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REPORT

Damage Caused to the Environment by Reforestation Policies in Arid and Semi-Arid Areas of China

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Abstract Traditional approaches to ecosystem restoration have considered afforestation to be an important tool. To alleviate land degradation in China, the Chinese government has therefore invested huge amounts of money in planting trees. However, the results of more than half a century of large-scale afforestation in arid and semi-arid China have shown that when the trees are not adapted to the local environment, the policy does not improve the environment, and may instead increase environmental degradation. When precipitation is lower than potential evaporation, surface soil moisture typically cannot sustain forest vegetation, and shrubs or steppe species replace the forest to form a sustainable natural ecosystem that exists in a stable equilibrium with the available water supply. The climate of much of northwestern China appears to be unsuitable for afforestation owing to the extremely low rainfall. Although some small-scale or short-term afforestation efforts have succeeded in this region, many of the resulting forests have died or degraded over longer periods, so policymakers must understand that these small-scale or short-term results do not support an inflexible policy of large-scale afforestation throughout arid and semi-arid northwestern China. Rather than focusing solely on afforestation, it would be more effective to attempt to recreate natural ecosystems that are better adapted to local environments and that thus provide a better chance of sustainable, long-term rehabilitation.

Keywords Afforestation policy · Environmental degradation · Desertification · Environmental restoration · Livelihood · Soil moisture · Vegetation cover

INTRODUCTION

Land degradation is a major environmental problem around the world, and has become particularly severe in recent decades, particularly in China (Jiang et al. 2006). A half-century period of forest exploitation, monoculture planting, and overgrazing in China has led to large decreases in species diversity and large increases in insect and disease problems in monoculture plantations (Liu et al. 2003). To alleviate the problem of land degradation, the Chinese government has invested huge amounts of money in planting trees (e.g., the Three Norths Shelter Project, the Grain for Green Project). Recently, China allocated 60 billion RMB (US$7.3 billion) to combat dust storms by means of afforestation during its 10th Five-Year Plan Period from 2002 to 2006 (Jiang et al. 2006; Bureau of Forestry of China 2006). Although past government policies have encouraged environmental remediation through large-scale tree planting in semiarid and arid areas, such projects have proven economically costly and ecologically unsustainable (Wang et al. 2003; Su 2004; Huang 2006; Xu et al. 2006). In fact, most of the trees planted in the past have either died or are now dying, and the afforestation has not produced the desired ecological effects (Jiang et al. 2006). Given China's tremendous size, widespread afforestation failures will have important global consequences.

It is well known that afforestation can have many positive impacts on degraded land, including conservation of soil on degraded land by reducing soil erosion, as well as increasing soil organic matter, improving soil structure, sequestering carbon, increasing nutrient cycling, providing wildlife habitat, improving the landscape and biodiversity, and promoting the livelihood of farmers by permitting agroforestry that reduces the pressure on forested lands. However, afforestation is not a panacea. Although many small-scale or short-term assessments have shown clear benefits, this afforestation has often failed in the long term or over large areas when the species chosen for the project were poorly adapted to the local environment; the resulting environmental consequences have been severe. In the present article, we have summarized the literature on this subject for China to illustrate the frequently negative results of China's afforestation policy during the past 50 years, and have discussed the problems that led to these failures. In particular, we provide a preliminary assessment of the policy's impacts on water balances, on biodiversity, and on desertification.

DAMAGED WATER BALANCES

In general, trees will not become established without irrigation if rainfall is below 100 mm, and they are unlikely to form closed-canopy woodland without moderate to high precipitation levels, with the actual minimum level depending on the species. On this basis, the climate of arid and semi-arid northwestern China appears to be unsuitable for afforestation using the tree species that are currently being used, which have low water-use efficiency (Liu 2000, 2005); as a result, the natural climax vegetation of such areas is grassland or desert vegetation communities (Liu 2000, 2005). Historically, the forested areas of China have been distributed east of the 500-mm precipitation isoline, which defines the boundary with China's humid or semi-humid regions (Liu 2005). Unfortunately, afforestation is being practiced in many areas of this part of China where precipitation is insufficient to support tree growth, leading to greatly reduced growth or even mortality (Wang et al. 2003; Su 2004; Huang 2006). Where this is true, it seems more logical to carry out environmental remediation using the region's natural species rather than trees.

The afforestation with inappropriate species in northern China has decreased soil moisture levels (Wang et al. 2003; Cao et al. 2009), and seems unlikely to produce a stable equilibrium with the available water supply (Wang et al. 2003; Su 2004; Huang 2006), leading to further depletion of deep soil water. For example, most of the species selected for use in this project have low water-use efficiency. Because of the huge amount of evapotranspiration by these trees, Zhang and Sun (Zhang and Sun 2003) estimated an annual water shortage of 1.1×10^{11} m^3 in western China if the Three Norths Shelter Project achieves its goal of afforesting 14.4% of the project area.

Groundwater reserves have accumulated over historical periods, generally reaching equilibrium with an area's climate during periods of climatic stability. In arid regions, this water can sustain newly planted trees even when natural precipitation is inadequate, which is why afforestation of even arid areas can be initially successful. However, as afforestation expands, trees that cannot adapt to the shortage of water will gradually deplete groundwater to compensate for inadequate precipitation, until the remaining water can no longer sustain the trees (Su 2004; Cao 2008). Previous research in these regions has revealed that the monocultures typically used in afforestation consumed 20–40% more soil moisture than the steppe species the trees replaced, leading to drying of the soils, soil degradation, and greatly increased tree mortality (Duan et al. 2004).

DAMAGED BIODIVERSITY

As noted in the Introduction, afforestation has many potential benefits. Indeed, in parts of northwestern China with relatively high levels of precipitation, the afforestation program appears to have succeeded in the long term (Cao et al. 2008). It can also improve the livelihoods of farmers by permitting agroforestry that reduces the pressure on forested lands when suitable species are used (Cao et al. 2008). Unfortunately, afforestation can also reduce biodiversity when it replaces natural ecosystems, which are relatively diverse even after years of degradation, with monoculture plantations or exotic species (Cao et al. 2009; Kaiser 2000). When this alteration disrupts the original ecosystem's delicate balance, stability is lost and ecosystem degradation results (Groombridge and Jenkins 2003).

To support the high demand for domestic wood production, more than 80% of China's afforestation has involved monoculture planting, often using fast-growing species such as *Populus tremula* L. with low water-use efficiency (Su 2004; Huang 2006). As a result, it has decreased the number of plant species at afforestation sites by an average of 52% in northern China (Cao et al. 2009). In addition, water-stressed trees become increasingly vulnerable to disease and insects (Su 2004; Huang 2006), and a total of 4 million ha of *P. tremula* monocultures in northern China have been affected; for example, 120,000 ha $year^{-1}$ of plantations have died as a result of infestations by *Anoplophora glabripennis* Motsch. and *Anoplophora nobilis* Ganglb., two wood-boring beetles (Lu et al. 2004).

INCREASED DESERTIFICATION

Although the connection between wide-scale afforestation and increasing desertification in China is weak, it is clear that afforestation can severely degrade local soils, leading to erosion and further loss of vegetation cover that can potentially exacerbate desertification (Cao 2008). China's approach to afforestation has frequently ignored differences in topography, climate, and hydrology, all of which affect tree survival. Most of the trees that were planted in the past have either died or are dying, thus the afforestation program has not produced the desired ecological effects (Jiang et al. 2006). As a result, the overall survival of trees planted during afforestation projects was only 15% across the Three Norths Shelter Forest System Project (Su 2004). Decreased soil moisture in afforestation plots, combined with reduced sunlight under the tree canopies (which reduces the growth of most understorey vegetation), has decreased overall vegetation cover by 31% in many afforestation plots in northern Shaanxi China, even when trees could not form a closed canopy (Cao et al. 2008). Compared with the natural recovery processes in abandoned plots, it is clear that the overall vegetation cover has been decreased by afforestation, with a net 6% decrease in cover in northern Shanxi Province from 1998 to 2005 as a result of the Grain for Green Project (Cao et al. 2009). This decrease is frequently accompanied by locally increased desertification.

The presence of sparse trees can concentrate airflow between the trees, thereby increasing the wind's speed and erosive force and increasing soil desiccation and erosion when the trees fail to block strong winds (Cao 2008). With less vegetation to protect the soil, the area of degraded land expands, intensifying the local severity of desertification and potentially increasing sandstorm frequency (Cao et al. 2009). Although the available data does not let us calculate the increase in desertification caused by inappropriate afforestation, it is worthwhile noting that despite China's huge investment in environmental restoration during the past half century, desertification has expanded by an average of 10,000 km^2 annually in China since 2000 (Wan et al. 2005). This suggests the need for long-term research that focuses on the relationship between afforestation and desertification at sites where the abovementioned processes are likely to affect vegetation cover.

DISCUSSION

Under light to moderate levels of water stress, plants can regulate their stomatal conductance or leaf morphology (e.g., leaf area and shape) so as to limit their transpiration. However, when trees are planted in areas where a large open area permits strong advection to occur, particularly in areas such as arid and semi-arid China where strong winds are common, evapotranspiration can increase, leading to the development of severe water stress. Because the effects of this process on tree survival can take considerable time to become apparent, many small-scale or short-term assessments of afforestation have provided only positive results both in China and elsewhere in the world (Liu 2000; Cao et al. 2008). As afforestation expands and more trees begin growing in areas with inadequate precipitation, the trees will gradually deplete the groundwater to compensate. For example, during the 1970s, the afforestation conducted to restore the environment of Jingbian County in the Mu Us Sandland was initially successful, and was thus used as a model for the rest of China (Cao 2008). Unfortunately, 20 years later, almost all of the planted *Hippophae rhamnoides* L. and >70% of the planted *Populus davidiana* Dode had died, and vegetation cover had declined below the levels that existed before the afforestation as soil moisture shortages were exacerbated and renewed desertification erased the early gains. As a result, the overall tree survival rate decreased to around 15%, and groundwater depth increased from 2 m before the project to between 40 and 50 m over a period of 30 years (Cao 2008).

When precipitation is lower than potential evapotranspiration, the available soil moisture usually cannot sustain forest vegetation, and under natural succession, xerophytic shrub or steppe species will replace the forest to form a sustainable natural ecosystem in a stable equilibrium with the available water supply. Because this succession can take years or even decades to become apparent, China's policymakers must understand that small-scale or short-term afforestation success does not necessarily support a policy of large-scale tree planting in arid and semi-arid northwestern China.

When grassland is invaded by shrubs and trees, soil erosion may increase significantly. For example, Mu et al. (2003) observed that the initially dense protective cover of annual plants decreased as shrub vegetation cover increased in Mediterranean grassland, and that the extent of the bare soil surface below the shrubs also increased. This suggests that in semi-arid regions such as those of China, similar effects are likely to occur. The method used to plant trees in China may contribute to this effect; the tree and shrub seedlings that have been used in Chinese afforestation are often planted in holes from which much of the surface vegetation has been removed so as to limit competition with the seedlings (Cao 2008). In addition, the natural biological crusts that protect the soil from erosion and that help to reduce evaporation from the surface soil are disrupted by tree planting, and can take years to recover; before the recovery is complete, soil erosion often intensifies, sand storms increase in frequency, and desertification expands (Jiang et al. 2006; Cao 2008; Zhang 2006). Regression analysis indicates that the rate of wind erosion decreases linearly with increasing plant density, aboveground biomass, species richness, and vegetation cover (Li et al. 2005; Xu 2006). Thus, the lower vegetation and decreased tree survival that result from afforestation in arid and semi-arid areas are likely to strengthen desertification processes.

Although many scientists have pointed out the damage caused by China's afforestation policy, the many small-scale or short-term assessments that have provided positive results have led the government to ignore this criticism (Jiang et al. 2006; Xu et al. 2006). The Bureau of Forestry is another problem: if the government ends large-scale afforestation, the bureau will lose more than 80% of its funding, and bureaucrats naturally want to protect their jobs by protecting their budget. More generally, the central authorities have failed to realize the importance of restoring the natural ecological structures of the project area (Xu et al. 2006). Too much attention has been given to environmental impacts rather than their underlying causes. Although there is a growing realization in China that afforestation alone is not appropriate, government attitudes have been slow to change (Xu et al. 2006).

Trees in various configurations may improve microclimatic conditions considerably, and their mitigation of air movement (i.e., their role as a windbreak) is an important factor. This is well known by farmers in traditional agricultural systems. But reviews of more than half a century of China's practices have demonstrated that large-scale afforestation has frequently created serious local environmental and economic problems as a result of localized desertification, reduced grassland productivity and biodiversity, and increased occurrence of dust storms (Wang et al. 2003; Su 2004; Huang 2006; Cao 2008). In China, and particularly in northwestern China, research has indicated that inappropriate use of the land (including inappropriate afforestation) has contributed to serious desertification—defined here as land degradation in arid, semi-arid, and dry sub-humid areas as a result of various factors, including climatic variation and human activities (Xu et al. 2006; Cao 2008; Tong et al. 2004). There is a clear relationship between a declining soil water balance and afforestation of grassland and farmland due to the large amounts of soil moisture consumed by fast-growing trees (Vitousek et al. 1997).

Tree planting is a popular approach to restoring degraded sites, and can often lead to clear long-term rehabilitation of these sites. However, plantation failures can occur when inappropriate species are selected or when early stand management is inadequate or inappropriate, especially in arid and semiarid areas (Jiang et al. 2006; Mu et al. 2003; Koulouri and Giourga 2007). However, the solution to land degradation may require mitigation of the sources of the degradation rather than treatment of the symptoms. For example, much environmental degradation has been attributed to human activities, and especially to unsustainable livestock grazing and farming activities that decrease vegetation cover (Jiang et al. 2006; Xu et al. 2006). Therefore, restricting grazing and farming or promoting more sustainable forms of these activities should be investigated as potential alternatives wherever afforestation is currently being proposed for environmental restoration. Afforestation in arid and semiarid regions should be limited to the most mesic areas, with species such as dwarf shrubs chosen based on maximum water-use efficiency rather than based on economic goals such as the rapid production of wood fiber (Cao 2008).

In China, scientific research usually lags behind policy development and implementation because of the fast development and implementation of policy and limits on the temporal and spatial scales of research (Cao 2008). Our literature review found no published research on the long-term or large-scale impacts of China's afforestation policy on ecosystem function, including changes in ecosystem resilience; in soil physical, biological, and chemical properties; or in vegetation structure, composition, biomass, and net primary productivity. However, there have been many small-scale and short-term studies that have failed to confirm whether their positive results will be maintained over larger scales and longer time periods. We fear that dramatic failures will occur if techniques that prove to be successful over small scales or short terms are expanded to larger scales and longer terms without careful monitoring to confirm their sustainability.

To prevent such undesirable results, we recommend careful observations of ecosystem functioning over large temporal and spatial scales. China's policymakers should learn from international approaches, which are increasingly focused on re-establishing near-natural forests (Liu 2000, 2005; Cao 2008, 2008). In addition, they should learn from the successes reported by the Chinese Academy of Sciences for the restoration of natural vegetation in Inner Mongolian grasslands, in which managers prioritized restoration of the region's natural climax vegetation rather than afforestation (Jiang et al. 2006). Sustainable strategies for land restoration and policy development and implementation must explicitly examine each site to determine the most appropriate solution rather than clinging to the current approach, which is based on a single inflexible recipe for all sites.

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