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Research article

Ecosystem water imbalances created during ecological restoration by afforestation in China, and lessons for other developing countries

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ABSTRACT

Land degradation is a global environmental problem that jeopardizes human safety and socioeconomic development. To alleviate severe soil erosion and desertification due to deforestation and overgrazing, China has implemented historically unprecedented large-scale afforestation. However, few studies have accounted for the resulting imbalance between water supply (primarily precipitation) and water consumption (evapotranspiration), which will affect ecosystem health and socioeconomic development. We compared the water balance results between restoration by means of afforestation and restoration using the potential natural vegetation to guide future ecological restoration planning and environmental policy development. Based on estimates of water consumption from seven evapotranspiration models, we discuss the consequences for water security using data obtained since 1952 under China's large-scale afforestation program. The models estimated that afforestation will increase water consumption by 559–2354 m^3/ha annually compared with natural vegetation. Although afforestation is a potentially important approach for environmental restoration, China's current policy has not been tailored to local precipitation conditions, and will have therefore exacerbated water shortages and decrease the ability to achieve environmental policy goals. Our analysis shows how, both in China and around the world, future ecological restoration planning must account for the water balance to ensure effective and sustainable environmental restoration policy.

1. Introduction

Degradation of the world's terrestrial ecosystems is a primary environmental problem that affects the sustainable development of human society. It directly threatens agricultural and industrial activity and human livelihoods, but can also indirectly jeopardize the sustainability of global socioeconomic development (D'Odorico et al., 2013). The ramifications of this process result from several factors, including natural factors such as ecological and climatic variations and anthropogenic factors such as agriculture and grazing (Steltzer et al., 2009). In many areas around the world where deforestation has occurred due to an unsustainable demand for wood fuel and where overgrazing has led to severe soil erosion and desertification, vegetation restoration efforts have been attempted (Chazdon, 2008). In many cases, this has taken the form of afforestation (Wang et al., 2011), with the world's most extensive afforestation program undertaken in China (Li, 2004). For example, from 1952 to 2011, 32.3% of China's territory (nearly 3.1×10^6 km^2) was afforested to provide wood for the forest industry, for ecological conservation, and for water-conservation reforestation, among other goals. At the U.N. Climate Summit on 22 September 2009, China's President Hu committed to expanding the country's forest area by 40×10^6 ha between 2006 and 2020 (Yin et al., 2010). China's goal is to increase forest cover from 16.6% in 2000 to 26% by 2050 by means of the largest tree-planting program in the world (Wang et al., 2007).

China is leading global afforestation efforts, with one-third of the world's total plantation forests now growing in China (Cao and Zhang, 2015). However, the vegetation's potential growth capacity in a region is limited by the region's precipitation resources, so new vegetation with low water-use efficiency, including many types of forest, may be unable to survive without supplemental irrigation; without this water input, the restored ecosystem will become

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unstable and begin to degrade, with decreased ecological functions (Yu et al., 2010; Wang et al., 2011). Because the water supply for vegetation derives primarily from a region's precipitation resources, water consumption by one component of an ecosystem (e.g., a forest) will decrease the availability of water to meet the needs of other ecosystem components. In some cases, the imbalance between inputs and outputs (net consumption) is sufficiently severe that it will permanently disrupt an ecosystem's water balance, causing unexpected results such as plantation failure, continuing degradation, and successional changes to a different ecosystem.

Therefore, ecosystem restoration must be based on solid science, and in particular, it must consider the impacts of new vegetation communities on regional water availability (Li, 2004). However, large-scale afforestation has complex and poorly understood consequences for the structure and composition of future ecosystems (Cao and Zhang, 2015). It is thus necessary for the international science and policy communities to examine whether afforestation truly represents a major step forward, or whether it may instead exacerbate a situation that is already severe in some parts of the world. The potential of forests to improve a region's water environment (Ellison et al., 2012) and to provide other ecosystem services (Molle and Berkoff, 2009) is well known, but it is not always clear whether this potential can be achieved. For example, poplar species (*Populus* spp.) grow rapidly (thereby providing significant biomass energy potential), can survive in a wide range of environments, and can be integrated within agroforestry systems (Ciadamidaro et al., 2013). However, Folch and Ferrer (2015) found that these species use water inefficiently; in their study in the Mediterranean basin, they found that consumption of aquifer water by poplar species averaged 2.40×10^6 m^3 ha^{-1} annually, which is equivalent to nearly 20% of the average annual recharge from precipitation; as a result, planting poplar under these conditions can have serious negative consequences for residents, farmers, and the environment.

In a previous research, Cao and Zhang (2015) investigated the political risks created by afforestation on the Tibetan plateau with the goal of guiding future ecological restoration planning. In order to understand the impact of afforestation on an ecosystem's water balance and guide future ecological restoration planning, water resource management, and development of environmental policy, the water balance resulting from ecological restoration was calculated by comparing restoration via afforestation with restoration based on the conservation of a region's potential natural vegetation. To do so, the water balance for artificial forestland of China was estimated using seven previously published evapotranspiration models (Chen et al., 2014). Details of this analysis are provided in the supplemental material of Cao and Zhang (2015). In the present study, we extended this analysis to the rest of mainland China. To support model development, we obtained data on the area of man-made forests at national and provincial levels from China's annual forestry yearbooks (State Forestry Administration, 1987–2012) and from China's 7th national forest resource inventory bulletin (State Forestry Administration, 2009). We also obtained precipitation data from climate yearbooks (State Climate Administration, 2002–2012).

2. Methods

We used afforestation data for all provinces from China's annual forestry statistics reports (State Forestry Administration, 1987–2012) in our analysis. This data included the area of man-made forest (i.e., plantations), ecological forest (i.e., forest established to create or enhance an ecosystem), and water-conservation forest (i.e., forest designed to decrease surface flows and increase water infiltration into the soil) established in each year. We used the most recent forest survival data that were available, from China's 7th national forest resource inventory bulletin (State Forestry Administration, 2009), to understand the impact of the afforestation on China's water balance. We compared the water needs of the surviving trees with those of natural vegetation based on the assumption that land with stable natural vegetation (generally, degraded natural grassland or steppe vegetation with little perceived economic value) would not be converted to forest. Note that the analysis does not calculate the change in water consumption between the pre- and post-afforestation states, since insufficient data was available to support such a comparison; instead, the comparison was between water use by two hypothetical vegetation types (natural vegetation versus forest). The choice of grassland or steppe vegetation as the standard of comparison was based on the afforestation data, which suggested that Chinese afforestation was predominantly conducted to restore degraded natural grasslands. We then obtained precipitation data for every province from the research literature (Chen et al., 2002) and from annual climate yearbooks (State Climate Administration, 2002–2012), and used this data to estimate the available water resource in each province in each year.

For determining the impact of afforestation on the water balance of ecosystems in different regions of China, we divided China into eight regions based on the total annual precipitation at a provincial scale. This is because Chinese data are currently only available at a provincial scale, so it was not possible to obtain data with finer resolution, such as at the level of individual watersheds. The eight regions are the arid northwest, semi-arid north, semi-arid Loess Plateau, cold and semi-humid northeast, cold and high-altitude Tibetan plateau, semi-humid southwest, warm and semi-humid central region, and warm and humid south.

To calculate the water needed by the trees that were established by afforestation, we estimated evapotranspiration by forests and the potential natural vegetation in each province using seven previously published models of evapotranspiration. For details of the models, see Chen et al. (2014); in summary, each of the models that we used accounts for the effects of key environmental variables (e.g., temperature, relative humidity) and key vegetation characteristics (e.g., vegetation type, vegetation cover) that drive evaporation and transpiration. It was not possible to select a single optimal model suitable for use for all of China's highly heterogeneous landscape and no evapotranspiration model has been parameterized and validated for the regions of China that we studied. Instead, averaging the results from multiple models should let the strengths of some models compensate for the weaknesses of other models. The locations of each new forest within a province or watershed are not accurately known, and other factors make it impossible to accurately estimate evapotranspiration for each individual forest; these include differences in water usage by restored vegetation with different ages, different plantation densities, variations in site fertility (thus, in growth rates and biomass production), differences in topographic complexity, and the uneven and poorly understood distribution of precipitation within a province or watershed. Thus, we used overall recorded afforestation areas and overall precipitation levels in our models rather than performing a spatially explicit analysis using site-specific data. Our goal was to provide an overall estimate of regional water budgets; as finer-grained data becomes available (e.g., at a watershed scale), it will become increasingly possible to adapt our methodology to support watershed-specific or even site-specific estimates.

To improve the accuracy of our results, we used seven different models that were previously tested and verified by Chen et al. (2014) to calculate evapotranspiration by the forests and potential natural vegetation in each province in each year. Details of our analysis are provided by Cao and Zhang (2015). In the present study, we averaged the values from all seven models to produce a single average value for each of the eight regions of China. We then compared these results with the corresponding estimates for the natural grassland or steppe vegetation that the forests replaced. In future research, calibrating and validating each model using data from each site, watershed, or region would let us select the best model for that scale of data and thereby improve the accuracy of our estimates; however, such an exercise is not possible given the currently available data, and is beyond the scope of the present study. We used the difference between the water consumption values of the artificial forests and natural vegetation to represent the amount of water that could potentially be saved if the natural vegetation was not converted to forest, but was instead protected or restored.

3. Results and discussion

3.1. Comparison of water consumption between natural vegetation and afforestation

We found that the water consumed by forests has increased greatly since 1952 (Fig. 1) because of increasing afforestation during this period. The seven models estimated that afforestation will increase net water consumption by 559–2354 m^3/ha annually compared with the amount that would be consumed by the potential natural vegetation. Based on the assumption that all the planted trees survived, then the trees planted in afforestation areas would have consumed a total of 2439.6×10^9 m^3 of water (ranging from 1952.7×10^9 m^3 to 2749.1×10^9 m^3 for the seven models) in 2011. The average proportion of the precipitation consumed by the trees planted in China has climbed from 0.1% in 1952 to more than 46.4% in 2011. In contrast, if the afforested land had been conserved as natural grassland or steppe (which is the dominant potential natural vegetation in most afforestation areas), the average decrease in water consumption in 2011 would total 432.3×10^9 m^3 of water (the average from the seven models), equivalent to nearly 8.2% of the precipitation in that year. This difference of 38.2 percentage points amounts to about 11 times the water stored in the Three Gorges Dam, which is the largest dam in the world, with a maximum water capacity of 39.3×10^9 m^3 (Yang et al., 2006).

From 1978 to 2011, China performed 70.3×10^4 km^2 of ecological restoration afforestation. These trees would consume an average (based on the estimates from the seven evapotranspiration models) of 47.3×10^9 m^4 of water in 2011, equivalent to 9.0% of the precipitation. This program is based on the belief by China's government that forests perform a wide variety of functions, such as soil and water conservation, prevention of wind erosion, fixation of

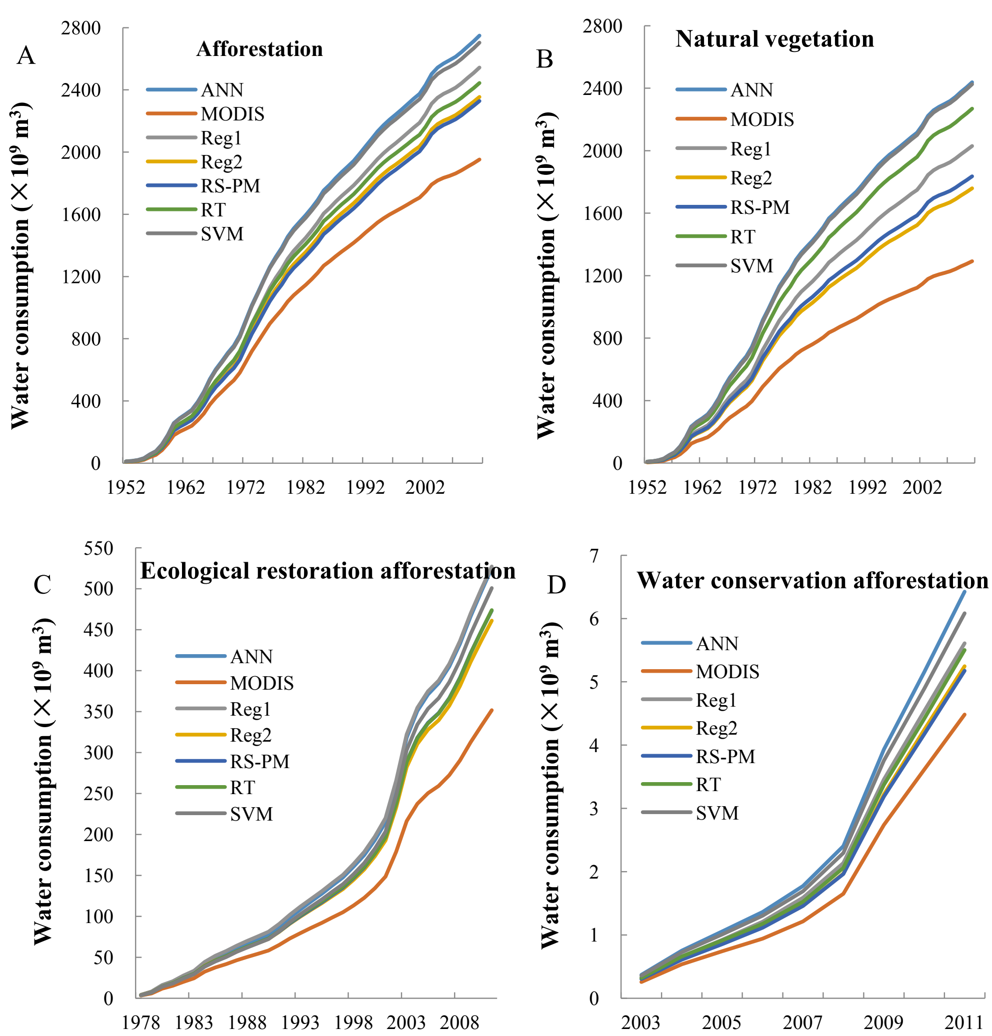

Fig. 1. Water consumption caused by (A) afforestation, (B) conservation of potential natural vegetation (grassland or steppe), (C) ecological and restoration afforestation and (D) water conservation afforestation using the seven evapotranspiration models. Note that the values on the y-axis decrease greatly from (A) and (B) to (C) and (D).

mobile sands, climatic regulation, and pollution reduction (Dou et al., 2006; Wang et al., 2011). However, forests cannot always simultaneously produce multiple positive ecosystem services because of the trade-offs among competing functions (Normile, 2007; Wang et al., 2011). Nonetheless, in addition to the ecological restoration, 7.0×10^3 km^2 of land were planted under the "water-conservation afforestation" program from 2003 to 2011; given the present results, this may be an inappropriate name. Although the goal of protecting the quality of water resources to sustain humans and socioeconomic activity is laudable, the planted trees would have consumed a total of 5.5×10^9 m^3 of water in 2011 (average value based on the seven models; Fig. 1).

Because of deforestation, mortality, natural self-thinning, and unsustainable logging, the actual plantation area is far lower than the values shown in Chinese statistical yearbooks. For example, China's 7th national forest resource inventory bulletin suggests that survival of the planted trees was only 20.6% from 1952 to 2008 (State Forestry Administration, 2009). To understand the impact of tree survival on the water balance of terrestrial ecosystems in different regions of China, we calculated the water consumption in the existing plantations based on the most recent (2008) survival data that was available. Afforestation in the arid northwest, semi-arid north, and semi-arid Loess Plateau regions consumed 40.8×10^9, 47.5×10^9, and 20.7×10^9 m^3 of water in 2008, respectively. In contrast, if the natural vegetation were conserved, this would have potentially saved an average of 10.5×10^9, 5.3×10^9, and 6.0×10^9 m^3 of water in 2008 in these regions, respectively, for a total saving of 21.8×10^9 m^3 (Fig. 2). These savings are significant given that China's government plans to invest a total of 71.4×10^9 USD to divert 45×10^9 m^3 of water annually from southern China to the north under the south-to-north water diversion project (Liu and Yang, 2012).

The size of the water imbalance caused by these afforestation projects suggest a high risk of plantation failure. For example, field evidence in the northern arid and semiarid regions showed that the soil moisture content in the afforestation plots is 42.8–63.2% lower than that in comparable abandoned plots (Cao and Zhang, 2015). In addition, it is very difficult to restore the level of groundwater once the water table depth has increased (Gates et al., 2008), which suggests that these changes may lead to permanent decreases in the ground's capacity to store water. Decreased soil moisture in the afforestation plots, combined with reduced sunlight under the tree canopies (thereby reducing the growth of understory vegetation), has decreased the vegetation cover by 30.5% in the afforestation plots in arid and semi-arid regions of northern China (Fig. 3). In addition, afforestation is an expensive ecological restoration policy because the afforestation program has cost more than 70×10^9 RMB annually (approximately US$11 $\times 10^9$ based on the exchange rate in July 2015) since 2000, whereas conserving natural vegetation while also saving large amounts of water in some areas would be more cost-efficient and would permit reallocation of the water to more important uses, such as restoring aquifers (Duan et al., 2004).

3.2. Implications for China and the world

Large-scale afforestation that fails to account for the impacts on water consumption may exacerbate land degradation, such as the desertification that is occurring in dry areas of China, and this will, in turn, have adverse effects on socioeconomic development (Bosch and Hewlett, 1982; Brown et al., 2005). The present results show the huge amounts of water consumed in afforestation-based ecological restoration, which are much larger than the amounts that would be consumed by restoration based on preserving or enhancing each region's natural vegetation. Although the assumption of 100% planted tree survival is unrealistic, complementary planting has been conducted in many areas to maintain the tree cover achieved by afforestation, so it may not represent an unacceptable exaggeration. And, it is important to note that the present analyses did not account for how water consumption by trees changes as the trees mature; this could change the net effect of afforestation from positive to negative at some time after the planting. No data is currently available to support such an analysis, which remains an important problem to be solved by future

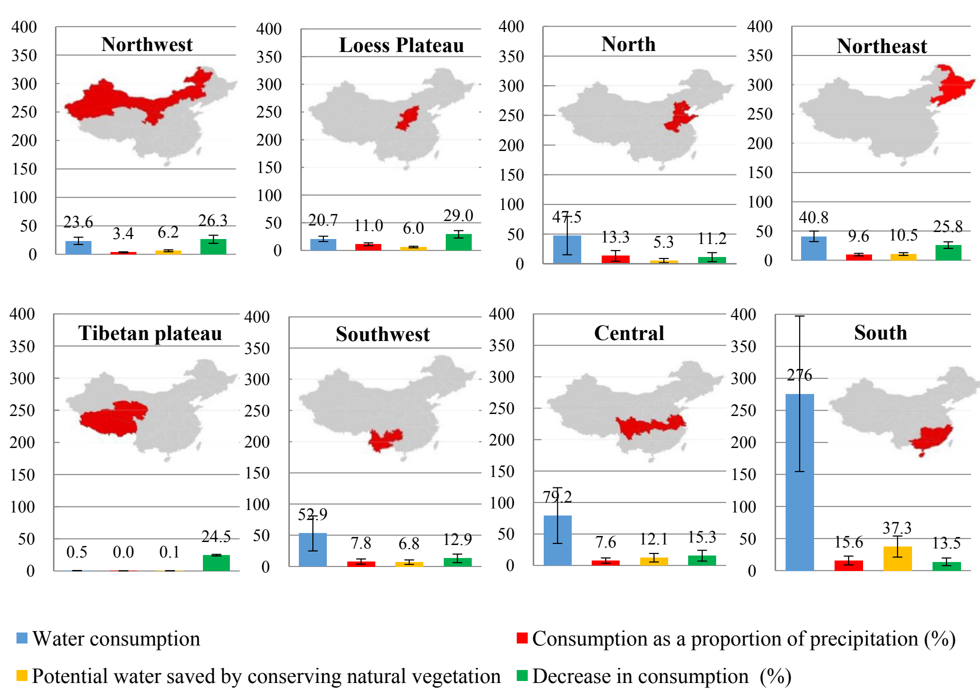

Fig. 2. Water consumption in China by the trees that survived after afforestation. Values represent the mean ± SD for the output from the seven evapotranspiration models.

Fig. 3. An example of the natural vegetation cover (top left) and the vegetation cover in afforestation plots (top right) in China's northern Hebei Province, and the natural vegetation cover (bottom left) and the vegetation cover in afforestation plots (bottom right) in China's southern Inner Mongolia Autonomous Region.

research.

This conclusion suggests that the pressure on northern China's water resource may be more serious than the pressure in the south. Compared with the southern regions, the northern region's lower precipitation and higher evaporation make it more vulnerable to water depletion, particularly since residents of these regions also have a heavy water demand. The competition for water between local people and trees is likely to increase as a result of the large-scale afforestation program, which may not be sustainable, because the afforestation will increasingly deplete soil moisture.

If the ecological restoration strategy can be shifted from afforestation to the protection or re-establishment of grassland and steppe communities, the water-use efficiency could increase by an average of 20% in northern China and 13% in southern China (excluding the Qinghai-Tibetan Plateau). However, it is important to note that despite the large improvement for grassland versus forest vegetation, grassland may not be the most appropriate vegetation for all regions of China or even for all watersheds within a region. First, there may be different vegetation communities (e.g., desert steppe) that are more suitable for some regions. Second, ecological restoration must consider more factors than just vegetation cover. For example, it must be integrated with social development to ensure that local residents can support rather than fight against the restoration programs; that is, the programs must encourage these residents to engage in sustainable development.

The second point is particularly important. In the long term, China's ecological goals cannot be achieved without active participation from its population, and this participation cannot be achieved without offering them the hope of social progress. Because most of the regions where ecological restoration projects have been launched are impoverished and remote, any future restoration projects must be implemented to avoid conflicts with local communities. China's large-scale afforestation often fails to meet this requirement; if residents of an area are not offered new forms of employment, the requirements of survival may force them to return to the old practices that cause deforestation or grassland degradation (Cao and Zhang, 2015). Properly understanding the water balance created by restoration projects is important, but the social consequences of restoration cannot be neglected.

The concept of a carrying capacity for water resources requires a complex consideration of the water needs of both nature and society over large scales. A region's population, resources, environment, ecology, society, economy, and many other factors interact in the form of both positive and negative feedbacks (Feng and Huang, 2008). Global population growth and socioeconomic development increase both the demand for water and the vulnerability of modern society to water shortages (Campana et al., 2012). Conflicts between environmental and human uses intensify during population growth and socioeconomic development, and mechanisms (some planned, but many not) develop to rebalance water allocation among the many consumers of water (Molle and Berkoff, 2009). Between 1.5 and 2 billion people rely on groundwater for domestic consumption, including 1 billion Asian urban residents, almost 99% of the rural United States population, and 80% of India's population (Molle and Berkoff, 2009). Choosing an appropriate mix of policy parameters to provide water to meet their needs and those of their environment is difficult, although scientific research based on system dynamics techniques can help (Feng and Huang, 2008). Policy parameters such as economic data, development rates, and long-term strategies undoubtedly affect the size of the population that can be supported by a region's water resources (i.e., its water carrying capacity), whether or not sustainable socioeconomic development is possible, and whether the regional ecosystem can be sustained.

China has the largest population in the world, but has only 25% of the global average per capita water availability (Luo et al., 2013).

With the rapid socioeconomic development that is currently occurring, the national shortage of water resources has become critical; more than 500 million Chinese citizens experienced serious shortages of drinking water in 2011 (Liu and Yang, 2012).

Climate change seems likely to exacerbate this situation, since the current warming trend will increase evapotranspiration, leading to even more severe water shortages during dry years. This may even be true in humid regions; for example, unusually dry summers in 2004, 2006, 2009, 2011, and 2012 created a shortage of drinking water for 7.2×10^6, 27.0×10^6, 18.1×10^6, 17.9×10^6, and 6.3×10^6 residents, respectively, of southern and southwestern China (Cao and Zhang, 2015). The problem is not limited to China, since other countries such as India that depend on monsoon rains are vulnerable to water shortages that could be exacerbated by inappropriate afforestation (Batchelor et al., 2003). Our models suggest that afforestation would consume 37.3×10^9 and 6.8×10^9 m^3 more water than the potential natural vegetation in southern and southwestern China, respectively.

The strong linkages between economic trends, agricultural policies, and water use will require both researchers and managers to adopt an integrated modeling approach based on input from experts in multiple disciplines (Fraiture, 2007). One important solution will be to manage the demand for water; that is, it will be necessary to make better use of the available water rather than trying to increase the water supply (Molle and Berkoff, 2009). This approach requires an improvement in the economic efficiency of water use by increasing the productivity per unit of water consumption and improving the social welfare that can be obtained from alternative uses of the water. As the present results show, afforestation may not be a sustainable option because of its low water-use efficiency.

4. Conclusions

The present results demonstrate excessive water consumption by afforestation in eight regions of China and discuss the implications for the management of China's water resources. Afforestation greatly increased the imbalance between a region's water supply and its consumption (by up to 2354 m^3/ha annually in our modeling) compared with the potential natural vegetation, even in areas such as southern and southwestern China that have high annual precipitation. This finding has important implications for other developing countries where similar afforestation programs have been proposed: before implementing afforestation, these countries must carefully assess the effects on the regional water resource and whether other alternatives might be more effective both ecologically and socially.

Although afforestation is a potentially important approach for environmental restoration, China's current policy has not been tailored to local precipitation conditions, and has therefore exacerbated water shortages and decreased the ability to achieve environmental policy goals. To make more water available to sustain human lives and socioeconomic development, it would be more effective to restore degraded ecosystems using species such as dwarf shrubs and natural grassland or steppe vegetation that are chosen based on maximizing water-use efficiency rather than based on economic goals such as the rapid production of wood fiber.

Given the complexity of climate change and the wide range of pedological, hydrological, and landscape factors in a country as large as China, managers must understand the tradeoffs among ecological and socioeconomic benefits, and between short-term and long-term benefits, with the tradeoffs determined based on the unique constraints in each region. Scientists have an obligation to help managers account for the findings of our study so as to provide a more scientific basis for ecological restoration. Ecological managers elsewhere in the world must make similar efforts to learn from China's example and determine how it applies in their own unique contexts. Formulating a more sustainable restoration policy based on integrated solutions that balance environmental constraints with the need for ecological restoration and the need for socioeconomic development will require policymakers and scientists to work together to avoid problematic policies such as China's current emphasis on afforestation.

Conflicts of interest

The authors declare no conflict of interest.

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