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Impact of three soil types on afforestation in China's Loess Plateau: Growth and survival of six tree species and their effects on soil properties

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Abstract

Soil chemical and physical characteristics can significantly affect the growth and distribution of all types of vegetation, particularly in arid environments. Because of soil erosion, most of the topsoil has disappeared from China's arid Loess Plateau, exposing parent material or soils with low nutrient content in many locations. However, little research has been done on the impact of these soil conditions on afforestation efforts. Conventional afforestation in the area is only thought to be possible on loess soils because the local foresters consider the two other main soil types (red clay and bedrock-derived soils) too barren to support trees. In an attempt to determine whether these soils could also support afforestation, we planted trees on all three soil types in a hilly area of the Loess Plateau near Yan'an City. The results indicate that large-scale afforestation in loess soils could potentially increase the severity of soil water shortages, degrade the natural environment, and increase the risks of desertification and of serious economic losses because of over-consumption of soil moisture. However, survival rates on red clay and bedrock-derived soils were generally comparable to those on loess for individual species, and were superior to those on loess in mixed-species plantations, with less of an adverse impact on soil water. Both red clay and bedrock-derived soils could thus potentially sustain afforestation in low-lying areas with adequate soil moisture.

Keywords: Afforestation; Loess soil; Red clay; Bedrock-derived soil; Soil conditions; Loess Plateau

1. Introduction

Afforestation is a potential strategy for helping to conserve the soils on degraded land by reducing soil erosion (Oscar, 2001), and can increase soil organic matter, improve soil structure, serve as a carbon sink (Cornelis et al., 2002; Jackson et al., 2002), assist in nutrient cycling (Thomas, 2001), and provide habitat for wildlife by improving the landscape (Franco et al., 2003). In the coming decades, global climate change is expected to produce large shifts in vegetation distributions at historically unprecedented rates (Allen and Breshears, 1998; Woodwell, 2002). These shifts are expected to be most rapid and extreme within the ecotones at the boundaries between ecosystems, particularly in arid and semiarid landscapes. This is a particular problem in agricultural areas, and significant scientific advances and regulatory, technological, and policy changes will be needed to control the environmental impacts of agricultural expansion (Tilman et al., 2001). However, drought is a major constraint worldwide to the establishment of vegetation (Schume et al., 2004), particularly for trees, which often have a relatively low water-use efficiency (Wang et al., 2004; Zhao and Li, 2005). The Loess Plateau region of northern China poses a particular challenge for environmental restoration because of the area's aridity and the extent of desertification. However, there has been little research on the relationship between the region's soil types and the effectiveness of local afforestation processes.

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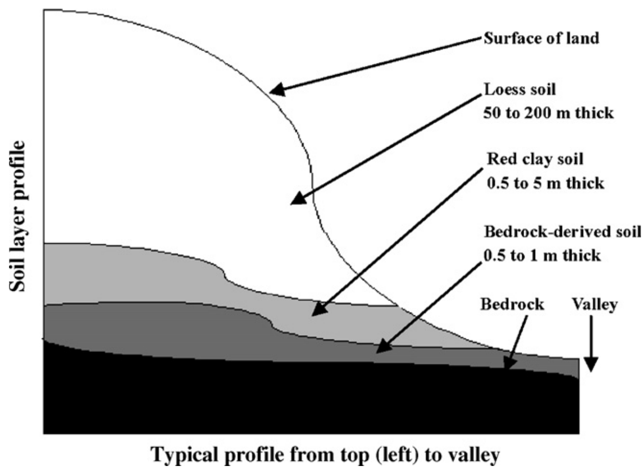

Fig. 1. Typical profile of the three main soil types found at the study sites.

The wide range of geological conditions and wide diversity in soil chemical and physical characteristics in the Loess Plateau have a major impact on the growth and distribution of vegetation (Dai, 1993). These factors are especially important in the hilly portions of the Loess Plateau, where there are three main soil types: loess soils (77.5% of the total area), red clays (5.6% of the area), and bedrock-derived soils (9.0% of the area) that are immature rocky soils above bedrock, with a high clay content (SWCT, 1985). The remainder of the land area is occupied by cities, roads, bodies of water, etc. Millions of years ago (Dai, 1993), the Loess Plateau was covered by a range of loess soils. Because of soil erosion, most of the topsoil has disappeared from China's Loess Plateau, exposing parent material or immature soils with low nutrient content in many locations. Currently, these soils are typically 50–200 m thick above a layer of red clay 0.5–5 m thick, which in turn overlies a layer 0.5–1 m thick of bedrock-derived soil above the bedrock (Fig. 1). Conventional afforestation in the area is only thought to be possible on the loess soils because local foresters believe that the other two soil types are too barren to sustain planted trees (Cao, 2001).

In an attempt to expand the range of soil types that are potentially suitable for afforestation, we investigated the possibility of planting trees on the red clay and bedrock-derived soils. We planted trees in each of the three soil types in a hilly region of the Loess Plateau in 1996, and monitored their performance from 1996 to 2005. After planting, our goals were to determine whether the conventional wisdom (that large-scale afforestation should only be carried out on loess soils) was valid, and whether the red clay and bedrock-derived soils were potentially suitable alternatives. To ensure that afforestation does not have long-term adverse effects on the sites, as has been the case in some afforestation projects (Vitousek et al., 1997; Liu et al., 2004), we also examined the effects of the planting on soil moisture and nutrient contents.

2. Materials and methods

Our study site was located within the small (121 ha) Xiao Bian Gou watershed, near Yan'an City in China's Shaanxi Province (36°32′N, 109°26′15″E). Ranging in elevation from 993.7 to 1191.2 m above sea level, the watershed is undergoing severe soil erosion (15 Mg km^{-2} year^{-1}; Cao et al., 2006), and considerable damage is occurring to vegetation in the watershed, where the topography is very rough, with many steep slopes and deep ravines. There are three main types of soils at our study site. A loess soil that covers 77.5% of the area and averages 50–200 m in depth is found primarily on hill tops, level areas, and the upper slopes of valleys. Its composition is >20% sand (1.00–0.05 mm) and <30% clay (0.010–0.001 mm), with 3.76 g kg^{-1} of mean organic matter content and a mean porosity of 52.08%. A bedrock-derived soil derived from the uppermost rocks of the crust covers 9.0% of the area at a thickness of 0.5–1.0 m, and is found mainly on lower slopes near the bottoms of valleys. Its composition is >70% sand (1.00–0.05 mm) and >10% coarser materials (>1.00 mm), with 1.45 g kg^{-1} of mean organic matter content and a mean porosity of 41.89%. The third soil is a red clay that covers 5.6% of the area at a thickness of 0.5–5.0 m and is found primarily on slopes between deposits of the loess and bedrock-derived soils. Its composition is >40% clay (0.010–0.001 mm), with 2.3 g kg^{-1} of mean organic matter content and a mean porosity of 44.91%. The relationship between the positions of the soils is shown in Fig. 1 and S1 (SWCT, 1985). Local foresters consider the red clay and bedrock-derived soils to be barren and badly eroded, and thus, unsuitable to sustain tree growth. However, these soils are typically distributed on slopes near the bottoms of valleys, where moisture conditions may be better than those at higher elevations.

The mean annual temperature in the watershed is 9.4 °C, with 147 frost-free days per year. Precipitation averages 547.4 mm year^{-1}, of which 413.6 mm year^{-1} falls during the rainy season (May–October). Between 1996 and 2005, an average of 422.2 mm year^{-1} of precipitation occurred during the rainy season, and 71.2% of this precipitation was concentrated between June and September. All meteorological data were provided by the Yan'an meteorological station of the Chinese Academy of Sciences and represent 50-year averages (1950–2000). The potential evapotranspiration for the study area averages 793.7 mm year^{-1} (Cao et al., 2007).

2.1. Experimental design

At the study site, three 60 m × 360 m plots separated by 10 m were established for each of the three soil types (i.e., nine plots in total). In 1997, six species of trees were planted in each plot as single-species plantings of 400 trees per species, and mixed-species plantations were established with a total of around 400 trees each (200 trees per species). However, because of uneven terrain, the plots and plantations varied slightly in size, shape, and the number of trees. The following species were used:

- Single-species plantations (400 trees of each species in each plot): *Populus tremula* L., *Hippophae rhamnoides* L., *Platycladus orientalis* (L.) Franco, *Caragana korshinskii* Kom., *Robinia pseudoacacia* L., and *Acer truncatum* Bge.