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The influence of plant diversity on slope stability in a moist evergreen deciduous forest

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ABSTRACT

The influence of plant diversity on slope stability was investigated at early phases of succession in a mixed forest in Sichuan, China. The first phase comprised big node bamboo (*Phyllostachys nidularia* Munro) only. In the second phase, bamboo co-existed with deciduous tree species and in the third phase, deciduous species existed alone. Root density at different depths and root tensile strength were determined for each species. The factor of safety (FOS) was calculated for slopes with and without vegetation for each succession phase. For phase 2, FOS was determined for different species mixtures and positions. In phase 3, simulations were performed with a single tree at the top, middle or toe of the slope. Due to its shallow root system, bamboo contributed little to slope stability. In simulations with the tree at the top or middle of the slope, FOS decreased because tree weight added a surcharge to the slope. FOS increased with the tree at the bottom of the slope. Different mixtures of species along the slope had no influence on FOS. Differences in root tensile strength between species played a small role in FOS calculations, and tree size and density were the most important factors affecting slope stability, excluding hydrological factors.

1. Introduction

The Sichuan region in the south of China is subject to heavy rains in the monsoon season lasting from June to September. Landslides are frequent (Liu and Diamond, 2005; Zhang et al., 2006), particularly where the Tibet-Qinghai plateau descends rapidly onto the plains and steep slopes and gorges are abundant. Deforestation has been severe in the last 50 years (Démurger et al., 2005), but the recent government guidelines concerning the Sloping Land Conversion Programme have resulted in large areas of cropland being replanted with trees in order to combat erosion and landslides (State Council of the PRC, 2007; Stokes et al., 2008, 2009a). The question remaining to be asked is whether these plantations are useful at fixing soil on steep slopes, or whether natural regeneration would be a more efficient as well as an economic and ecological method of reinforcing soil?

Although many studies on how vegetation fixes soil on slopes have been carried out, few have examined how plant diversity may influence slope stability (Schmidt et al., 2001; Roering et al., 2003; Cammeraat et al., 2005; Van Beek et al., 2005) and in particular, how a given combination of plant species might serve to increase soil reinforcement. Root architecture is highly variable depending on soil type, nutrient and water availability, but the inherent rooting pattern is nevertheless species dependent (Köstler et al., 1968; Stokes et al., 2009b). To stabilize a slope against landslides, the number and size of roots which cross the slip surface are extremely important (Cammeraat et al., 2005; Van Beek et al., 2005; Reubens et al., 2007). The thin roots play a major role in preventing soil slippage particularly in the surface layers of the soil profile (Coppin and Richards, 1990; Operstein and Frydman, 2000; Mickovski et al., 2007). The position of thin roots within a root system, i.e. where most thin roots are located with regard to depth and radial position around the root system, will therefore depend partly on species and partly on local environment. The thicker-diameter roots provide anchorage to the soil mass where the potential slip surface is shallow e.g. <2.0 m deep (Coppin and Richards, 1990; Norris et al., 2008). Plant species can grow differently depending on local conditions; therefore it can be expected that a wide diversity of plant species will allow for any detrimental effects of environment on root biomass or architecture to be buffered (Stokes et al., 2009b).

Although it might be expected that plant diversity increases slope stability (Pohl et al., 2009), this may not be the case through-

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out all phases of vegetation succession, especially in the period just after, e.g. a clear-felling has taken place. Pioneer species need to colonise the bare soil and may not possess the necessary rooting characteristics required to improve slope stability. Managers therefore need to ask the question whether it is better to let natural regeneration occur on bare soil, where a mixture of plant forms and species will develop; or whether young trees should be planted, and if so, which species or mixture of species? The immediate effects versus the long-term benefits and advantages also need to be considered. Aside from economical aspects, is a planted forest more effective at reinforcing soil on steep slopes than a naturally regenerated forest?

The long-term stability of a slope can also be affected by the position of trees: for instance, if the lower slopes have been cleared of vegetation leaving a heavily loaded forested upper slope, the weight of the vegetation on the upper slope may result in a decrease in the factor of safety (FOS), a measure of the risk of failure of a slope (Norris et al., 2008). Conversely, the additional load provided by the weight of the vegetation at the toe or lower part of the slope adds stability to the slope, increasing the FOS (Greenwood et al., 2004). However, few studies have focussed on this aspect and little quantitative data exist (Kokutse et al., 2006).

We carried out a study to examine the influence of plant diversity in a naturally regenerated moist evergreen broadleaf forest at an early age of succession in the Sichuan province of China. Root biomass distribution was determined at different soil depths and root tensile strength measured for several species. Results were used in a model of slope stability and the slope FOS calculated for different succession phases, combinations of species and positions of trees along a slope. Results are discussed with regard to how root biomass evolves over time in natural forests and how best to manage unstable slopes.

2. Materials and methods

2.1. Site characteristics

The study site was a 4 km-long valley located northwest of Chongzhou City, on the eastern limits of the Tibet-Qinghai plateau, Sichuan Province, China (30°48′104′N, 103°24′732′E), which belongs to the middle segment of Longmen Mountain, the south-east offshoot of Qionglai Mountain. The topography of the area is mountainous and characterized by gorges, steep hills and valleys, ranging from 960 to 3868 m in altitude (Zhu et al., 2006). The region is situated in the moist monsoon (lasting from May to September) zone and the climate is subtropical. Annual mean temperature is 12.3 °C with minimum temperatures of 6 °C in January and a maximum of 32.7 °C in July and August. Average annual precipitation is 1300–1450 mm with 70% of the annual average amount in June to August and only 5% from November to January (Zhu et al., 2006). Climate is characterized by misty days and high humidity (annual average relative humidity 86%), little sunshine (average annual sunshine = 641.6 h), and low wind speeds (annual average wind speed = 1.4 m s^{-1}). Soil parent material is mainly constituted of limestone, sandstone and granite and soil type was a reddish brown silty clay (Soil Taxonomic Classification Research Group, 1993). Soil thickness ranged from 0.5 to 1.3 m over bedrock with a humus layer of 0.01–0.03 m (Genet et al., 2006). Average soil cohesion (c_s) of fallow soil at a depth of 0.05 m was 28.3 kPa and the soil friction angle (ϕ) was 19.6°. Neither of these values differed significantly along the valley (Genet et al., 2008). Small but numerous shallow landslides occur in the area during the monsoon season (June–September), and the slip surface of these landslides was estimated at a mean depth of 0.6 m (Stokes et al., 2007). This area was severely affected by the Wenchuan earthquake on 12 May 2008, but as yet an inventory of mass movement due to the earthquake has not been completed.

The valley studied was extremely rich in flora, with over 300 different species inventoried (X. Cai, personal communication). The dominant vegetation comprised mixed and monospecific tree plantations of *Cryptomeria japonica* D. Don, *Cunninghamia lanceolata* Lamb., *Lindera limprichtii* H. Winkl., *Metasequoia glyptostroboides* Hu & Cheng., *Betula luminifera* H. Winkl. and *Carya cathayensis* Sarg. Major shrub species included *Cornus controversa* Helms., *Trachycarpus fortunei* H. Wendl. and *Salix guebriantiana* Schneid. Dominant grasses and herbs comprised big node bamboo (*Phyllostachys nidularia* Munro.), *Phragmites communis* Trin., *Juncus effusus* L., *Plantago asiatica* L., *Iris tectorum* Maxim., *Pteridium latiusculum* Desv. and *Dobinea delavani* Baill. (Zhu et al., 2006; Stokes et al., 2007).

Three sites were chosen, representing three different phases of early succession in a forest undergoing natural regeneration, although not all species were native to the Sichuan. All sites were located close together on the same soil type and slope angle (35°) and at approximately the same altitude (1205, 1300 and 1215 m, respectively). At each site, plots of different sizes were selected randomly, which contained species representative of the surrounding flora (Site No. 1—first succession phase had two plots, each being 10 m^2. Site No. 2—second succession phase had two plots: 84 and 32 m^2 each. Site No. 3—third succession phase had one plot only: 101.25 m^2). The dominant woody species were identified and stem density measured (Tables 1 and 2). In sites representing succession phases 2 and 3, the same species were not present and it was not possible to find naturally regenerated sites where all species could be found at different ages. At site 1, where vegetation was in the first phase of succession, only big node bamboo (*P. nidularia*) was present. Big node bamboo dies back after flowering, although the exact number of years between flowerings is not known (Huang et al., 2002). As soon as big node bamboo dies back, trees grow quickly and become dominant, thus causing shady conditions for the understory and preventing further growth of big node bamboo (Stokes et al., 2007). The second phase of succession then begins. To determine approximate tree age in phases 2 and 3, wood cores were removed at the base of each tree using a Suunto©increment borer and the number of annual rings determined using dendrochronological techniques (Stokes and Smiley, 1968). Trees at site 2 were between 5 and 7 years old and trees at site 3 were between 15 and 20 years old.

2.2. Root sampling

Using the method given in Genet et al. (2008), to determine root biomass and tensile strength, soil cores were taken from each site representing the three phases of succession. Each core had a diameter of 0.19 m and length of 0.15 m, taken at 0.15 m depths to 0.60 m

Table 1
Characteristics of bamboos (*Phyllostachys nidularia*) growing at site 1 (first succession phase) and trees growing at sites two and three, corresponding to the second and third succession phases respectively.

Succession phase	Age (years)	Mean DBH (mm)	Mean height (m)	Density (stems ha^{-1})	Basal area (m^2 ha^{-1})	Number of core samples
First	2	20.4 ± 0.13	4–5	89000	29.09	68
Second	5	38.9 ± 0.17	3–4	7269	7.46	75
Third	20	98.4 ± 0.89	12–17	2963	29.00	68