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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