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Risk analysis of water scarcity in artificial woodlands of semi-arid and arid China

Junze Zhang*, Zhaowei Ding, Mengting Luo

Faculty of Geographical Science, Beijing Normal University, No. 19, Xinjiekouwai Street, Haidian District, Beijing, 100875, PR China

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ABSTRACT

All activities are inherently risky, including seemingly beneficial activities such as ecological restoration. However, small risks are easy to ignore, even if they may accumulate to create a large cumulative risk. Therefore, the long-term ecological benefits and risks of any ecological restoration project must both be considered. However, quantitative evaluation of the risk of afforestation in arid and semi-arid regions has been insufficiently studied. Here, we present a method for evaluating the risk associated with ecological restoration, using water shortages in artificial woodlands in China's arid and semi-arid regions as an example of cumulative risk. We found an annual risk that amounted to 5174 RMB ha^{-1} in 2014, which was 17% of the ecological service value of the forests. However, this cost depends on changes in the price, availability, and use of water in these regions. If ecological degradation occurs, it will trigger a series of serious consequences, and its cost may far exceed the expected benefits. Our inability to predict natural disasters such as drought and the problem of imperfect communication among stakeholders must be considered to achieve ecological restoration. The method described in this paper will provide theoretical support for future risk evaluations and guidance for the allocation of natural resources such as water, thereby increasing the likelihood of successful environmental management.

1. Introduction

Risk refers to the possibility that a desirable outcome may not be achieved or that an undesirable outcome may occur, and some measure of risk accompanies any potential benefit. Though cost–benefit analysis has been widely used to evaluate projects and policies that affect ecosystem services, and to guide the selection of projects that should deliver maximum net benefits from the flow of these services to society, these analyses have generally been incomplete because they failed to account for risk (Birch et al., 2010; Wegner and Pascual, 2011). This is because it is difficult to predict risk and the associated cost during project planning or at the start of a project, particularly since a series of small risks seem easy to ignore, even though they may eventually add up to a very large cumulative risk. Even when risk can be predicted, large risks may be considered acceptable if they are likely to generate large benefits and there are good ways to reduce the risks or their consequences; conversely, small risks may seem to be unacceptable if they are likely to generate only small benefits or cannot be easily reduced (Gao et al., 2011; Zhong et al., 2013; Fischhoff, 2015). These contrasting problems complicate the task of making sound ecological restoration decisions, since decisionmakers must compare the expected risks, costs, and benefits of the available options, especially where one or more critical resources are sufficiently limited to create risks for the project.

Because forest ecosystems can provide many valuable ecological services, such as blocking strong winds (thereby encouraging sand fixation), carbon fixation, and oxygen release, as well as providing recreational opportunities, forests have a potentially high ecological services value. Costanza et al. (2014) assessed the annual ecological service value for the current global forest ecosystem at \$3800 ha^{-1}. To take advantage of these services, China's government has carried out several national-scale afforestation projects, such as the Grain for Green Program and the Three Norths Shelter Forest Project, to remediate degraded ecosystems and the resulting desertification in arid and semi-arid regions after the desertification problem began to receive widespread attention in the 1970s (Cao et al., 2011).

However, planners of these programs failed to adequately consider local climate and soil conditions and determine whether forest was the most appropriate vegetation type for a given region (Li et al., 2015). Moreover, a lack of communication among the many stakeholders led to a failure to consider key issues such as the livelihoods of the people affected by these programs. This fail-

* Corresponding author.
E-mail address: zhangjunze427@126.com (J. Zhang).

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ure is a common problem in many types of ecological restoration project planning (Fischhoff, 2015). As a result of these failures, forests have proven to be an unsuitable choice in much of the project region (Cao, 2008). For example, the Three Norths Shelter Forest Project initially achieved impressive results. From 1980 to 1990, the vegetation cover in project areas increased significantly, and desertification appeared to be under control. Unfortunately, from 1991 to 1999, many parts of the project region exhibited serious forest degradation. Many trees became dwarfed because there was insufficient water to support normal growth, and other trees grew so fast that they consumed too much water, leading to severe drying of the surface soil and the death of much vegetation, including (eventually) the trees. As a result, the area of desertification increased rapidly, especially from 1995 to 1999, when it increased by 52 000 km^2 from the 1994 value, an annual increase of 10 400 km^2 (Wang and Hui, 2005).

After analyzing the lessons to be learned from this failure, China's government managers looked for ways to use more appropriate vegetation types, more effective ways of establishing the vegetation, and alternative ways to manage the land (Cao, 2008). As a result, vegetation cover in arid and semi-arid areas began to increase and ecosystems recovered greatly (Liu and Gong, 2012; Tu et al., 2016). However, these and previous research results suggest that there is a high risk associated with establishing artificial forest in arid and semi-arid areas, even though forest ecosystems have a high ecological services value. The risk arises from the region's severe shortage of water resources (Feng et al., 2015). In arid and semi-arid China, annual precipitation is generally less than 500 mm, with potential evapotranspiration being at least twofold higher and with high interannual variation (Li et al., 2012). In contrast, closed forest vegetation is usually considered to be sustainable only when annual precipitation is at least 500 mm (Gao et al., 2014). This means that insufficient water is available to support the artificial forests.

The key to maintaining ecosystem health in China's arid and semi-arid regions is to reduce the risk of ecological degradation, since this degradation frequently leads to rapid desertification in this region. However, although we now understand that there are ecological risks associated with the establishment of artificial forests (Cao, 2008), few researchers (to the best of our knowledge) have attempted to quantify these risks (Zhang et al., 2016). To justify the afforestation program for any given area, it's clearly necessary to quantify the associated risks so that planners can weigh the costs, benefits, and risks of this approach to ecological restoration (Birch et al., 2010; Polasky et al., 2014). To accomplish such an analysis, it's necessary to estimate the values of the benefits, and compare these with both the known costs and the known and unknown risks of the proposed projects. This is necessary so that decisionmakers and stakeholders can fully understand the impact of a project on the environment and on economic development in the areas affected by the project.

The goal of the present study was to develop a method for evaluating the risk created by afforestation, specifically in the form of unsustainable water consumption by forests in China's arid and semi-arid areas (Gong et al., 2012). Given the inadequacy of regional water supplies and the risk of decreasing water availability as a result of global warming, this study has great significance for helping regional managers to optimize their use of the available water resource and to avoid projects such as afforestation when they have an unacceptably high cumulative risk, thereby increasing the likelihood of long-term sustainability of human residency in this ecologically fragile region.

2. Hypothesis

In this study, we hypothesized (based on our review of the literature) that the risks associated with afforestation projects in China's arid and semi-arid regions had been largely neglected both by government planners and in previous research. To quantify the risks associated with the establishment of artificial woodland, we focused on a key environmental constraint that has been shown to have serious consequences for afforestation: water shortages (Guan et al., 2011; Zhang et al., 2016). There are clearly many other risks associated with afforestation, including the opportunity cost of replacing farmland with forests (e.g., a risk to food security, loss of income from sales of food) and the specific effects on certain groups of stakeholders such as livestock herders (e.g., a loss of income). These are beyond the scope of the present study, and remain an important challenge for future research. To support this analysis, we obtained data on the afforestation that was performed from 1952 to 2014. We made the following assumptions in this study. First, the objective of this study was to assess the impact of water shortages due to afforestation on a relatively large scale, and it is difficult to obtain accurate meteorological data that describes the variation in precipitation and evapotranspiration at a high spatial resolution throughout such large areas. Therefore, we obtained aggregate data at the level of whole provinces or autonomous regions (hereafter, "provinces" for simplicity) and assumed meteorological homogeneity within those regions. In future research, it will be necessary to repeat this analysis with much finer resolution as data becomes available to account for heterogeneity within these large regions.

Second, when there is insufficient precipitation to meet the needs of vegetation, growth will decrease and mortality will increase. On this basis, we defined the risk created by water shortages as the cost of water required to compensate for a lack of sufficient precipitation to sustain healthy growth of the artificial forests. To quantify this cost, we assumed that the additional water needed for forest growth would be transferred from other water users. That is, afforestation creates an economic cost for other residents of the study area, and this can be used as an initial estimate of the risk to these residents created by reallocation of that water to forests. On this basis, we calculated the cost of this water shortage as the amount of water transferred to support tree growth and survival, multiplied by the price of water for the sectors that transferred the water. For the purposes of the present analysis, these sectors were industrial and agricultural production, domestic consumption, and ecological water uses. Here, ecological water use refers to the water used by natural ecosystems outside the area of artificial woodlands.

We performed this analysis from the perspective of the balance between supply of and demand for water resources at a regional scale. First, we evaluated the water shortage for the artificial woodlands based on the difference between evapotranspiration and rainfall, which was estimated using the method developed in a previous study. (See the Methods section for details.) Next, we obtained data on the market price of water resources, and used it to estimate the cost of reallocation of water to compensate for the water shortage. Based on the results of these calculations, we discuss the impact of imbalances in water supply and demand caused by the establishment of artificial forests for the arid and semi-arid regions of China. Our results clarify the costs and benefits of China's afforestation programs and will help managers improve the allocation efficiency of natural resources by better understanding a previously unappreciated risk, thereby contributing to ecological restoration and sustainable development in the study area.