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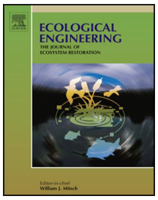

Effects of large-scale afforestation project on the ecosystem water balance in humid areas: An example for southern China

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ABSTRACT

Massive afforestation and reforestation programs have been implemented around the world to restore degraded land and respond to climate change. Many studies suggest that such large-scale campaigns may be counterproductive if there is insufficient water to sustain the trees, especially in dryland. However, we suggest the large-scale afforestation may become a new problem even in humid regions with abundant water, and that the problem will be exacerbated by climate change. To test this hypothesis, we compared the water surplus (evapotranspiration) of natural vegetation and planted trees in 15 provinces of southern China using eight evapotranspiration models. The planted forests consumed considerably more water than natural vegetation, thereby utilizing water that would otherwise be available to support other uses. It may raise water conflicts among sectors in climatic change. We found that if artificial restoration by afforestation or reforestation were replaced by restoration of the natural vegetation, water-use efficiency would improve by 9.97–16.34% in different regions. Uncritical acceptance of large-scale planting of woody vegetation may therefore reduce the ecosystem's resilience against climate change in the short term and increase the long-term risks of water conflict in society in long run if major climatic shifts over. It is therefore necessary to carefully assess whether the benefits of the planted forests outweigh the potential negative environmental and socioeconomic consequences.

1. Introduction

Widespread deforestation or degradation of forests around the world have impoverished the environmental, economic, and esthetic characteristics of these landscapes, and may have exacerbated the effects of climate change (Lamb and Gilmour, 2003; Bates et al., 2008). Many countries and international organizations have chosen afforestation or reforestation as a way to expand or restore these forests and mitigate the effects of climate change. Such projects include the REDD$^+$ program (Reducing Emission from Deforestation and Degradation) implemented by the United Nations and the forest conservation programs implemented by the International Union for Conservation of Nature and the World Wildlife Fund (Lamb and Gilmour, 2003). China has emerged as a world leader in afforestation because of the nation's massive investments in tree planting. From 1990 to 2010, China's forest cover improved from 12% to 18% of the land area through massive planting programs combined with a national ban on logging in many areas (Ridder, 2007; World Bank, 2010). Since 2000, China's forestry investments have sharply increased and have now exceeded the total investments from 1949 to 1999 (Wang et al., 2007). The Chinese government invested 936×10^9 RMB between 2000 and 2011 (NBS, 2009). At the 2009 Copenhagen climate summit, former president Hu Jintao promised that China would add 4×10^6 ha of forest between 2005 and 2020 to combat climate change. This will require continuing implementation of the world's most ambitious afforestation project.

Afforestation and reforestation are key responses to climate change, since forests can partition large amounts of carbon and protect soil carbon from processes such as exposure to direct sunlight that would accelerate the loss of carbon from the soil. As a result, afforestation has been implemented in many areas of the world. Unfortunately, artificial forests (usually quick growing

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species) often consume more water than the natural vegetation they replace (e.g., native trees, shrubs, and grasses), which can lead to an imbalance between the supply of and demand for water. This potential for such an imbalance has not been critically examined by enough researchers, particularly from the perspective of its simultaneous impacts on socioeconomic development and the environment. Failure to account for these problems is likely to exacerbate the vulnerability of the altered systems to climate change. Although the importance of such an evaluation is increasingly obvious for arid and semi-arid regions, it may also be highly significant even for regions with relatively abundant water; examples include southern China, where about 47% of China's total afforestation has occurred, possibly because water availability has traditionally been assumed to be suitable for long-term forest growth and survival (NBS, 2009). Many studies have been published about the water balance in arid and semi-arid regions (Cao et al., 2011a; Yang et al., 2014), but little attention has been paid to humid or semi-humid regions. Since abnormal drought periods caused by climate change have affected southern China in recent years (Chen et al., 2014a), it is urgently necessary to examine the water balance in this region to determine whether the intensive afforestation program may decrease the regional resilience against climate change.

To fill this gap in our knowledge, we compared water surplus of artificial forests with that of the natural vegetation they replaced, with the goal of revealing the influence of this difference on the regional water balance, and thus, on socioeconomic development and ecosystem resilience. Our goal was to emphasize the importance of evaluating the impacts of any ecological restoration project, including afforestation, on the regional water balance. To do so, we focused on the 15 provinces of southern China in the context of current climate change trends. We use this case study to illustrate the dynamic interactions between ecosystems and climate over time, and based on this principle, to show how evaluations of planting programs must be based both on present conditions and on predicted future conditions. To support this assessment, we (1) calculated water surplus in southern China by planted forests and natural vegetation based on estimates from eight evapotranspiration (ET) models; (2) analyzed and discussed the impacts of China's massive tree planting projects on the regional water balance; and (3) propose a simple framework for optimizing water investments in different socioeconomic sectors and in the environment.

2. Materials and methods

2.1. Survival rate estimation

To identify the area of planted forests in southern China, we obtained data on the planting areas for each province from China's annual forestry statistical yearbooks from 1949 to 2012 (State Forestry Administration, 1960–2012). We also collected data on survival rates of trees in the planted forests from China's 7th national forest resource inventory (Published in 2012) to estimate the actual areas of planted forest that have resulted from the planting program (State Forestry Administration, 2009):

$$\text{Survival rate} = \frac{\text{Total Area}_{2012}}{\Sigma\Sigma\text{area}_{p,y}}$$

where p and y refer to province and year, respectively; $\Sigma\Sigma\text{area}_{p,y}$ means total area from 1949 to 2012 in all southern provinces. We assume survival rate is relative constant for the past 60 years. Therefore, we can calculate the actual planted areas every year:

$$\text{Actual planted areas}_{p,y} = \text{Survival rate} \times \text{area}_{p,y}$$

2.2. ET estimation

Estimating terrestrial ecosystem ET by remote sensing has become a trend. Many methods have been employed, for example, the most widely used ET model is the MOD16A2 product from the MODIS-Terra sensor. However, modelling results of global ET estimates have revealed large differences (Chen et al., 2014b; Vinukollu et al., 2011). Dirmeyer et al. (2006) point out that the mean annual global ET ranged from 272 to 441 mm yr^{-1} among 15 models, and the maximum estimate was 1.5 times the minimum, according to results of Global Soil Wetness Project-2 (GSWP-2).

Because of southern China's complex vegetation types and ecosystem structure, it is unrealistic to attempt a precise estimate of the actual ET of the region's natural vegetation. Considerable afforestation in southern China has been achieved on the lands which were almost covered by grass and steppe vegetation, especially in mountainous regions. For simplicity, we therefore estimated the ET of natural vegetation which was transformed by planted trees using natural grassland or steppe vegetation as a proxy. The resulting ET estimates would be lower than the ET of the actual natural vegetation, which includes a diverse mixture of native trees, shrubs, and grassland. To compare ET between the natural and artificial vegetation, we used eight popular ET models (five empirical models and three process-based models: ANN, MODIS, PT-JPL, Reg 1, Reg 2, RS-PM, RT, SVM) as in Chen et al. (2014b). The ANN model is composed of several elements called neurons or nodes, and we used the back-propagation artificial neural network to find the best fit with the training data. Regression-tree (RT) algorithms typically predict class membership by recursively partitioning a dataset into a more homogeneous membership, and we used a modified regression-tree algorithm implemented in the Cubist software (RuleQuest Research. Pty Ltd. Company, 30 Athena Avenue, St. Ives, NSW 2075, Australia). The Reg1 model estimates evapotranspiration using surface net radiation, air temperatures, and a vegetation index as the dominant variables that control evapotranspiration, and we used the model to predict evapotranspiration under a wide range of soil moisture contents and land cover types. The Reg2 model divides evapotranspiration into energy control (ETe) and atmospheric control (ETa) components, and the model uses surface net radiation, air temperature, wind speed, and a vegetation index as the model's forcing data; The process-based algorithm (PT-JPL) was based on the Priestley-Taylor equation, with dynamic coefficients estimated from atmospheric moisture and vegetation indices to downscale potential evapotranspiration to actual evapotranspiration; The process-based algorithm (MODIS) was developed based on the Penman-Monteith equation; The process-based algorithm (RS-PM) is also a Penman-Monteith type model, but modified by Yuan et al. (2010). SVM is a supervised non-parametric statistical learning technique. SVM models can transform nonlinear regressions into linear regressions by converting the low-dimensional input space into a higher-dimensional feature space (Vapnik, 1998) (more details can be found in the Supplementary Information for details). All of the models have been validated by Chen et al. (2014b) for China, finding that these models could explain between 61 and 80% of the variability in ET based on data from 23 eddy covariance sites that included seven major terrestrial biomes.

We used the average results from the eight models to represent ET in each region, so we can get ET_n and ET_a which represent natural vegetation's ET and planted tree's ET respectively. Although one or more models would likely provide superior results for a given region, our approach can be justified by the complexity of the regions and the lack of calibrated parameters for each model based on regional field data; for practical purposes, it would be impossible to identify the best model for each region within the scope of the present study. The result is likely to provide a better overall