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Spatial distributions of optimal plant coverage for the dominant tree and shrub species along a precipitation gradient on the central Loess Plateau

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ABSTRACT

The Loess Plateau in China has the most severe soil erosion in the world. Increasing plant coverage can effectively control soil erosion; however, low water availability in this region limits plant growth. The objective of this study was to determine the optimal plant coverage for the two non-native plants mainly used in vegetation restoration (*Robinia pseudoacacia* and *Hippophae rhamnoides*) on the Loess Plateau. We analyzed the spatial distribution of the mean actual evapotranspiration (AET), net primary productivity (NPP) and maximum leaf area index (LAI) along a precipitation gradient transect on the central Loess Plateau. The modified Biome-BGC model was used to simulate the dynamics of AET, NPP, and LAI for the two plants. The model was assessed by using the only available parameter that had been continuously determined in the field (i.e., AET) that pertained to the two plants growing at two sites that had validated physiological parameters. The validated model was subsequently used to simulate the dynamics of AET, NPP and maximum LAI for the two plants at 75 representative sites along the transect. The results indicated that annual NPP and maximum LAI did not present significant trends over time for either plant. Spatial distributions of the mean AET, NPP, and LAI exhibited decreases along the southeast to northwest precipitation gradient on the Loess Plateau, which was consistent with the spatial distribution pattern of the mean annual precipitation (MAP) in the studied area. In the non-native tree zone where MAP was greater than 550 mm, the optimal plant coverage (given by the mean maximum LAI value) ranged from 2.5 to 3.5. In the non-native shrub zone where MAP ranged from 250 to 350 mm, the optimal plant coverage ranged from 0.8 to 1.5. In the mixed zones of non-native trees and shrubs where MAP ranged from 350 to 550 mm, the optimal plant coverage ranged from 1.5 to 2.5. These quantitative findings giving optimal plant coverages for different precipitation regions should be useful for guiding non-native vegetation restoration on the Loess Plateau.

1. Introduction

The Loess Plateau of China is a region with an area of 640,000 km^2 that has highly erodible loessial soils. Under the extensive monsoonal influence, precipitation presents a strong gradient that decreases from the southeast to the northwest (Fig. 1), and along which the climate ranges from sub-humid to arid. On average, over 75% of the annual precipitation (AP) occurs between June and September. The region is reputed to have the most severe soil erosion in the world, which has made it ecologically fragile (Han et al., 2009). The Chinese government has implemented vegetation restoration practices that include planting trees and shrubs in order to improve the environmental quality and to reduce water and soil losses on the Plateau. However, an incompatibility exists between the limited soil water availability and the extensive plant coverage required for protecting the land surface (Zhou et al., 2006; Xia and Shao, 2008).

Hou et al. (1991) showed that in the hilly–gully region of the Loess Plateau, soil loss decreased with increasing plant coverage. Furthermore, the plant coverage required for effective soil erosion control was between 60% and 70%, with little soil loss occurring at all when the coverage was greater than 75%. Jiang et al. (1992) showed that, as compared with bare soils, when the plant coverage of *H. rhamnoides*, a dominant non-native shrub species, was 85% or

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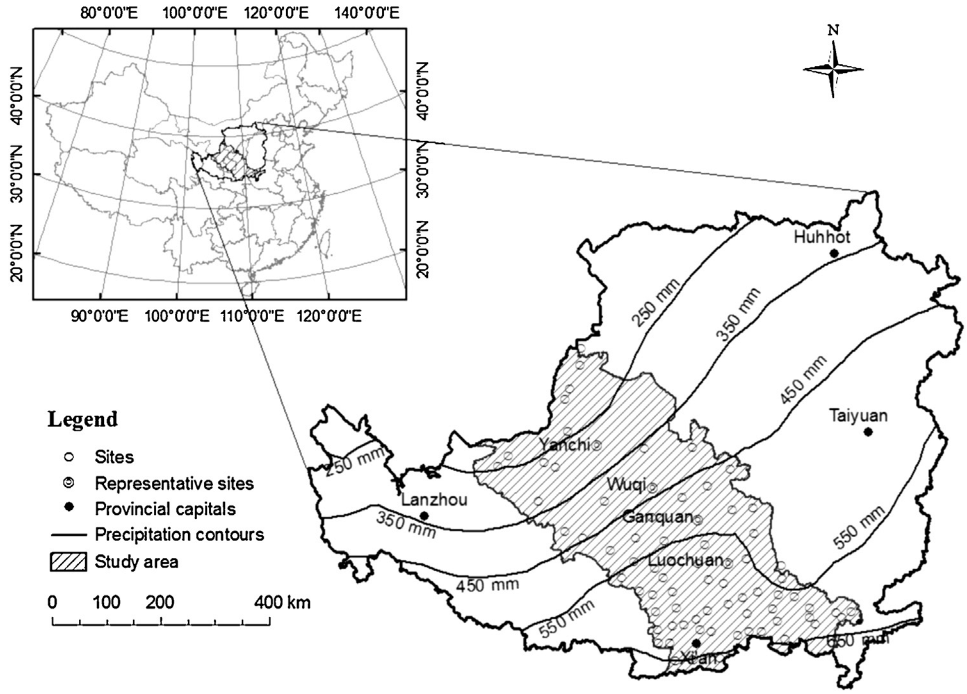

Fig. 1. The location of the study area in China and of the 75 sites that include the four representative sites, and precipitation contours in the study area.

more, the reduction in sediment yield was 98%; whereas when the plant coverage of *Robinia pseudoacacia*, a dominant non-native tree species, ranged from 65% to 80%, the reduction in sediment yield was 99%. Sediment yield increased rapidly when plant coverage was reduced below 40%.

Increasing plant coverage is an effective method for controlling soil erosion. However, the maximum plant coverage is determined by the limited soil water availability on the Loess Plateau, where the annual precipitation ranges from 200 to 700 mm. In this region, which is subject to large variations in precipitation, water scarcity is the most significant factor restricting the increase in plant coverage. Intensive vegetation restoration over large areas often results in plant water requirements exceeding the limited soil water availability. Extensive plant coverage also aggravates soil water scarcity and leads to the formation of a dried soil layer in the soil profile, which may present a considerable obstacle to sustainable plant growth (Wang et al., 2009, 2010).

Attaining an optimal plant coverage is vital to vegetation restoration projects in order to balance soil water consumption and maintain sustainable plant growth. Natural vegetation zones on the Loess Plateau are one of the important theoretical bases for vegetation restoration. Based on the change in mean annual precipitation (MAP) across the Loess Plateau, three natural vegetation zones can be identified: a deciduous broad-leaf forest zone where MAP exceeds 550 mm; a forest-steppe zone where MAP ranges between 450 and 550 mm; and a dry steppe zone where MAP is less than 450 mm (Zou, 2000). Based on these natural vegetation zones and the MAP, Yang et al. (1994) further divided the Loess Plateau into five vegetation zones that are based on water balance characteristics that can also be applied to non-native species. These five zones are: a tree zone where MAP exceeds 550 mm; a tree–shrub zone (MAP: 500–550 mm); a shrub–tree zone (MAP: 350–500 mm); a shrub zone (MAP: 250–350 mm); and a shrub–steppe zone (MAP < 250 mm). The partitions of these natural and non-native vegetation zones provide useful guidance for vegetation restoration on the Loess Plateau, but the optimal plant coverage for different plant species within each zone has not been considered until now, which reduces their effectiveness in practical applications.

Optimal plant coverage is defined as the maximum leaf area index (LAI) that can be achieved under a given climate condition, soil texture and vegetation type without the soil water content reaching the permanent wilting point (Fu et al., 2012). When plant coverage exceeds the optimal value, there is a series of consequences that not only constrain plant growth but also aggravate water scarcity and the degree and depth to which soil is desiccated (Xia and Shao, 2008). Therefore, it is vital to determine the optimal plant coverage for each of the five vegetation zones defined by Yang et al. (1994) in order to accelerate and achieve sustainable vegetation recovery on the Loess Plateau.

Some studies have determined optimal plant coverage at different spatial and temporal scales using a combination of field experiments and numerical models (Guo and Shao, 2004; Xia and Shao, 2008; Fu et al., 2012). Guo and Shao (2004) investigated the relationship between *Caragana korshinkii* planting density, water supply, and plant water consumption; established an empirical mathematical model using two years of experimental data; and then determined that the optimal coverage for 16-year-old *C. korshinkii* was 8115 plants ha^{-1} in the semi-arid area of the loess hilly region on the Loess Plateau. Xia and Shao (2008) developed a physically based model to calculate the optimal plant coverage using three years of continuously measured climate data; the optimal plant density was determined to be 2250 plants ha^{-1} for *C. korshinkii* and 2800 plants ha^{-1} for *Salix psammophila* on the northern Loess Plateau. Fu et al. (2012) combined field experimental data with a model, which derived a relationship between plant coverage and soil water depletion. They then calculated optimal coverages for two shrubs using a representative dry year from historical meteorological records. The calculated optimal plant coverage corresponded to a maximum LAI of 1.27 for *C. korshinkii* and 0.70 for *S. psammophila*.

The determination of optimal plant coverage must consider the variation in the long-term climate conditions due to the large fluctuations in AP that occur on the Loess Plateau. Although previous