the ERPs in the LRB and CRB areas.

Surface runoff changes and drivers

Surface water runoff in all selected subbasins exhibited a downward trend (section S3). The subbasins with significant declines in surface runoff (significance, <0.05 and 0.01) were all located in areas where ERPs have been implemented. All subbasins located in the revegetated areas exhibited abrupt changes in runoff in 1998, as verified by cross-validation of the Pettitt test and double-mass curve (Fig. 2 and section S4). The runoff before and after the abrupt change points is shown in Fig. 2, together with abrupt change point analysis.

In afforested areas, reference evapotranspiration and precipitation showed a downward trend from 1980 to 2015, while we observed the opposite trend for temperature (Fig. 3A). Before the abrupt change in runoff, forest area and forest quality [measured by normalized difference vegetation index (NDVI)] both increased substantially. After the abrupt change point, forest area expanded very slowly, although the ERPs were still in progress. Furthermore, forest quality fluctuated greatly and then eventually declined (Fig. 3B). In the period of rapid increase in forest area and quality, both were significantly positively correlated with actual evapotranspiration (Fig. 3C).

Considering the complex impacts of meteorological (i.e., precipitation and reference evaporation) and land use factors (i.e., NDVI and forest, grassland, farmland, wetland, and artificial land area) on surface runoff in the study area, we quantified their relative
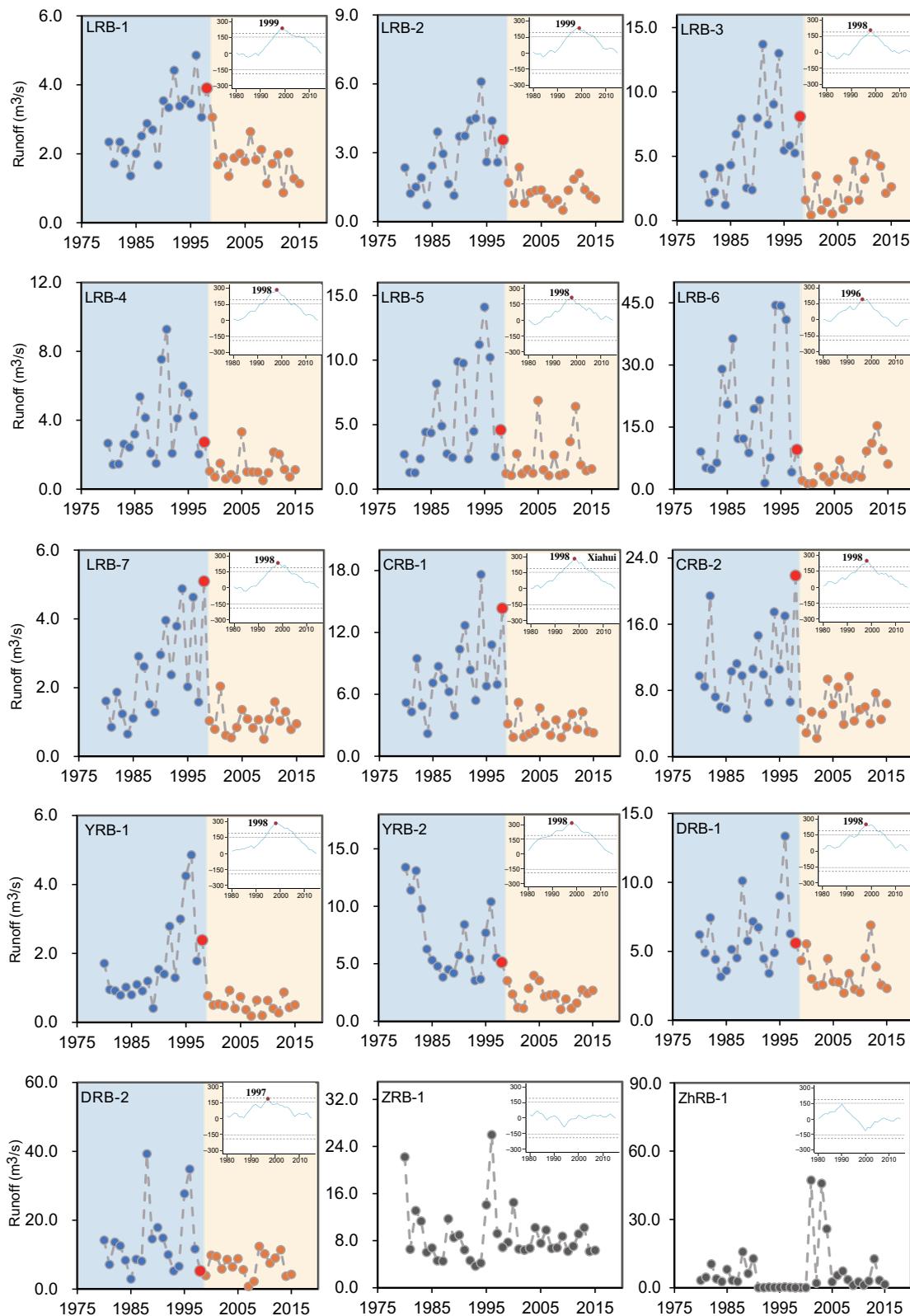
Fig. 2. Surface water runoff before and after abrupt change points in selected subbasins of HRB. For subbasins with abrupt changes in the volume of runoff, the blue and orange scatter diagrams represent annual runoff before and after abrupt change year (1998), respectively, and larger red points represent runoff in 1998. For subbasins with nonabrupt changes in runoff, the gray scatter diagrams represent annual runoff. Top right image inset in each figure is abrupt change point illustrated by Pettitt test (refer to section S4).
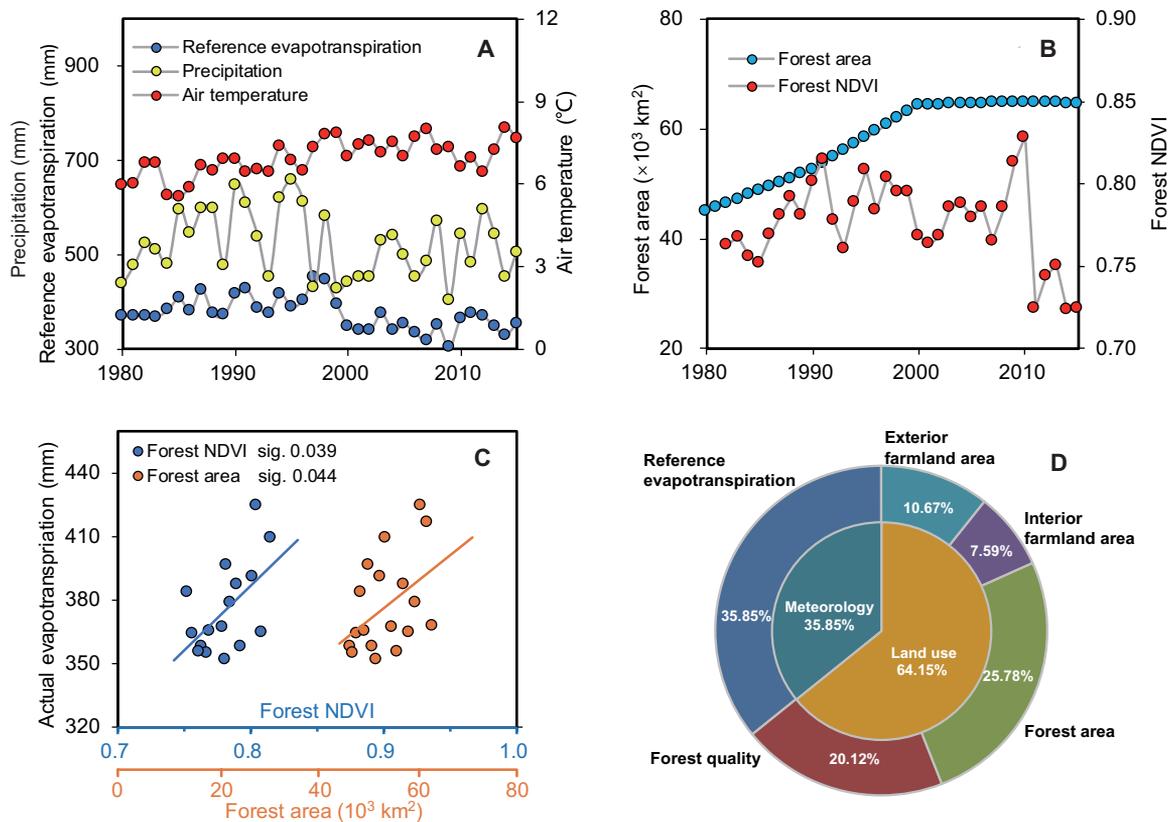
Fig. 3. Changes in meteorological and land use factors and their relative contributions to runoff reduction in afforested areas. (**A**) Changes in reference evapotranspiration, precipitation, and air temperature between 1980 and 2015. (**B**) Changes in forest area and NDVI between 1980 and 2015. (**C**) Relationship between actual evapotranspiration and forest area and forest NDVI. (**D**) Relative contributions of meteorological and land use factors to runoff reduction [coefficient of determination (R^2) = 0.72, significance (sig.) = 0.066]. Reference evapotranspiration showed greatest contribution to runoff reduction, followed by forest area, forest quality (forest NDVI), and exterior and interior farmland area.

relationships to runoff reduction. Land use patterns explained the most variation in runoff (64.15%), of which increases in forest cover (45.90% with 25.78% from forest area and 20.12% from forest quality) and farmland water consumption (18.26% with 10.67% from exterior mountainous area and 7.59% from interior) dominated. An additional 35.85% of runoff variation was due to reference evapotranspiration (Fig. 3D).

Response of vegetation growth and shallow groundwater depth

The NDVI for 26.29% of the revegetated area underwent an abrupt change in the past 30 years, primarily after 1998. A decreasing trend was exhibited in nearly 60% of the abrupt change region, while the remaining areas showed an upward trend (Fig. 4A). However, forest quality showed completely opposite trends before and after the abrupt change point in runoff. Before 1998, forest quality in 34.6% of the revegetated area increased significantly and only decreased in 0.7% of the revegetated area (Fig. 4B, sig. <0.05). After that, the area with a significant increase in forest quality halved, whereas the area showing a significant downward trend increased to 33.9% (Fig. 4C, sig. <0.05).

Compared with nonrevegetated areas [Figs. 1A and 5, Ziya River Basin (ZRB)], the cumulative relationship between shallow groundwater depth in the piedmont plain and surface runoff from the revegetated mountainous areas decreased sharply after the year (1998), showing abrupt runoff change (Figs. 1A and 5. LRB and YRB).

This indicates that the reduction in runoff accelerated the decrease in shallow groundwater in download areas.

DISCUSSION

As a result of large-scale revegetation programs, vegetation coverage and carbon storage have increased in northern and northeastern China (*26*, *27*), effectively reducing the risk of soil degradation and erosion and improving soil stability (*28*). Our case study revealed that the sandstorm prevention service has also been enhanced by the revegetation programs in the HRB. However, substantial trade-offs have occurred between the sandstorm prevention service and provision of surface runoff during the implementation of the ERPs. The sandstorm prevention service has come at a substantial cost for basin water yield, with surface runoff downstream primarily bearing the brunt, although not noticed until years later.

The principal factor contributing to surface runoff reduction has been the expansion and growth of artificial forests. Forest quantity and quality are together associated with 45.90% of runoff reduction. To 2015, forest area has increased by 1.05×10^4 km² in the revegetated subbasins. Early stage revegetation (across nearly half a century) from ERPs in northern China involves mostly fast-growing, monocultural, and nonnative trees (*29*). Compared with natural endemic forests, artificial forests consume 559 to 2354 m³ ha⁻¹ a⁻¹ of additional water as they grow due to the increase in total canopy
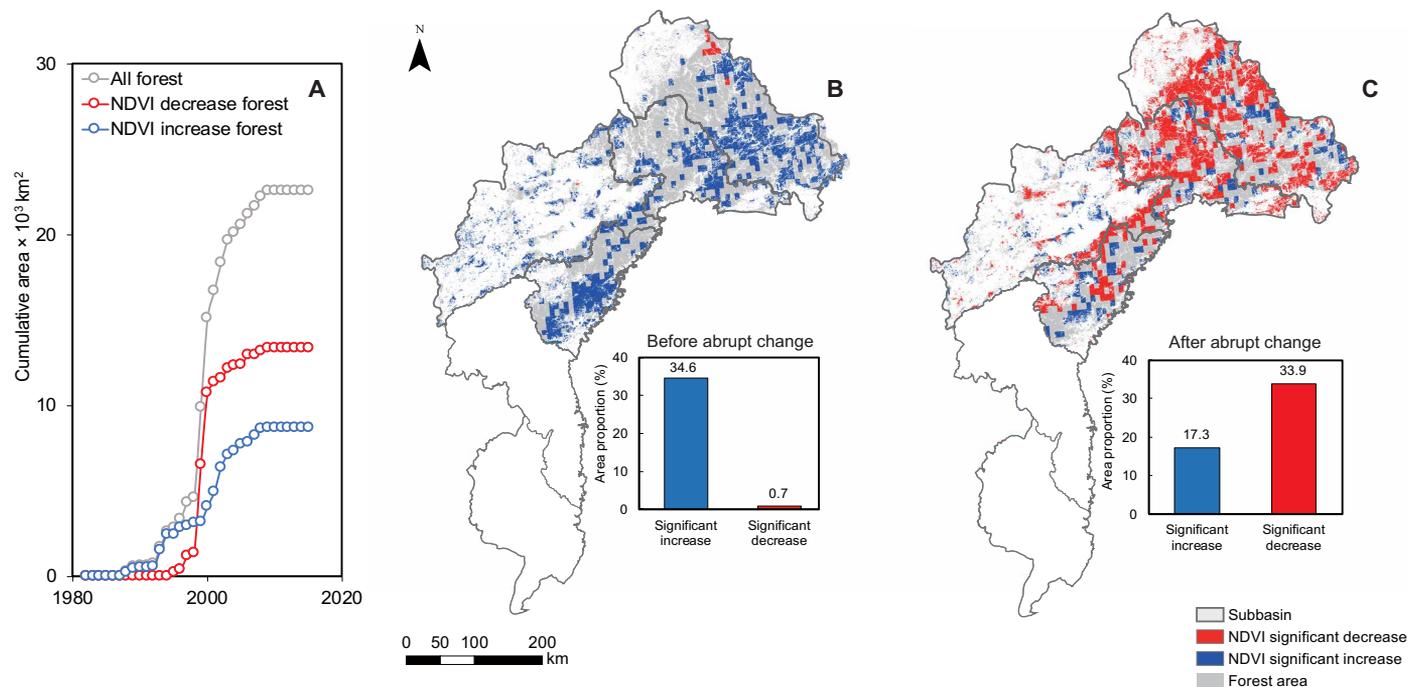
Fig. 4. Cumulative forest area and areal proportion of forest with significant changes in forest quality (NDVI). (**A**) Accumulation of abrupt change forest area with significant changes in NDVI. Gray, blue, and orange dot-dash lines represent all significant changes in forest area, significant decreases in forest area, and significant increases in forest area, respectively. (**B**) Distribution and areal proportion of forests with significant changes in NDVI before abrupt change year. (**C**) Distribution and areal proportion of forests with significant changes in NDVI after abrupt change year.

evapotranspiration (*30*), reduction in surface runoff, and alteration of water balance (section S5 and fig. S4) (*31*), which not only deplete the water supply but also potentially result in increased regional water conflicts (*11*, *32*).

Two decades after the initiation of various ERPs in the HRB, the artificial forests entered the half-mature and mature stages in 1998, the period of maximum water consumption (*33*). In these stages, artificial forests generally show a notable increase in evapotranspiration and reduction in surface runoff compared to native forests, especially in dry and semiarid climates (*23*, *34*). Consequently, variations in forest quantity (area) and quality (NDVI) were the primary factors related to surface runoff decline in the region. In the revegetated subbasins, forest quality showed a severe decline after 1998, consistent with previous studies. For example, Fan (*35*) investigated the NDVI in the HRB from 1982 to 2015 and detected a downward trend in the upstream parts of the LRB and CRB subcatchments, while an overall upward trend was apparent before 2000 in the same area (*36*).

Furthermore, soil water, an important link connecting forest evapotranspiration and surface runoff, followed a similar trend. In the revegetated regions, 1998 was also the dividing line in soil water content variation. Before that, all forest soil water content showed an increasing trend, but after 1998, half of the forest area had declining soil water content, most of which was in the north where precipitation was already low (Fig. 6). A possible reason for this shift is that the rapid increase in forest area and quality exceeded the carrying capacity of the relatively limited precipitation, resulting in a decrease in surface runoff and accelerated decline in soil water. Consequently, the declining water resources inhibited forest quality.

Climate change and agricultural water utilization can also accelerate the reduction in surface runoff. As an integrated indicator of multiple meteorological factors, such as precipitation, air temperature, solar radiation, and wind, reference evapotranspiration showed the greatest contribution to runoff decline (35.85%), indicating that climate change has also significantly increased the uncertainty and risk of ERPs. In addition, as agricultural water accounted for 62.5% of the total water resource consumption and the consumption rate of agricultural water was 77.1% in 2015 in the HRB (*37*), both up- and downstream farmland also contributed to surface water decline via direct extraction from streams and groundwater sources (*12*).

Last, additional human interventions, such as reservoir construction and operation, and social development can also influence runoff production. Across long time scales, human activities are a secondary factor affecting runoff compared with meteorological factors. However, these interventions can affect downstream runoff locally or, in the short term, by altering the underlying surface and hydrological cycles (*38*, *39*). In this watershed, these factors appear to have had relatively small impacts on surface runoff reduction. On the one hand, in selected subbasins, large and mid-sized reservoirs and dams for local flood control and irrigation have been in operation since before 1972, with only one of these (Taolinkou Reservoir) reconstructed in 1996 to supply water for a downstream city. The reservoir regulates runoff within a year, and the hydrological station is located upstream of the diversion channel. Therefore, the annual runoff data used for analysis avoided the influence of reservoir operation on runoff variation. On the other hand, the expansion of artificial land and population are not as rapid in this mountainous area as in the downstream plain areas because of the
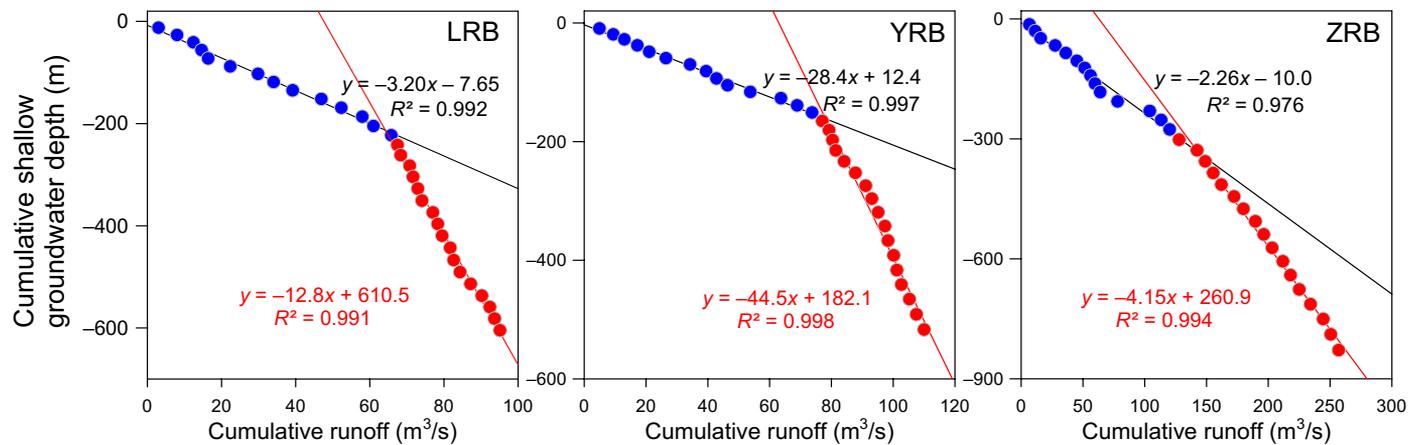
Fig. 5. Cumulative relationship between shallow groundwater in Piedmont plain and surface runoff from revegetated mountainous areas. Blue dots and lines represent observations and fitted trend lines before 1998, respectively; red dots and lines indicate period after 1998, respectively. ZRB, Ziya River Basin (Shijiazhuang Station) (Fig. 1A).
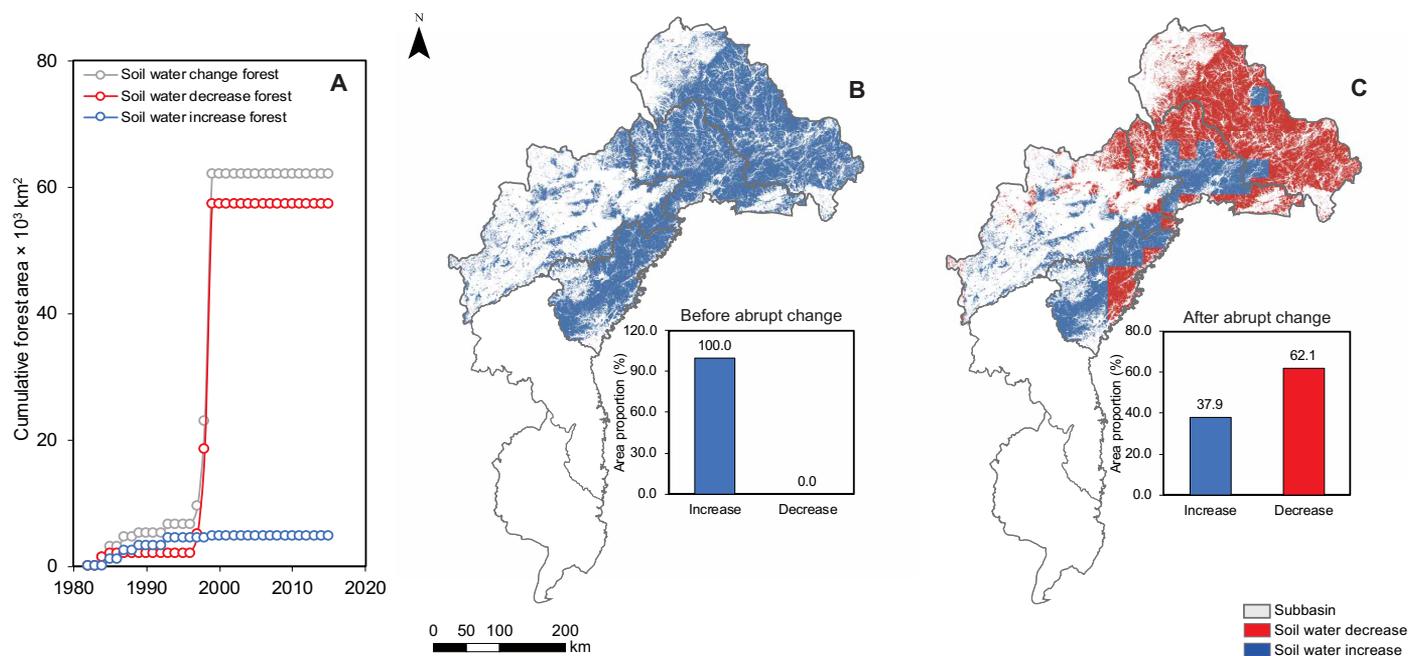

Fig. 6. Cumulative forest area and areal proportion of forest with changes in soil water. (**A**) Cumulative area of forest with abrupt change in soil water. Gray, blue, and orange dot-dash lines represent forest with soil water change, forest with decreasing soil water, and forest with increasing soil water, respectively. (**B**) Distribution and areal proportion of forest with soil water variation before abrupt change year. (**C**) Distribution and areal proportion of forest with soil water variation after abrupt change year.

terrain and local forest and farmland protection policies (section S5 and fig. S4) (*40*).

The pathways affecting runoff decline in the HRB mountainous area are complex and even influenced by nonlocal factors at the subbasin scale, thus highlighting the necessity of large-scale evaluation of ERPs. Moreover, runoff reduction triggered multiscale consequences. Because of the severe shortage of surface water resources in the HRB, groundwater accounts for more than half of the accessed water, much of which is drawn from shallow groundwater sources (*41*). Recognizing the consequences of groundwater overexploitation, the proportion of water from groundwater sources has decreased since the late 1990s (*42*). However, the piedmont plain

groundwater depth continues to decline, especially downstream of revegetated areas. Because surface water is the main source of groundwater recharge in the HRB (*37*), it can be reasonably inferred that, on the basis that groundwater still dominates agricultural water consumption, upstream runoff reductions caused by revegetation programs will accelerate the decline in shallow groundwater depth in the piedmont plain.

In addition to declines in groundwater depth, other successive ecological problems downstream have been induced by runoff reduction in the mountainous areas of the HRB. For instance, the amount of water flowing into Bohai Bay has decreased markedly, with changes in the water-sediment balance reducing the flood

carrying capacity (*43*). The continuously declining groundwater levels have aggravated subsidence in the plain areas and seawater intrusion in the coastal areas of the HRB (*44*). Water conservation facilities, used for tide interception and water storage, have also destroyed the connectivity in stream networks and habitats for aquatic organisms, leading to regional ecosystem degradation in the HRB (*45*).

Last, but not least, on the basis of the degradation that can occur following afforestation programs (*11*), matching afforestation species—ideally native—and designs with local hydrothermal conditions is critical for effective restoration. Biodiversity conservation, which can provide many other ES benefits, hinges on native plant species at the base of the food web. Here, we emphasize the importance of considering large-scale spatial trade-offs and temporal accumulation when ERPs are implemented if catastrophic effects on ecosystems are to be avoided. These considerations are essential to sustain ERPs and improve ecological management and policies, which will be of great benefit to ES synergy in China and elsewhere across the world.

MATERIALS AND METHODS
HRB and vegetation restoration programs
The HRB, located in mideastern China, has a semiarid/semihumid climate, with an annual mean temperature of 0° to 14°C and an annual mean precipitation of 547 mm. The mountainous region, which has an elevational range of 6 to 2 940 m and an area of 16.94×10^4 km^2, is the main water yield area of the HRB (Fig. 1A and section S1). The HRB is a political and economic center. With its high-density population and high rate of urbanization, the HRB has the highest water resource exploitation among China's river basins and has experienced long-term water resource shortages (*37*). Years of water supply and demand imbalance have triggered a series of problems, including surface runoff decrease, lake and wetland shrinkage, groundwater over extraction, water pollution exacerbation, and ecosystem degradation (*45–47*).

Because of the adjoining deserts to its north and west, the HRB is frequently plagued by sandstorms (*48*). To prevent these storms and conserve water and soil, the Chinese government implemented two vegetation restoration programs. The Three-North Shelter Forest Program began in the late 1970s, with a 70-year plan (*49*), and the Beijing-Tianjin Sandstorm Source Control Project started in the early 2000s. These programs aimed to control sandstorm and soil erosion hazards, improve the regional environment, and enhance local and regional communities (section S2). Understanding the effectiveness of ERPs at the junction of arid and semiarid areas is particularly important because of the challenge of desert containment and restoration in dry lands. The mountainous area of the HRB is found within the Taihang Mountains. The indigenous vegetation is mainly broad-leaf deciduous forest, mixed with coniferous forest (*49*). According to afforestation program data, poplar is the major afforestation species, accounting for almost 40% in the area, followed by Chinese pine (~30%) and *Pinus sylvestris*. The other species used are deciduous broad-leaf species, such as oak and willow (*50*). In this study, 15 subbasins in the HRB mountainous area were selected. The reservoirs involved in water conservation projects in the 15 subbasins were built before the 1970s, and effects on runoff did not change during the study period. The locations of the hydrological control stations in the subbasins are shown in Fig. 1.

Data sources
This study used land use, hydrological, and climatological data from 1980 to 2015, as well as NDVI data from 1981 to 2015. Thematic mapper images used to extract land use were obtained from https://glovis.usgs.gov/app?fullscreen=1. The NDVI data were obtained from the National Center for Atmospheric Research (*51, 52*). Hydrological and climatological data were collected from hydrological and meteorological stations (Fig. 1A), and meteorological data were interpolated by spline function based on the ArcMap 10.1 platform. Soil data were downloaded from http://www.ncdc.ac.cn, and elevation and slope data were extracted from the digital elevation model of the HRB, obtained from https://earthexplorer.usgs.gov/. Hydrological data were used for trend analysis of water yield in the mountainous area. Land use, NDVI, precipitation, and air temperature data were used to explore their influence on runoff changes in the study area. Reference evaporation was calculated by the Food and Agriculture Organization Penman-Monteith method (*53*), as shown in section S8. Land use, soil, and geographical data were also used for calculation of sandstorm prevention service provision. The actual evapotranspiration dataset, from 1982 to 2015, was provided by the National Tibetan Plateau Data Center (http://data.tpdc.ac.cn), and the soil water dataset from 1982 to 2014 was provided by the Global Land Data Assimilation System (*54, 55*). The spatial accuracy of all raster data was made consistent at 1 km.

Land use and vegetation quality change
Land use data were extracted from thematic mapper images. According to "Current Land Use Classification" (*56*), land use was classified into six types, including forest, grassland, farmland, water, artificial land, and other. In the mountainous area of the HRB, the combined area of forest, grassland, and farmland exceeded 85% of the entire area, whereas, in the plain area, farmland was the dominant land use type. The NDVI is a comprehensive reflection of vegetation type, cover form, and growth status and was used for forest quality assessment. For details of land use variation between years, please refer to section S5.

Sandstorm prevention service assessment
Wind erosion, one of the three soil erosion pathways, is a key cause of land degradation in northern China. Sandstorm prevention refers to sand retained in an ecosystem within a certain period (*1*). Here, we used the RWEQ to quantify sandstorm prevention service. The RWEQ combines empirical and process modeling and has been extensively tested under broad field conditions. It estimates sand/soil loss at a specific point as a function of several factors, i.e., weather, soil erodibility, soil crust, surface roughness, and vegetation cover. The RWEQ allows estimation of the maximum wind transport capacity from an area. For details, please refer to section S6.

Hydrological and meteorological analysis
Mann-Kendall trend analysis was applied for tendency analyses of water runoff, temperature, and precipitation in the HRB. This method does not require data to follow normal distribution. A Pettitt test and double-mass curve were applied for abrupt change point identification of surface runoff for cross-validation. In addition, to reveal the spatial delivery of water provision services, a double cumulative curve method was applied to analyze the relationship between shallow groundwater and surface runoff in relation to

upstream forest quality. Three monitoring stations with relatively abundant records were selected to study the long-term trends in shallow groundwater in the piedmont plain of the HRB (Fig. 1A). There is a lack of long-term data on shallow groundwater in the region, but data are available for the Tangshan (located at the Luan River outlet, northern HRB), Beijing (located at the Yongding River outlet, central HRB), and Shijiazhuang stations (located at the Ziya River outlet, southern HRB). For details, please refer to section S7.

Relative contribution rate of surface runoff reduction

Surface runoff is largely influenced by meteorological and land use factors as well as human utilization. Here, Spearman's rank correlation was first used to analyze the strength and direction of correlations between runoff variation and various influencing factors [including precipitation; air temperature; reference evaporation (section S8); area of forest, grassland, farmland, wetland, and artificial land; and NDVI], and to eliminate correlated variables. Multiple linear regression was then used to identify the main influencing factors (meteorological and land use). Next, the differences before and after the driving force change point were used as independent variables in the selected subbasins, while the difference in surface runoff was used as the dependent variable. Last, the sum of squared deviations from the mean was used to quantify the relative contribution of each main factor using variance analysis (57). For details, please refer to section S9.

SUPPLEMENTARY MATERIALS

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