Journal of Cleaner Production xxx (2016) 1–10

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

# Ecological restoration by afforestation may increase groundwater depth and create potentially large ecological and water opportunity costs in arid and semiarid China

Chenxi Lu [a], Tingyang Zhao [b], Xiaoliang Shi [c, d], Shixiong Cao [b, *]

[a] Center for Earth System Science, Tsinghua University, MengMinwei Science Building, Qinghuayuan 1, Beijing 100084, China
[b] College of Economics and Management, Beijing Forestry University, No. 35, Qinghuadong Road, Haidian District, Beijing 100083, China
[c] College of Economics and Management, Shenyang Agricultural University, Shenyang 110866, China
[d] Chinese Research Academy of Environmental Sciences, Beijing 100012, China

ARTICLE INFO

*Article history:*
Received 15 July 2015
Received in revised form
26 March 2016
Accepted 26 March 2016
Available online xxx

*Keywords:*
Afforestation
Ecological restoration
Evapotranspiration
Groundwater table
Opportunity cost
Water scarcity

ABSTRACT

Water scarcity is a global environmental problem that jeopardizes human safety and socioeconomic development. Since 1952, China has implemented a large-scale tree-planting program in the country's arid regions to combat desertification. However, there is a serious risk this program will exacerbate water shortages and lower the groundwater table: the trees selected for this program were not chosen based on local environmental constraints, and their evapotranspiration exceeds the regional precipitation. However, no data on the afforestation's effects on the groundwater table is available. This is problematic because any loss of groundwater will severely constrain socioeconomic development in China's arid and semiarid regions, which already face severe water shortages. The economic concept of a groundwater opportunity cost could be used to guide socioeconomic activities to improve the sustainability of groundwater use and mitigate the potential problems caused by the Chinese afforestation program. In this paper, seven evapotranspiration models were used to provide the first estimate of the opportunity cost created by afforestation's adverse effects on the groundwater resource. The results showed that the groundwater table declined yearly throughout the study area, with mean water opportunity costs in 2011 ranging from $0.04 \times 10^9$ RMB to $11.1 \times 10^9$ RMB under nine provinces in arid and semiarid China. This study provides the first solid evidence that afforestation in arid and semiarid northern China will exacerbate the groundwater decline while creating enormous opportunity costs. Thus, the afforestation program must be urgently reassessed and the water-use efficiency of vegetation must be considered when planning future ecological restoration both to make the restoration more cost-effective and to protect the ecosphere.



## 1. Introduction

During China's rapid economic growth, land degradation (including soil erosion and desertification) became widespread as a result of unsustainable agriculture, overgrazing, and other human activities. In addition to the serious environmental consequences, this has begun to jeopardize socioeconomic development (Sivakumar, 2007; Steltzer et al., 2009). To alleviate these severe problems, China has invested huge sums of money to implement the largest tree-planting program in history, with one-third of the world's total area of plantation forest now growing in China (Li, 2004; Wang et al., 2007; FAO, 2013). Most of these programs have been implemented in the arid and semiarid regions of northern China to combat desertification and to control the dust storms that threaten densely populated areas to the south and east (Li, 2001; Yang, 2004; Liu et al., 2008). Under these programs, $28 \times 10^6$ ha of forests were planted from 2000 to 2005 alone (Chazdon, 2008). China's afforestation managers aim to increase the nation's forest cover to 26% of the total land area by 2050 (Wang et al., 2007).

It is well known that forests can potentially protect and sustain a region's water environment (Ellison et al., 2012) and provide many additional ecosystem services (Molle and Berkoff, 2009), such as

* Corresponding author. Tel.: +86 10 6233 7038; fax: +86 10 6233 7674.
*E-mail address:* shixiongcao@126.com (S. Cao).

http://dx.doi.org/10.1016/j.jclepro.2016.03.046
0959-6526/© 2016 Elsevier Ltd. All rights reserved.

prevention of wind erosion, fixation of mobile sands, climate regulation, and pollution reduction (Dou et al., 2006; Wang et al., 2011). However, it is not yet clear whether this potential can be achieved by China's afforestation programs, and some researchers have expressed doubt (Wang et al., 2010; Cao et al., 2011). Afforestation managers tend to establish short-lived trees or shrubs that are fast-growing, and that offer attractive short-term gains in terms of forest regeneration and environmental restoration, since relying on natural succession processes could take a century or more to achieve similar results (Chazdon, 2008).

However, there is a reason why natural succession is slow in arid areas: growth of the vegetation is strongly constrained by the low amount of available water. In many areas, the carrying capacity for forest vegetation is determined by the amount of precipitation (Donohue et al., 2007). In addition, many plant communities are highly susceptible to annual and seasonal changes in the depth to the groundwater (Le Maitre et al., 1999). Yet most of the programs that were implemented in northern China were not tailored to the local precipitation conditions or to local hydrological, pedological, climate, and landscape factors (Wang et al., 2010; Cao et al., 2011). The transpiration by trees and shrubs that have been planted in arid and semiarid areas tends to be greater than that of the natural climax vegetation, which typically forms communities of small halophytic subshrubs, steppe and savanna vegetation, and some herbaceous vegetation on aeolian sands and other soils that are vulnerable to wind erosion (Wang et al., 2006, 2008a). For example, poplars (*Populus* spp.) have been widely planted in China's arid areas to restore abandoned farmland or fix mobile sands, as well as to perform other ecological functions (Gao, 2007), even though poplars tend to have low water-use efficiency. A recent experiment by the Chinese Academy of Forestry showed that transpiration by 8-year-old poplar was 9.4% greater than the precipitation received during the same period (Wang et al., 2006). Under such conditions, "thirsty" vegetation must exploit deep soil water to survive. However, because this water is recharged primarily by precipitation, the groundwater table will steadily decline until the water is too deep for even the trees to reach. Long before that point is reached, shallow-rooted vegetation that depends on near-surface soil water may be unable to survive (Duan et al., 2004; Cao et al., 2011).

This is particularly unfortunate given that shallow-rooted vegetation is the dominant form of natural vegetation in arid northern China (Wang et al., 2006, 2008a). When the natural vegetation degrades sufficiently, it can no longer protect the soil or intercept the surface flows of water that would ordinarily be used to recharge groundwater. The water may instead flow over the surface, causing erosion and exacerbating the soil water deficit. As the groundwater continues to decline, the trees will also begin to experience moisture stress, and mortality will begin to occur, thereby impairing the forest's ecological functions (Xu et al., 2010; Yu et al., 2010; Wang et al., 2011; Ellison et al., 2012). The result may be worse desertification than before the trees were planted. If this problem is widespread in northern China, then the afforestation program may have a huge negative effect due to its effect on groundwater and may make the ecological environment even worse.

At a global scale, fresh water (both surface water and groundwater) is essential for human survival, and water supplies are under a growing threat (Allen and Chapman, 2001). Thus, sustainable management of water resources is essential for the present generation as well as for future generations. In semiarid and arid regions, groundwater is a potentially stable and widely distributed resource that plays a fundamental role in socioeconomic development and human survival (An et al., 2015). Because groundwater often requires little or no treatment before use in industrial or domestic situations, many local authorities and industries make the groundwater an economic potion (Gray, 1994). China's groundwater is an endangered resource, and water scarcity is an issue of growing concern for China, particularly in the north (Scott, 2014). Across the whole country, 164 major groundwater areas are being exploited unsustainably, causing the depth to the groundwater table to increase by an average of 1.5 m per year in the arid and semiarid regions in the north (Wang et al., 2008b). For example, the groundwater table has dropped by 65 m in Beijing's urban area since 1965 (Li, 2000). This has resulted from a combination of factors, including a trend of decreasing precipitation and increasing human activities such as reservoir construction and agricultural irrigation (Wang and Jin, 2000). However, although these factors are generally well understood, researchers have neglected the impact of China's national ecological restoration programs, including the afforestation program. According to some researches, the main influence of afforestation on water resources, regardless of the type of forest cover, is to reduce the water yield, which is the proportion of total rainfall that reaches the soil surface and either infiltrates the soil or becomes surface runoff (Bosch and Hewlett, 1982; McCulloch and Robinson, 1993). This reduction would increase the depth to the water table. In contrast, clearcutting could potentially increase the water yield (Hibbert, 1967). However, most afforestation research has focused on its positive economic and ecological effects. Economic effects include the provision of a supply of wood pulp and timber and a decrease in the loss of the remaining natural forests. Jiang et al. (2003) estimated that China's plantation forests will potentially provide $130 \times 10^6$ $m^3$ of wood annually by 2015, which is enough to meet domestic needs. The ecological effects include improved nutrient cycling, improved soil quality, and increased carbon sequestration (Buscardo et al., 2008; Berthrong, 2009; Rey Benayas et al., 2009; Zhao, 2008). Other researchers have studied how to improve survival of the planted forests and their management (Chen, 2010).

In contrast, there has been relatively little research on the potential adverse effects of the afforestation program on soil nutrients, biodiversity, and other factors. Afforestation based on fast growth of trees and subsequent biomass harvesting may deplete nutrients and degrade soils if the forests are managed improperly (Mendham et al., 2003; Merino et al., 2004; Zhang et al., 2004; Berthrong et al., 2009). If these problems occur, afforestation will decrease tree productivity in future rotations and reduce the land's long-term potential as a carbon sink (Bi et al., 2007). Although these problems are important, the enormous size of China's afforestation program makes it urgently necessary to learn its effects on groundwater, especially in arid and semiarid areas. The risk of socioeconomic impacts is becoming increasingly serious as competition for the scarce available water increases, and this reinforces the importance of detecting any adverse impacts before they cause irreversible damage.

To understand the impact of afforestation on groundwater and the cost of the groundwater consumed by afforestation in China's arid and semiarid areas, the present study focused on nine provinces and provincial-level regions (Beijing, Hebei, Henan, Shanxi, Shaanxi, Ningxia, Inner Mongolia, Gansu, Xinjiang) that have been the focus of China's tree-planting program and that are also located in environmentally fragile arid or semiarid regions that currently face a water scarcity. Although ecological problems are obviously important, they are difficult to quantify because of the long time it can take for the problems to become apparent, and the risk is therefore difficult to communicate to decision makers. The potential problems caused by afforestation were therefore expressed in terms of water opportunity costs; these arise because the water lost as a result of the increased evapotranspiration that occurs after afforestation can no longer be used for other purposes, such as to meet residential, industrial, and agricultural needs. Data from these

Please cite this article in press as: Lu, C., et al., Ecological restoration by afforestation may increase groundwater depth and create potentially large ecological and water opportunity costs in arid and semiarid China, Journal of Cleaner Production (2016), http://dx.doi.org/10.1016/j.jclepro.2016.03.046