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Full Length Research Paper

The root anchorage ability of *Salix alba var. tristis* using a pull-out test

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The vegetation materials may reduce soil erosion and runoff, create space for breeding and habitat and they are commonly used in river ecological engineering. Therefore, it is important to select the soil-bioengineering plant by taking its growth characteristics and the soil solidity of its root system as the major considerations. Because *Salix alba var. tristis* has a strong capability of keeping moisture, preventing drought and reducing wind, we selected it as a model species for soil bioengineering research and application in Beijing, China. In this study, we aimed to investigate the soil-reinforcing effects by *Salix alba var. tristis*. We performed a pull-out test on 4 year live stakes and measured their morphological characteristics. Our results showed that, the plant had a satisfactory root development after 4 years, and the pull-out resistive force had the strongest correlations with the morphological parameters of plant, such as height (R^2 = 0.79, P < 0.001) and diameter at shoot base (R^2 = 0.69, P < 0.001).

Key words: *Salix alba var. tristis*, uprooting resistance, live stakes, soil bioengineering.

INTRODUCTION

When a channel is redesigned to reduce excessive bank stresses, soil bioengineering methods such as vegetated banks can be used. These methods involve combinations of natural fiber matting and lifts of soil covered with densely rooting species (Gray and Sotir, 1996). The matting degrades over several years as the root zones of the plantings begin to stabilize the reshaped bank. This method also has a cost- effective and aesthetically attractive approach. The potential value of soil bio-engineering techniques has attracted wide attention on river ecological restoration in Beijing, China. As one of common and easy soil bioengineering techniques, live stakes are often laid in trenches along contours on a slope surface or inserted in a staggered pattern on a slope (Schiechtl, 1980). Root and sprouting of live stakes can further enhance the stability of the slope. This approach has been demonstrated to be effective, affordable and environmentally friendly, highlighting that simple measures are appropriate to solve the critical problems.

In the last few years, Beijing Forestry University (China) and the University of Natural Resources and applied Life Sciences (Austria) have examined the suitabilities and capabilities of soil bioengineering techniques under the local condition of Beijing. One of the plant species used was *Salix alba var. tristis*. Previous studies have examined the growth and usage of this plant in the natural environment. As an easy-to-root species, it is suitable for anticipated environment conditions. However, the soil stabilization effect still remains unknown.

Many studies on vegetation-reinforced soil have been carried out, including laboratory shear tests on soils with plant roots (Waldron, 1977) or soils reinforced by fiber simulating roots (Shewbridge and Sitar, 1996; Wu and Waston, 1998) and *in situ* shear tests on soils with roots (Bibalani, 2008; Wu and Waston, 1998). Several indirect methods are available to estimate the increased strength of the soil due to the presence of plants, including the pull-out test. The uprooting resistance force provides

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valuable information on the role of root hairs in anchorage (Bailey et al., 2002). The lateral pulling test was used to simulate a certain bamboo failure during a landslide (Stokes, 2007) and also was used to ascertain the resistance the vetiver grass root system can provide when torrential runoffs and sediments are trying to uproot the plant by (Mickovski et al., 2005). When a plant is pulled vertically from soil, the force is transmitted to the root system and as a result, the root-soil bond and the strength of the root themselves are in tension. A single vertical force applied to a stem is transmitted to numerous roots, because of either lateral branching or adventitious roots from the stem base (Ennos, 1993). In their study, many factors were found to be related to anchorage, such as diameter, biomass and root number. It is highly important to evaluate and predict the plant resistance to uprooting from simple plant traits in order to define the most efficient plant strategy for future restoration of eroded slopes (Burylo et al., 2009).

While uprooting resistance tests have been performed on plants or roots in several studies, there is little information about the apparatus in the tests (Anderson et al., 1989; Denis et al., 2000; Norris and Greenwood, 2003b; Operstein and Frydman, 2000). The design of the apparatus is usually based on a simple clamp, jack or pulley system to extract the roots, which has an ability to record the resistance of pull-out or extraction force and displacement (Norris, 2005).

In the present study, we performed the pull-out test, in which the whole plant was dragged vertically out of the soil. The aim of our study was to quantify the amount and distribution of root and to understand the soil stabilization effects of *S. alba var. tristis* as live stakes.

MATERIALS AND METHODS

Site and tree species

The pull-out tests were conducted in April, 2009 within a block of farmland, which is near the village of Yiduhe (40°20′ N, 116°30′ E) in the south of Huairou district of Beijing, China. The district has an average annual temperature of 7 to 12°C and the local climate is affected by dry spring with an average summer temperature of 26°C and cold winter with an average temperature of -4°C. The average annual precipitation of Huairou district is approximately 660 mm, with around 83% of the rainfall during June to August. Thus, the hydrology of the catchment areas is different from other regions and the hydrological range from a wet to a dry season is very high. The farmland is covered with 20 to 30 cm soil layer. Underneath the soil layer is exposed gravel and cobble of various size.

S. alba var. tristis is a kind of medium-sized golden weeping willow. It requires damp soil and tolerates wetland conditions. The pale to medium green leaves are borne on long, pendant yellow stems. At the research site, live and vegetated *S. alba var. tristis* stakes with a diameter of approximately 1.5 cm were cut into 20 cm length poles. Then, poles vertically were inserted into the ground at a standard depth of 15 cm using a hand hammer. The interval distance between each pole was 1 m. The alignment of the cuttings was arrangement in a row. In most cases, the bark of the cutting was damaged and for this reason clear cut was conducted to prevent the cutting from drying.

Plant and root system morphology

A complete excavation method was used to assess the root distribution system of 4-year-old live stakes of *S. alba var. tristis*. This method is very straightforward and can be used even when no information is available about the species of interest. The excavation involved initially digging around the stem to find the roots and then, carefully digging along the course followed by the roots in the soil (Puri et al., 1994). Small hand spades were used and hand excavation was performed to avoid root damage. The total depth, root number, length and basal diameter were also measured. Root systems were separated from the stems with sharp blade and placed in an oven to dry over 24 h at 70°C. Then, the weight of dry root mass was measured as previously described (Böhm, 1979). Before the root excavation, the shoot was cutoff at the base and the plant height and diameter at the base were measured with a tape.

For uprooted plants, aboveground characteristics such as the plant height and the average diameter at the base were measured with a measuring tape. The root system characteristics for each tested plant were measured, including root number, root length, the diameter of each root close to the stem base and dry root mass.

Field pull out tests

In order to investigate the pull-out resistance of *S. alba var. tristis*, 20 plants were randomly chosen from the plantation and used as test samples. Before each pull-out test, the plant height and stem basal diameter were measured. Then, the stem was cut at a height of 30 cm. A non-stretch rope was tight to the stem base at one end and to a portable force gauge at the other end, which was connected to a small winch (500 kg). A vertical traction force was then applied manually until the plant was uprooted. Similar to the pull-out test of Burylo et al. (2009), the main drawback of the test is the pulling speed. In our study, the traction force was applied as slowly and regularly as possible, in order to avoid affecting the results. The test was terminated once the resisting force sharply dropped or the plant was uprooted. Immediately after the pull-out test, the surface broken area was measured.

Statistical analysis

Cross-sectional areas (CSA) at root base (CSAbase) were calculated as an area of a circle with a diameter of roots close to the stem. The results of the pull-out tests were analyzed using the statistical package SPSS (version 17.0). Regression between maximal uprooting force and individual or combined plant morphological characteristics were performed.

RESULTS

Pullout resistance

In total, we performed 20 pull-out tests to investigate the stabilization effects of willow soil. Among the 20 plants, 15 were uprooted and the other five were not uprooted due to the rope failure or because the willow was too big to pull out.

The investigated *S. alba var. tristis* plants did not show any movement upon the first several forces. With the increase of the force applied, the plants started to move. The uprooting force and displacement were also measured and Figure 1, shows a typical pullout force-

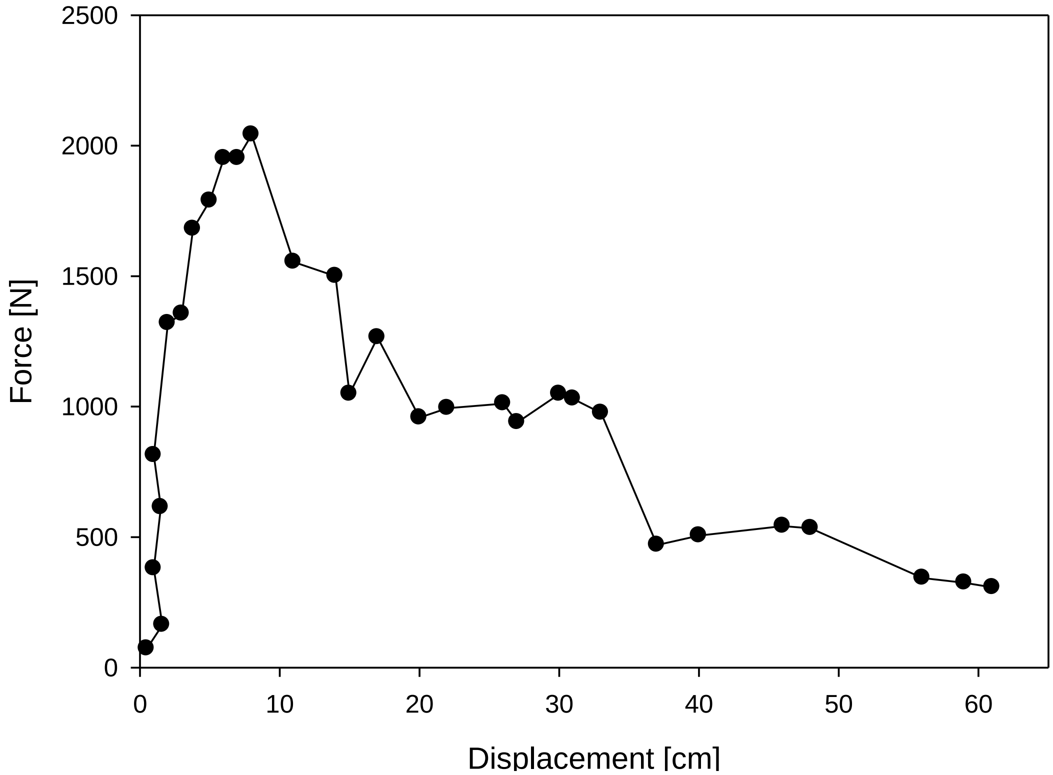

Figure 1. A typical uprooting–displacement curve for *S. alba var. tristis*.

displacement curve of *S. alba var. tristis* with a diameter of 5.2 cm. The maximum uprooting resistance is 2,041.6 N, which also the second largest force to pull out the trees in all testing samples. The resulting force-distance diagrams showed a steep slope until the maximal force (F_{max}) was reached and the root breakage occurred (Figure 1). After the highest peak, several peaks occurred probably because other accidental forces made roots broken. The maximum uprooting resistance of 15 investigated plants ranged from 254.5 to 2,511.5 N, with an average of 1,284.1 ± 741 N.

Plant traits and their relationship with resistance to uprooting

Radial roots (Figure 2) of a 4 year old tree extended from the trunk. During the excavation, we found that *S. alba var. tristis* adventitious roots consisted of various lateral roots in the soil immediately below the surface and the deepest roots were concentrated directly below the stem. There were very few obliquely oriented roots between the horizontal and vertical directions.

A complete excavation plant was 5.3 m in height and 4.8 cm in diameter. As shown in Figure 3, the root biomass distribution at various depths showed the 74% of roots were distributed in the surface soil (< 20 cm depth). We also found that, the lateral root spread of investigated plants ranged from 32 to 206 cm with an average of 64.3 ± 9.78 cm and became disappeared under 40 cm soil depth. The maximal rooting depth could reach 72 cm.

Table 1 shows the morphological characteristics of 15 uprooted *S. alba var. tristis*, the regression equations between maximal uprooting force (F_{max}) and the morphological characteristics of dependency plants. Most roots were broken during uprooting and on average only 16.8% of roots per plant slipped out of the soil rather than being broken during loading. The slipped out roots were usually lateral and very long. The mean distance at which roots became broke was 29.2 ± 1.32 cm (Table 1). Table 1 summarizes the correlations between the pullout resistances of the investigated plants and their morphological characteristics. Regressions of uprooting force with root morphology showed that except the total root number, the correlations of the uprooting resistance with plant height, stem diameter at base, average root diameter, cross-sectional areas (CAS) of all root at base and root dry mass are statistically significant ($P < 0.05$). Uprooting resistance had the strongest correlations with plant height and stem diameter at base ($P < 0.001$). The statistical analysis on plant height and stem diameter at base showed that, they had a strong correlation ($R^2 = 0.768$, $P < 0.001$).

Figure 4 and 5 show the dependency of uprooting force on the plant height and the stem diameter at the base of tested *S. alba var. tristis*, respectively. The plants with

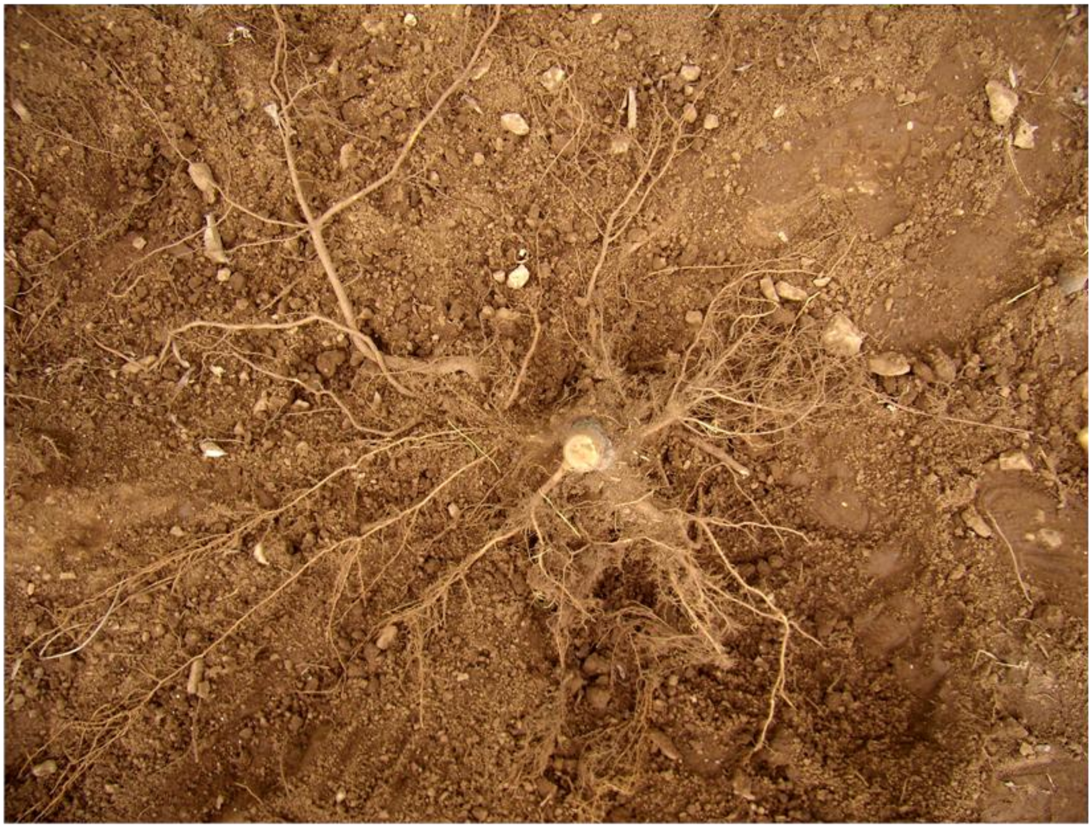

Figure 2. Photograph of *S. alba var. tristis* root system in the horizontal plane during excavating.

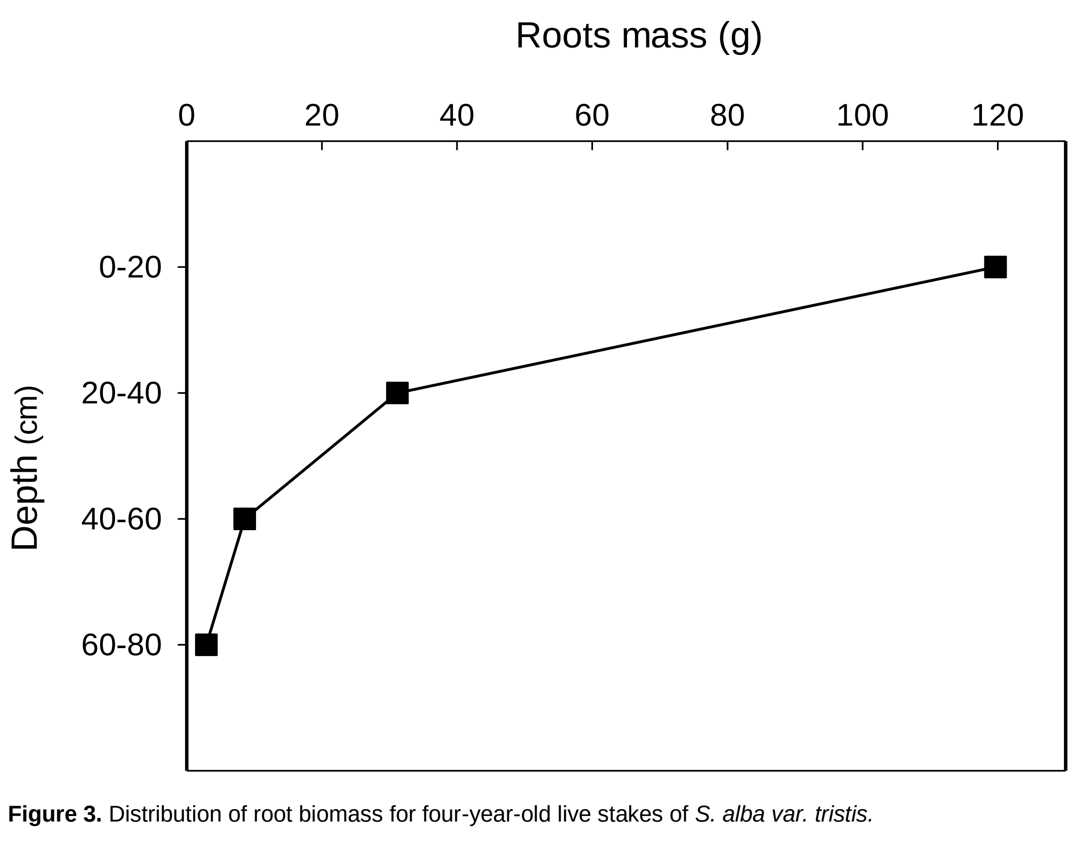

Figure 3. Distribution of root biomass for four-year-old live stakes of *S. alba var. tristis.*

Table 1. Morphological characteristics of 15 uprooted *Salix alba var. tristis* plants and regression equations between maximal uprooting force (F) and plant morphological characteristics.

Morphological characteristic	Mean	SE	Regression equation	R^2	P
H: Plant height (m)	5.3	0.15	$F = -5049.3 + 1184.5H$	0.79	<0.001
D_{stem}: Stem diameter at base (cm)	4.4	0.18	$F = -2620.4 + 882.98 D_{stem}$	0.69	<0.001
D_{root}: Average root diameter (cm)	1.2	0.09	$F = -656.48 + 1631D_{root}$	0.54	0.002
N: Total number of roots	9.6	0.67	$F = 349.67 + 93.17N$	0.10	0.244
CSA_{root}: CAS of all root at base (cm^2)	54.7	7.36	$F = 418.39 + 15.09CSA_{root}$	0.33	0.026
M_{root}: Root dry mass (g)	113.7	6.46	$F = -1179.4 + 23.4M_{root}$	0.60	0.001
Root broken length (cm)	29.2	1.32	-	-	-

* Significant at 0.05 level.

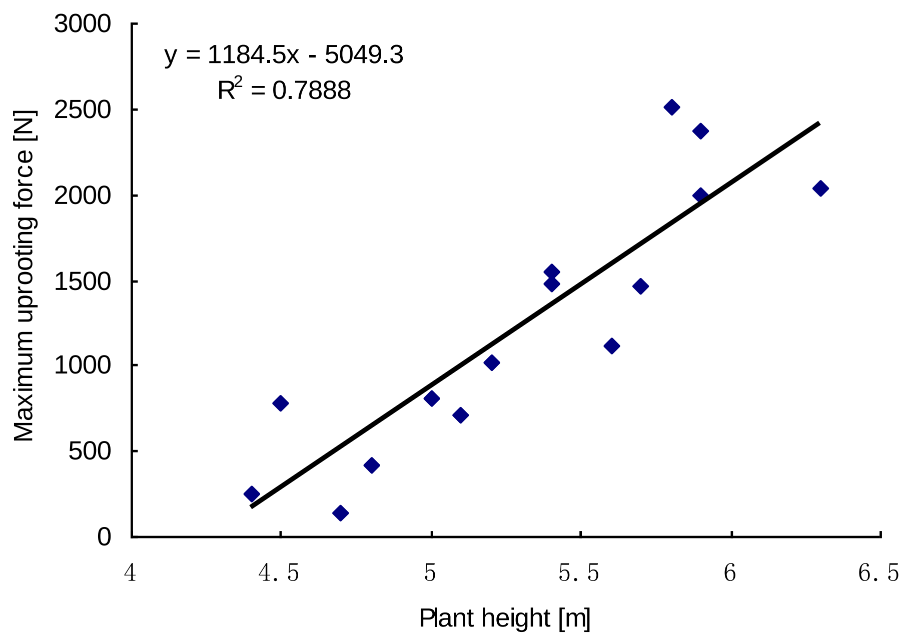

Figure 4. The relation between the maximum uprooting force and the plant height of *S. alba var. tristis*.

bigger size were able to better resist uprooting than the smaller ones.

Broken surface area in the pull-out test

We also calculated the relationship between the pullout resistance and the affected broken surface area during the pullout test (Figure 6). With the increase of pullout resistance, there was an increase in the broken surface area indicating that the area affected by soil reinforcement is increased with the pullout resistance.

DISCUSSION

The interaction of a plant with its environment is highly complex, but the local condition largely determines the depth and spread of the root system (Schenk and Jackson, 2002). This is may be because the top soil stored most water and nutrients available to the plants at our research site, as the huge amount of plant roots were distributed in the surface soil (< 20 cm depth).

As for the vertical pull-out test, little published data is available to compare with our study on 4-year-old *S. alba var. tristis* live stakes. Devkota et al. (2006) performed the pull-out test on several grasses with a high root biomass up to 12.7 g and they found that, the pull-out resistive force of different grass species was between 6 to 49 Newton (N). Karrenberg et al. (2003) performed the uprooting test on several young riparian tree species between 2 and 6 years old with the root biomass between 19.9 and 27.3 g and they found that, the average uprooting resistance ranged between 299 to 638 N.

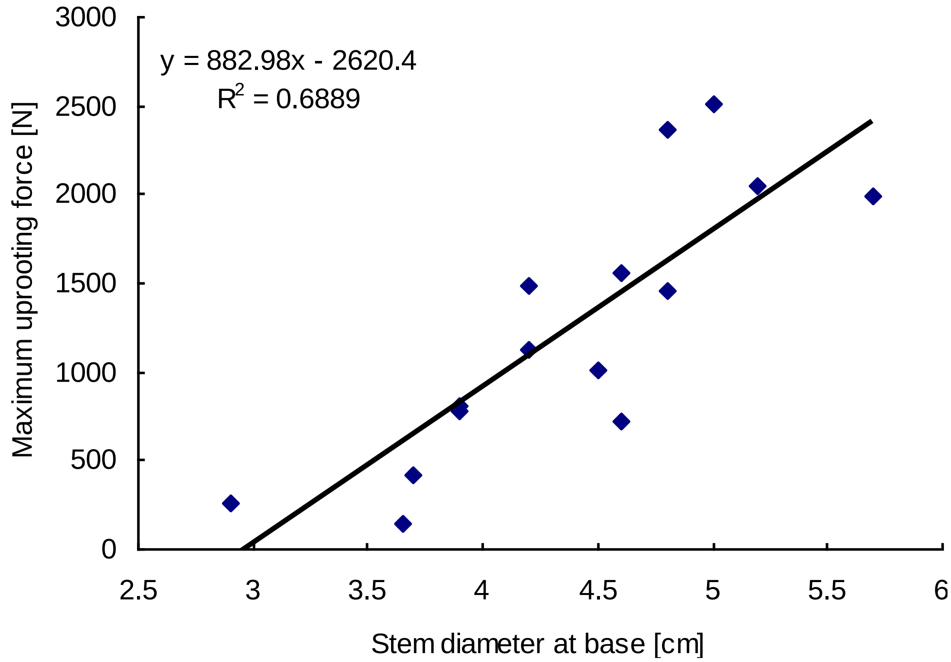

Figure 5. The relation between the maximum uprooting force and the stem diameter at base of *S. alba var. tristis*.

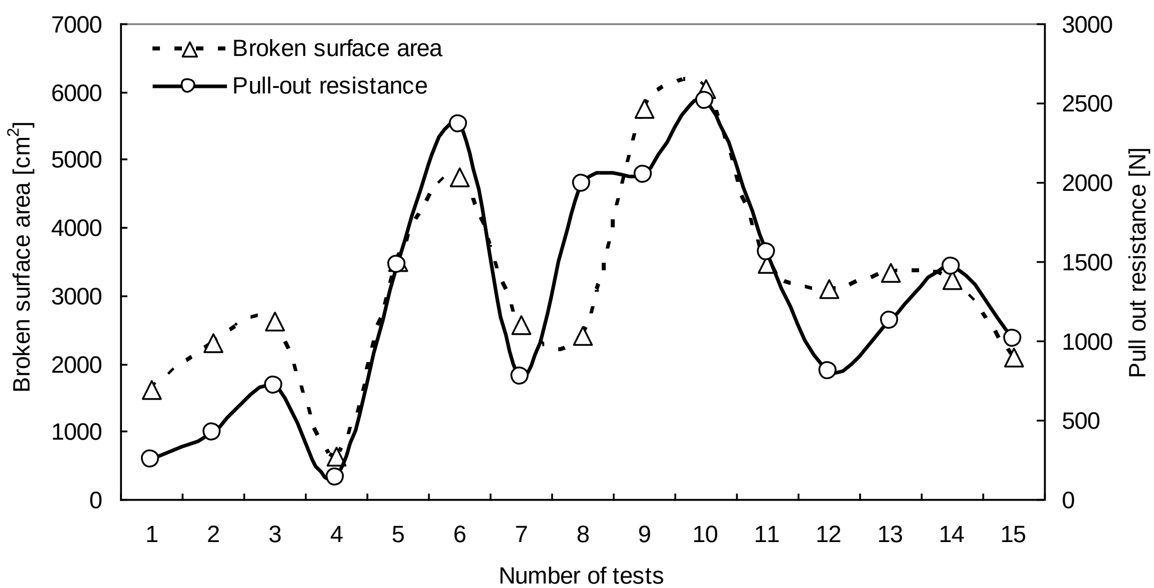

Figure 6. Uprooting resistance with broken surface area during the pull-out test.

Compared with these studies, the average uprooting resistance of 1,284 N observed in our study seems reasonable with a mean root mass of 113.7 g (Table 1).

The correlation and regression analyses showed that, the best predictors of uprooting resistance were plant height and stem diameter at base, indicating that the larger the plant, the higher its anchorage. This result is consistent with previous studies on other types of plants (Burylo et al., 2009; Mickovski et al., 2005; Schutten et al., 2005).

During our pull-out test, 73.2% of the roots were broken. The longest roots were almost unbroken and usually drag out from the soil during the pull-out tests, possibly because they were distributed immediately under the surface (<10 cm) and the traction force between the roots and the soil was too weak to broke them. The broken area increased with the pull-out resistance force, which implies a positive correlation between the plant size and the soil reinforcement ability.

Recently, soil bioengineering methods have regained worldwide attention including China, for their utilization in river and civil engineering projects (Florineth, 2002; Gao et al., 2008; Li and Eddleman, 2002; Li et al., 2006). However, the related scientific research in China is quite limited when compared with other countries. In this study, we performed the vertical pull-out test on the 4-year-old growing *S. alba var. tristis* as live stakes, which is one of the commonly used soil bioengineering techniques. We have estimated the root development and soil reinforcement ability of *S. alba var. tristis* used as live stakes. To our best knowledge, this is the first study on such techniques in China and there has been no published data on the soil reinforcement ability of *S. alba var. tristis* before. In the future, more efforts are needed to understand the soil reinforcement ability of this plant on river bank better as well as to compare its ability with that of other plants.

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