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Root reinforcement and slope bioengineering stabilization by Spanish Broom (*Spartium junceum* L.)

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Abstract

The present paper deals with the characteristics of the root system of Spanish Broom (*Spartium junceum* L.), a species that is worth taking into consideration for its capacity for adaptation and resistance to drought. In particular, the aims of the study were 1) to investigate the plant's bio-mechanical aspects and 2) to verify whether root reinforcement and the field rooting ability of stem cuttings enhance its potential for use in slope stabilization and soil bio-engineering techniques, particularly in Mediterranean areas.

Single root specimens were sampled and tested for tensile strength, obtaining classical tensile strength-diameter relationships. Analyses were performed on the root systems in order to assess root density distribution. The Root Area Ratio (RAR) was analyzed by taking both direct and indirect measurements, the latter relying on image processing. The data obtained were used to analyze the stability of an artificial slope (landfill) and root reinforcement. The measurement and calculation of mean root number, mean root diameter, RAR, root cohesion and Factor of safety are presented in order to distinguish the effect of plant origin and propagation.

Furthermore, tests were performed to assess the possibility of agamic propagation (survival rate of root-ball endowed plants, rooting from stem cuttings). These tests confirmed that agamic propagation is difficult, even though roots were produced from some buried stems, and for practical purposes it has to be ruled out.

Our results show that Spanish Broom has good bio-mechanical characteristics with regard to slope stabilization, even in critical pedoclimatic conditions and where inclinations are quite steep, and it is effective on soil depths of up to about 50 cm, in agreement with other studies on Mediterranean species. It is effective in slope stabilization, but less suitable for soil bio-engineering or for triggering natural plant succession.

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1 Introduction

Soils covered by vegetation run less risk of erosion from both water and land movement (Burroughs and Thomas, 1977; Ziemer, 1981; Sidle et al., 1985; Greenway, 1987; Coppin and Richards, 1990; Gray and Sotir, 1996). The role roots play in slope stabilization has been recognized for many years (e.g. Gray and Sotir, 1996; Gray and Leiser, 1982), whereas interest in bio-mechanical tests on roots (of Mediterranean species in particular) has arisen only during more recent years (Operstein and Frydman, 2000; Mattia et al., 2005; Tosi, 2007; De Baets et al., 2008). De Baets et al. (2007, 2008) showed how some typical Mediterranean plants increase topsoil resistance to erosion and shallow landslides from runoff and superficial flow.

Some Mediterranean species were submitted to root tensile strength tests, shear stress tests of rooted soil in the laboratory and/or pull-out tests: Operstein and Frydman (2000) studied three species (all dicotyledonous shrub species); Gallotta et al. (2000, 2003) studied seven species; Amato et al. (1997, 2000) studied 16 species; Mattia et al. (2005); studied the characteristics of three other species. De Baets et al. (2008) investigated the bio-technical characteristics of 25 Mediterranean species. Authors studied Mediterranean species including Spanish Broom (*Spartium junceum* L.): Norris and Greenwood (2003), Laranci et al. (2004) with other seven species, Tosi (2007) with other three pioneer species that grow on and stabilize clayey Apennine hills.

With regard to the architecture of the Spanish Broom root system when grown on slopes, it has been observed that its orientation and root density undergo a modification. Its root growth is asymmetric and follows the orientation of the slope, concentrating mainly on the uphill direction (with respect to the stem) (Chiatante et al., 2001, 2003a, b). This is a characteristic that guarantees the stability of the plant (Chiatante et al., 2001, 2003a, b; Di Iorio et al., 2005). The development of the root system is influenced by genetic and environmental factors, e.g. its lignin and cellulose content, soil structure and texture, temperature and water availability, seasons and altitude (Genet et al., 2005).

In nature a wide variety of root systems can be observed, both on a horizontal and on a vertical plane (Stokes et al., 2008). Consequently, their impact on soil reinforcement is somewhat heterogeneous. As far as fine roots are concerned, they increase the contact between plant and soil because of the wider contact with the land surface. Therefore, they also increase the resistance of the rooted soil (Gray and Leiser, 1982). Moreover, finer roots have a higher tensile strength per unit (Operstein and Frydman, 2000). On the other hand, thicker roots can be likened to biological nails, which probably tend more to pull out than break (Coppin and Richards, 1990; Greenwood, 2005); the latter use just a small part of their tensile strength (Burroughs and Thomas, 1977; O'Loughlin and Watson, 1979; Ziemer, 1981; Schmidt et al., 2001). De Baets et al. (2008) highlighted the importance of fine roots. The literature also reports that differences in tensile strength among different species are more meaningful than differences within the same species, with regard to the spatial distribution of roots (Abernethy and Rutherford, 2001).

Wu (1976) and Wu et al. (1979) pioneered a model that has been applied in numerous studies for the assessment of how roots contribute to soil shear reinforcement. The impact of root reinforcement on soil is generally expressed as an increase in soil cohesion (Borroughs and Thomas, 1977; Wu et al., 1979; Wu, 1984a, b; Sidle et al., 1985; Sidle, 1992; Wu and Sidle, 1995; Abernethy and Rutherford, 2001; Stokes et al., 2007; Stokes et al., 2008 in Norris et al., 2008). A number of factors influence the tensile strength test: species, season, age, soil compaction, deformation of roots, soil and root moisture, root preservation, field or lab test, type and size of testing equipment, procedure for clamping the root, test speed, and rate of elongation (Rienstenberg, 1994; Cofie and Koolen, 2001; Fan and Su, 2008).

The planting method, quality of planting and root pruning (undercutting) influence the root development when establishing a planted stand, except for species and soil conditions. Three main methods can be used: direct seeding on site, transplanting of seedlings sown in containers, planting of bare-root seedlings and transplanting of cuttings (bare-root or in containers) (Stokes et al., 2008).

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Various studies have documented the good results obtained by using Spanish Broom to recover badlands. This species has a marked adaptability and resistance to drought. Its thick covering makes it appropriate for protecting slopes that show superficial erosion phenomena (Leopardi, 1845; Bagnaresi et al., 1986; La Mantia and La Mela Veca, 2004; Tosi, 2007). Such studies have used seed plants, plants with a root ball and plants with bare roots. Laranci et al. (2004) studied the survival of rooted plants and their ability to develop adventitious roots after burying a portion of the stem. This study used rooted plants grown in pots. Tests showed that, once planted, Spanish Broom cannot develop adventitious roots from its stem. However, its root system can develop quite satisfactorily, and it grows more than other species. Morone et al. (2005) and AA.VV. (2006) conducted some micropropagation tests on Spanish Broom plants. Auxinic plant growth regulators were used at different concentrations (indoleatic acid (IAA) and indolebutyric acid (IBA)) to induce rhizogenesis in green stem cuttings. This protocol allows a high rate of production of young plants in a short period of time. Quatrini et al. (2002) proposed using plants that were inoculated with nitrogen-fixing bacteria.

The present study focused on this typical Mediterranean species and studied the following features on an experimental basis by distinguishing transplanted and spontaneous Spanish Broom specimens: its bio-mechanical characteristics, the spatial distribution of its roots and the statistical variability of RAR at each depth. Root tensile strength tests were carried out using devices that were custom-built in our Faculty laboratories. In addition, we calculated the Factor of safety (*Fs*) of the slope. For the calculation of supplementary cohesion, the well-known Wu and Waldron formula was adopted for each soil horizontal cross section and the conditions set out in the following sections, where all tests are described in detail. To determine the potential for use in soil bio-engineering, we tested the rooting ability of stem cuttings in the field, as this was not considered in the abovementioned studies. The ability of Spanish Broom cuttings to root was studied in order to assess the potential for agamic propagation, as well as to understand its root architecture and the resulting Root Area Ratio (RAR).

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2 Materials and methods

2.1 Study area

The study was conducted in the area of San Casciano Val di Pesa (Florence), in the heart of Tuscany (Italy), just a few km south of Florence (Fig. 1). Fieldsite was located in the Gentilino area on a slope belonging to the Municipality of San Casciano. The hill slope has a 50% inclination and a southeastern exposure.

The slope where the tests was performed is artificial, being made of landfill (Fig. 1). In order to control and/or avoid erosion and shallow landslides, Spanish Broom was transplanted upon completion of the artificial slope. Nonetheless, in 2007 a small landslide occurred at the foot of the slope (Fig. 1). Eleven plants were sampled, eight from the study area and three from spontaneously-growing plants from nearby areas (Gabbiola and Spedaletto sites are ex-agricultural areas colonised by natural shrubs 300 m away from Gentilino area, in Table 2). The eight plants from the study area had come from a nursery and had been transplanted with their root balls at the time the slope was being restored. All the plants (from the nursery and the spontaneous ones) were of the same age, about seven years old.

2.2 Hydrology

The climate of the study area is Mediterranean (Köppen classification). Data for the rainfall as well as the maximum, average and minimum temperatures gives the daily average potential evapotranspiration Tp, the rainfall frequency λ_0, and the average intensity of rain events α values shown in Table 1 (data from http://agrometeo.arsia.toscana.it/).

Rainfall Intensity-Duration-Frequency data gives the curve equation $I=21.65\,Tr^{0.18}D^{0.21}$, where I = rainfall intensity [mm/h], Tr = return time interval [years], D = rainfall duration [h], and the runoff coefficient value is equal to 0.66 according to previous studies on Flood Regionalization (Regione Toscana, 2007).

2.3 Soils

Analysis of the soil began by obtaining three soil profiles. To classify the soil, geotechnical tests were carried out according to the standards of the AASHTO system (adopted in Italy by the CNR-UNI 10006 norm). The percentages in the fine part of the soil were determined with a soil hydrometer. With regard to the limits of Attemberg, the Casagrande bowl was used. In order to determine the friction angle, three soil shear tests were carried out with loads of 50, 100, 150 and 200 Kpa.

2.4 Estimation of Root Area Ratio (RAR)

The spatial distribution of the Spanish Broom roots was evaluated by digging out the soil and exposing the root system. There are several methods that can be used to assess the Root Area Ratio, i.e. ratio between root area and rooted-soil area (RAR). One is known as core-break sampling (Schmid and Kadza, 2002). Another consists of counting roots using a profile trench (Schmid and Kadza, 2001, 2002). A further method involves extracting the plant from the soil without damaging its roots; this can be done by using jets of water (Tosi, 2007). In the case of the trench profile, roots can be measured either directly or from a photograph (Vogt and Persson, 1991; Bischetti et al., 2005). The plant was excavated by hand removing the earth from the roots, starting from the collar and then along the whole length. The RAR of all samples was measured with the direct method. The indirect method was also used for four plants in order to compare the two methods. As far as the indirect method is concerned, after excavating the root system, we interposed it by a grid (Fig. 2) of known dimensions, and a photo was taken, displaying the roots in the position in which they had been in the soil. Afterwards we rectified the image in order to avoid image distortion errors (Dani and Preti, 2007) and we counted and measured the diameter of the roots using AutoCAD™. The direct calculation was carried out in the laboratory. The excavated plants were brought to our laboratory while they were still fresh. For both methods, measurements was taken at horizontal cross sections for each 5 cm depth and the minimum diameter we measured was 0.5 mm. The rooted area (Ar) for each depth level (5 cm intervals) was measured by summing the areas of the single roots. The formula we used to estimate RAR was the following:

$$\mathrm{RAR}(z) = \sum_{i=1}^{m} \frac{Ar(z)_i}{As(z)} \cong \sum_{i=1}^{m} \frac{d(z)_i^2}{D_s^2}$$

where:

$Ar(z)_i$ = area of the i-th root

$As(z)$ = rooted-soil area

z = depth

$d(z)_i$ = diameter of the i-th root

D_s = largest soil diameter explored by the root system (if a cylindrical rooted volume is assumed)

m = number of roots at z depth.

The distribution curve of the RAR was obtained by counting the number of roots in the different diameter classes and by determining the values for each soil level explored.

2.5 Lab tensile tests on roots

Tensile strength tests were performed at the Laboratories of Wood Technology, Department of Forest Environmental Sciences and Technologies, University of Florence. Two machines were used for the tests: the "Remo-Mat" and "Amsler". The Remo-Mat is a prototype machine, engineered and built in the same laboratory for the tensile testing of small wooden specimens, with digital control and recording systems. The Amsler Universal Testing Machine is an hydraulic testing machine, having a 40 kN maximum load, that was improved by installing a load cell and transducers. It is connected to a computer for digital data acquisition. Measurements for assessing the tensile force value of Spanish Broom were performed on 98 samples whose diameters ranged from 0.65 to 9.9 mm (including root bark). Tests were performed about one hour after removing the root samples from the field and storing them in moist conditions. There was no need for preservation in alcohol, as there was no chance for withering to occur. The small diameter roots ($d<2.5$ mm) were tested with the Remo-Mat, while the bigger ones were tested on the Amsler machine. Breaking of specimens was achieved in about 90 s in the Amsler machine, while breaking time ranged from 150 to 300 s on the Remo-Mat, due to the different method of control, the first being analogue and the second, digital. The two testing machines have similar cylindrical anchoring systems.

After testing, some of the specimens were used to determine moisture content (*M.C.*). The weight of the specimens was measured; then the roots were put in a dry oven at a temperature of 103°C (±2°C). The measurements, taken 24 h later, were used to determine moisture content with reference to the dry weight ($M.C. = (Mu-M)/Mo$ where Mu is the weight at the moment of the test while Mo is the dry weight).

2.6 Root cohesion

The values of the additional soil cohesion (Cv) were calculated with the following formula, according to the Wu (1976) and Waldron (1977) model:

$$Cv(z) = K \sum_{j=1}^{n} Tr_j \left(\frac{Ar(z)_j}{A(z)} \right)$$

where:

$Tr(z)_j$ = tensile strength of the j-th diameter class;

$Ar(z)_j$ = sum of all the root areas of the j-th diameter class;

n = number of diameter classes at z depth.

According to Pollen and Simon (2005), Preti (2006) and De Baets et al. (2008), the Wu and Waldron model overestimates root cohesion values (by putting $K = 1.2$ as standard, root cohesion values could be considered maximum values). Nevertheless, the so-calculated cohesion values were used to rank Spanish Broom according to its potential to reinforce the soil (Tosi, 2007). Cv was calculated for each plant for each depth. In doing so, the contribution of each root was taken into account. By calculating the average Cv among all plants at a certain depth, the values in Fig. 10 were obtained.

2.7 Factor of safety

In order to consider the effect of vegetation on stability, we adopted the infinite slope method (Coppin and Richards, 1990; Schimdt, 2001), in the following form (Preti, 2006):

$$F_s = \frac{(c' + c'_v)}{\gamma_{sat} \cdot z \cdot \cos\beta + W_v \cdot \sin\beta} + \frac{\gamma \cdot z \cdot \cos\beta + W_v}{\gamma_{sat} \cdot z \cdot \cos\beta + W_v} \cdot \frac{\tan\phi'}{\tan\beta}$$

where:

Fs = Factor of safety

c' = soil cohesion [kPa]

c'_v = root cohesion [kPa],

z = slope's breaking surface depth [m]

β = slope angle [°]

ϕ' = soil friction angle [°]

$\gamma = \gamma_{sat} - \gamma_w$ "submerged" bulk unit weight [kN/m^3]

γ_{sat} = saturated bulk unit weight [kN/m^3]

W_v = overload due to vegetation [kPa]

In the following, the Fs was calculated under the measured conditions: saturated bulk unit weight [kN/m^3] $\gamma_{sat} = 20\,\text{kN m}^{-3}$, water unit weight $\gamma_w = 9.8\,\text{kN m}^{-3}$, slope angle $\beta = 26.5°$, soil friction angle $\phi' = 20°$, soil cohesion = 1 kPa. The surcharge on the soil slope owing to the presence of plants (W_v) was calculated on the basis of both the average weight of the Spanish Broom transplanted and spontaneous plants and their density (60×60 cm), giving a value of 20–40 kg/mq, which is equivalent to 0.196–0.4 kPa, respectively.

2.8 Spanish Broom propagation

Normally Spanish Broom propagation occurs by seed. Sowing takes place in spring in seedbeds, and the seedlings are later transplanted to their permanent locations.

However, our interest lay in investigating agamic propagation in the field and resulting root system development. A total of 360 cuttings taken from existing plants in the study area were planted at four different times: August, October, November 2007 and February 2008 (Table 3) to ascertain the best rooting period for stem cuttings (Cervelli et al., 2004). For purposes of comparison, 360 new root-ball specimens were planted in the same area in which Spanish Broom had been transplanted seven years previously (Fig. 1).

The synthetic chemical products used for inducing rooting were indolbutirric acid (IBA) and naftalenacetic acid (NAA), although other auxins can be used. They were the most effective with regard to obtaining adventitious roots on stem cuttings. These chemical products are available either in powder or liquid form, and the latter can be diluted in water to the appropriate concentration. Woody species that take root with greater difficulty must be treated with products at high hormonal concentrations whereas species that are tender, herbaceous and take root easily must be treated with less concentrated preparations. The cut at the base of the stem cutting must be fresh: i.e. it must be made just before dipping the cutting into the powder in order for the latter to adhere. The powder that sticks to the stem cuttings after they are lightly pressed onto the product is sufficient. Dampening the base of the stem cuttings beforehand in order to improve adherence can be useful (Hartmann et al., 2002). Some stem cuttings were treated with root-stimulating substances (NAA, containing alpha-naphthyl acetic acid as the base).

Two sites of the study area were singled out and roped off (site A and site B in Fig. 1). Site A (Fig. 1) was next to where the root-ball Spanish Broom plants were planted; site B was 30 m away on the same contour line, isolated from the other Spanish Broom plants. This distribution was chosen in order to verify a possible relationship between the soil that was already colonized by *Bradyrhizobium* spp., bacteria and *Glomus* fungi on one hand and the rooting ability on the other (only for the first test) (Quatrini et al., 2002). In turn, the two sites were divided into two sections: stem cuttings with or without use of plant hormone for rooting. The plant hormone we used contained alpha-naphthyl acetic acid (NAA), a very common exogenous synthetic phytoregulator. The stem cuttings used for the first test were 20–25 cm long (herbaceous cuttings), and those for the subsequent tests were 60–70 cm long (semi-woody cuttings). In this case cuttings were planted at 20–30 cm depth. At the time of planting, all sites were irrigated with about 15 l of water each. A second irrigation was performed two days later, again with 15 l of water, and a third one 10 days after planting. Forty stem cuttings were planted on each site, 20 of which were treated with hormone (left side, if looking at the slope from below) and the other 20 untreated (right side). Another 20 stem cuttings were planted in pots, 10 of which were treated with hormones and the other 10 untreated. The soil used in the pots was from the testing site. The purpose of planting in pots was to have more control over the stem cuttings by using irrigation (Table 3).

3 Results

3.1 Soil analisys

Within the soil profile only one horizon B was observed (up to 50 cm), overlapped by a thin layer of undecomposed organic matter. When wet the soil was very sticky, which is typical of clay-silty soils. The colour was light brown, with many gray streaks (clay) and some tending more towards red (sandier). The distribution of rocks of various sizes (some measuring more than 10 cm) along the slope was heterogeneous. Fragments of bricks and other aggregates were found in the soil, along with other construction-site-wastes. According to USCS nomenclature, the soil generally has a texture defined as ML. The soil characteristics are shown in Table 2. The liquid limit and the plastic limit were 48% and 28%, respectively. The activity index was 0.59 (inactive clays). Friction angle resulted about 20° and a cohesion ranging from 0 to 0.2 Kpa. Excavated soil was very clayey, with little skeleton, and when placed under light pressure, it crumbled to a minimum particle size of 4 to 10 mm. This size depended on the amount of moisture

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present.

3.2 Root distribution analysis

Figure 4 shows the comparison between the direct and indirect measurements of RAR. Figure 5 shows the root average number of transplanted and spontaneous plants separately, at the various depths. The mean diameter of roots for each plant was averaged grouping transplanted and spontaneous plants, at the various depths (Fig. 6). The large root at shallow depths (from 0.0 to 0.10 m) influences the value of the root mean diameter, and for larger depths, the root system of spontaneous plants branches off and the root mean diameter remains quite constant up to 0.7 m. Table 4 shows the values of the maximum, minimum, mean, standard deviation and Coefficient of Variation ($C.V.$). It can be observed that $C.V.$ values are almost similar. The maximum depth of the main root was 70 cm for spontaneous plants, while about 40 cm for transplanted plants. The trend of the average RAR of Spanish Broom for each depth can be described as an exponential curve, as shown in Fig. 7. In order to assess the variability in the study area, the two plants grown in the natural soil next to the slope were taken into account as well. Figure 8 shows the trend and the variability of the average RAR for population of Spanish Broom. Analysis of the mean of the samples showed that the variability of RAR at the various depths is RARmean(z)%±(t_νSE) where:

z = depth

t_ν = t-distribution value for ν degrees of freedom with 95% confidence limits

SE = Standard Error.

3.3 Tensile strength tests

The regression curves obtained for tensile force tr versus diameter (Schmidt et al., 2001) were as follows (Fig. 9): $tr = 0.0203\,\mathrm{d}^2 + 0.0062\,\mathrm{d}$ $R^2 = 0.94$ SD = 0.287 for all 98 samples, $tr = 0.0233\,\mathrm{d}^2 + 0.0034\,\mathrm{d}$ $R^2 = 0.93$ SD = 0.334 for the data obtained by the Amsler, and $tr = -0.0176\,\mathrm{d}^2 + 0.0241\,\mathrm{d}$ $R^2 = 0.62$ SD = 0.027 for those obtained by

Remo-Mat.

Each machine works on different diametric ranges with an overlap of 1.3 mm. The minimum diameter was 0.65 mm and the maximum 9.9 mm.

The unit tensile strength *Tr* of roots is not constant but instead increases as diameter decreases. The minimum, maximum and mean values of the unit tensile strength resulted 9.7, 65 and 31.7 MPa, respectively. The data indicate the same general tendency, which is explained by the power law model and has been widely reported in the literature for different species (e.g. Mattia et al., 2005; Bischetti et al., 2005; Tosi, 2007; De Baets et al., 2008). In some cases the breakage measurements for the wooden root and the bark were similar. The tensile strength was calculated using the maximum value. In some thick roots breakage occurred away from the centre of the specimen, inside the clamp.

The roots tested immediately after extraction from the field had a high moisture content, above the fibre saturation point (conventionally stated as 30% of dry weight in wood). The mean value of the moisture content (*M.C.*) of the specimen, determined in relation to the dry weight, was about 40%.

3.4 Stability and hydrological analysis

By correlating the measured tensile strength with measured RAR (Fig. 7), the additional cohesion due to the presence of roots in the soil is obtained according to the Wu and Waldron model. The *Cv* was estimated taking into account the tensile strength value obtained from regression curve (Fig. 9) for each root at the horizontal cross section of soil. The variation in *Cv* depending on depth is shown in Fig. 10.

Fs on saturated soil at various depths is shown in Fig. 11 for different scenarios: unvegetated soil, transplanted stand and natural slope.

Considering the above-mentioned rainfall-duration curve ($h = a'Tr^m t^n$) and the saturated landslide depth, the return time *Tr* of the hydrological instability threshold can be calculated. We obtained an acceptable *Tr*~10 years for a rainfall duration of 24 h, by considering the known runoff coefficient value and the estimated upslope contributing area (connection with the urbanized area in Fig. 1).

3.5 Spanish Broom propagation

Surveys on vegetative conditions were conducted in February, March and June, as shown in Fig. 12. Almost a year after planting, all the root-ball plants had rooted, 98.9% of stem cuttings without hormone treatment had died, and 100% of stem cuttings with hormone treatment had died. Of the stem cuttings planted in pots, the survival rate was 10%. As shown in Fig. 3, roots (about 20 cm long) developed only from the deeper regions of the stem cutting (October 2007 planting).

4 Discussion

4.1 Root distribution

The root systems analyzed did not show substantial differences in their architecture. The photogrammetric method used to assess RAR (Fig. 4) was comparable with and more convenient than the direct type of measurement and offers a number of advantages: measurements can be taken at a different time from when the picture is taken; therefore it is not necessary to take steps to prevent the plants from drying out.

The root number (Fig. 5) and mean diameter (Fig. 6) are different between transplanted and natural plants. The root distribution of the transplanted plants (Figs. 5, 6, 7) could be due to plant origin and soil condition. Container grown seedlings often have a limited root system, with lateral roots spiralling around the container and bare-root seedlings are often deformed during transplanting and roots damaged or bent (Lindström and Rune, 1999; Nörr, 2003). The soil diameter explored by the root system D_s is less large for transplanted plants and consequently the average RAR displays a similar trend (Fig. 7). The difference between soils (Gentilino clay soils and natural slope less clayey soil) resulted only in a lower average rooting depth at Gentilino (Schenk and Jackson, 2002a, b; Laio et al., 2006; Preti et al., 2008).

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RAR variability decreases as depth increases and below 25 cm of depth is almost constant. At depths between 10 and 50 cm the root system branches off, while at depths greater than 50 cm, it is basically only the tap root that contributes to the RAR.

Our values are consistent with the average diameters reported by Tosi (2007), who found an average diameter of 8.8±6.8 mm Standard Error at 5 cm of depth.

4.2 Tensile strength tests

Figure 9 show that the tensile force values measured in the laboratory (in our study, 98 samples after having excluded values from anomalous samples, $R^2=0.94$) are consistent with Tosi's curve (2007), as far as lab is concerned (48 samples, $R^2=0.96$) The regression equation of tensile strength [MPa] Tr versus root diameter [mm] of Spanish Broom curve is $Tr=37.605\,\mathrm{d}^{-0.306}$ $R^2=0.29$, where the coefficient of the power law curve corresponds to the tensile strength for a diameter equal to 1. Moreover, this value is more meaningful than the average of values measured for comparison both within and between species (Preti, 2006). Norris and Greenwood (2003) and Tosi (2007) found a mean tensile strength value of 17 MPa and 30 Mpa, respectively, while Laranci et al. (2004) reported values between 20 and 81 MPa for diameters of presumably up to 2 mm.

In the previous study conducted by Tosi (2007) the humidity of samples was very low (always under 30%) and was about half the humidity we calculated here (always over 30%), both for dry and wet weight. This factor does not seem to influence the tensile strength (Fig. 11) but only the elastic deformation, although, conventionally, as far as wood is concerned, there are small variations in the mechanical characteristics beyond the threshold of 30%. Viscoelastic phenomena (rather significant on wet wood and bark) did not occur due to the test rate (Cofie and Koolen, 2001). Roots from naturally regenerated plants could have higher tensile strength than container plants (Lindström and Rune, 1999), whereas no differences have yet been found between cuttings and container grown seedlings (Stokes et al., 2008).

4.3 Root reinforcement and hydrological conditions

In order to assess the potential stabilizing effect of Spanish Broom a stability analysis was performed, using the infinite slope model (Fig. 11). The *Fs* values obtained in saturated conditions harmonized satisfactorily with the measured landslide scarp (Fig. 1) and with Tosi's results (2007) from the clay slopes of the Apennines. A satisfactory agreement between the statistically estimated occurrence return time of the rainfall event occurred and the calculated one by means of the stability model was obtained.

It can be noticed that transplanted plant are effective for slope stabilization on soil depth of up to 40 cm, while natural plants up to 70 cm. Actually naturally regenerated and direct sown seedlings are the most mechanically stable and more difficult to uproot and the soil stabilization is probably due to a well developed and undisturbed root system (Halter and Chanway, 1993; Lindström and Rune, 1999; Stokes et al., 2008).

4.4 Spanish Broom propagation

Under ideal conditions, Spanish Broom has a high germination rate, as do all legumes (Piotto and Di Noi, 2001) and can also be micropropagated. In fact, Spanish Broom is commonly used to restore greenery to slopes by using plants with root balls or bare roots, a method that leads to excellent rooting-taking results. In a recent study concerning the reforestation of marginal areas (La Mantia and La Mela Veca, 2004) 369 bare-root plants were used. After 4 years, the survival rate was 93.8%, with an average height of 1.70 m. Spanish Broom can develop a crown of up to 60 to 80 cm in 14 months (Laranci et al., 2004).

In our study Spanish Broom plants had a very high survival rate when planted with a root ball. The canopy increased rapidly and did not allow other species to grow. The percentage of rooting in stem cuttings was very low (almost zero). If rooting takes place, development only occurs in the area around the cut and not along the stem (Fig. 3). Rooting is only possible with particular treatment and care. This method is inappropriate where the need exists to allow plants to grow autonomously (AA.VV., 2006).

As far as the architecture of the root system that develops from a cutting is concerned, it was clearly not possible to verify whether there are any differences when using agamic propagation. We can nevertheless state that in the rooted cutting in Fig. 3 it was possible to observe a large number of small roots, in contrast to what was found in plants of more than 5- to 6-years-old. This is probably due to the phenological phase of adventitious root emission for survival. We presume that with further development the root system assumes the characteristic conformation of this species. Close observation of Fig. 3 revealed that among all the roots, there were three or four that prevailed over the others, in particular one vertical and two horizontal roots, which would probably later constitute the main branches.

The essential difference between seedlings and cuttings is that the latter can develop a taproot only after five years (Khuder et al., 2007). Plants which were generated from cuttings are usually smaller and have a lower number of roots than the seeds grown ones. Cuttings do not generate lateral and vertical with the same facility, at least in young plants. The uprooting of cuttings is easier than the uprooting of seedlings at the same age, but these differences may disappear after several years (Khuder et al., 2007).

Root-ball plants gave excellent results and created dense land cover.

5 Conclusions

The Spanish Broom is a species capable of adapting to types of soil characterized as difficult (dry, clayey). When the plant grows in clumps, it tends to prevent the growth of other plants, due to the wide ground coverage of its crown. Spanish Broom can also be used to control erosion because of this selfsame thick coverage, which greatly reduces the effect of driving rain. Its root system has a tap root structure. Its aboveground part has a negligible weight as far as overload is concerned. The root tensile strength is significant.

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The measurement and calculation of mean root number, mean root diameter, RAR, root cohesion and Factor of safety in saturated conditions have been carried out for transplanted and spontaneous plants. The indirect RAR estimation methodology correlated well with the direct measurements. By applying the Wu and Waldron formula, it was found that planting a steep slope with Spanish Broom brings about a considerable increase in cohesion in the surface layers of the soil. In transplanted plants we found an increased cohesion over 40 cm of depth, almost six years after planting, while we found it over 70 cm of depth with spontaneous plants of the same age, grown in a natural slope.

The rooting tests showed that, plants with root balls give excellent results: 100% of all plants with root balls had rooted. They had created a dense land cover and a network of root systems that significantly reduce soil erosion. Almost a year after planting, all stem cuttings (98.9%) had died, whether treated or not with rooting hormone. Consequently, seed propagation in the nursery and micro propagation in the laboratory are the only reproduction techniques that give good results. Agamic field reproduction of Spanish Broom can be ruled out for technical reasons, despite the fact that we did achieve rooting in controlled conditions. The fact that the plant is resistant to burial makes it feasible for use in soil bio-engineering in the Mediterranean climate, even though it does not facilitate the triggering of natural plant succession.

Finally, Spanish Broom has good bio-mechanical characteristics, even in critical pedoclimatic conditions and on steep slopes. It is most appropriate for use in soil bio-engineering aimed at plant adaptability and ground nailing rather than in endeavours where root reinforcement within the structures is required or where natural thick vegetation cover is desired.

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The presentation of the paper at the 2nd International Conference on “Ground Bio- and Eco-engineering. The Use Of Vegetation to Improve Slope Stability” held in Beijing, China, 14–18 July 2008, received the prize for Best Poster, based on scientific quality and aesthetic appearance.

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Table 1. Daily rainfall data parameters at Sambuca and Ponte a Moriano measured by rainfall gauges: Tp = potential evapotranspiration, λ = rainfall frequency, α = average rainfall intensity.

Summary climate parameters					
Gauge	Experimental Site	Tp [mm/d]	λ [event/d]	α [mm/event]	Time series data
Sambuca 1 680 260 E 4 829 130 N	San Casciano in Val di Pesa (Florence)	2.189	0.374	5.284	2001–2006

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Table 2. Soil sample characteristics.

	Clay	Silt	Sand	Porosity	Classification USDA
Site $A_{cuttings}$	44.0%	46.4%	9.6%	56.0%	Silty Clay
Site A_{α}	51.0%	41.5%	7.5%	50.0%	Silty Clay
Site A_{β}	18.3%	48.5%	33.2%	38.7%	Loam
Site A_{ρ}	31.1%	56.8%	12.1%	35.5%	Silty Clay Loam
Site A_{ϕ}	29.6%	58.4%	12.0%	39.3%	Silty Clay Loam
Site Bs	49.9%	42.2%	7.9%	57.0%	Silty Clay
Site Bp	53.6%	38.5%	7.9%	60.0%	Silty Clay Loam
Site Cs	14.9%	52.8%	32.3%	30.7%	Silt Loam
Site Cp	10.7%	35.5%	53.8%	27.3%	Loam
Site $Cp_{landslide}$	28.7%	34.2%	37.2%	42.0%	Clay Loam
Site $Cs_{landslide}$	49.2%	37.2%	13.6%	49.0%	Clay
Gabbiola Bs	29.1%	49.0%	21.9%	24.5%	Clay Loam
Gabbiola Bp	31.0%	47.5%	21.5%	20.6%	Silty Clay Loam
Gabbiola A	31.1%	48.7%	20.2%	23.3%	Silty Clay Loam
Spedaletto	30.4%	48.4%	21.2%	24.5%	Silty Clay Loam

Table 3. Number of planted stem cuttings for different experimental conditions.

	Site A		Site B		Flowerpot		
	with NAA	no NAA	with NAA	no NAA	with NAA	no NAA	Total
08/2007	20	20	20	20	10	10	100
10/2007	20	20	20	20	10	10	100
11/2007	20	20	20	20	–	–	80
02/2008	20	20	20	20	–	–	80
Total	80	80	80	80	20	20	360

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Table 4. Root diameter of transplanted and natural plants.

Root diameter	transplanted	spontaneous
Max [mm]	33.1	34.0
Min [mm]	0.3	0.5
SD	4.6	3.7
Mean [mm]	4.1	3.3
C.V.	1.125	1.145

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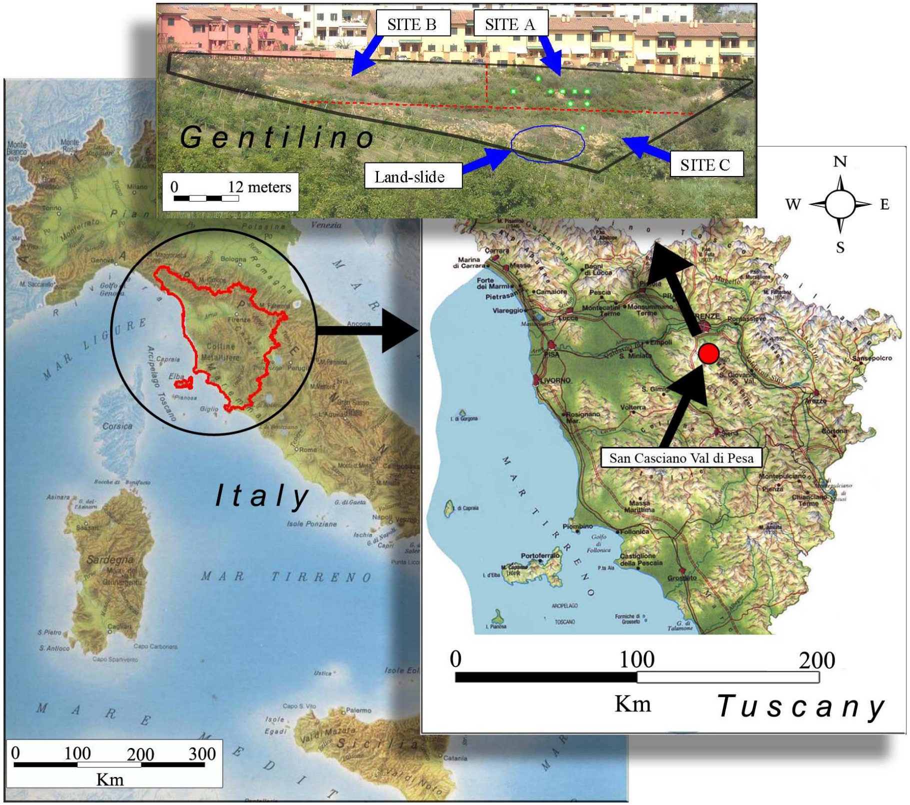

Fig. 1. Localization of the study area: Gentilino experimental sites (A, B and C), the sampling points and the site of a recent landslide. Gabbiola and Spedaletto sites are ex-agricultural areas colonised by natural shrubs 300 m away from Gentilino area.

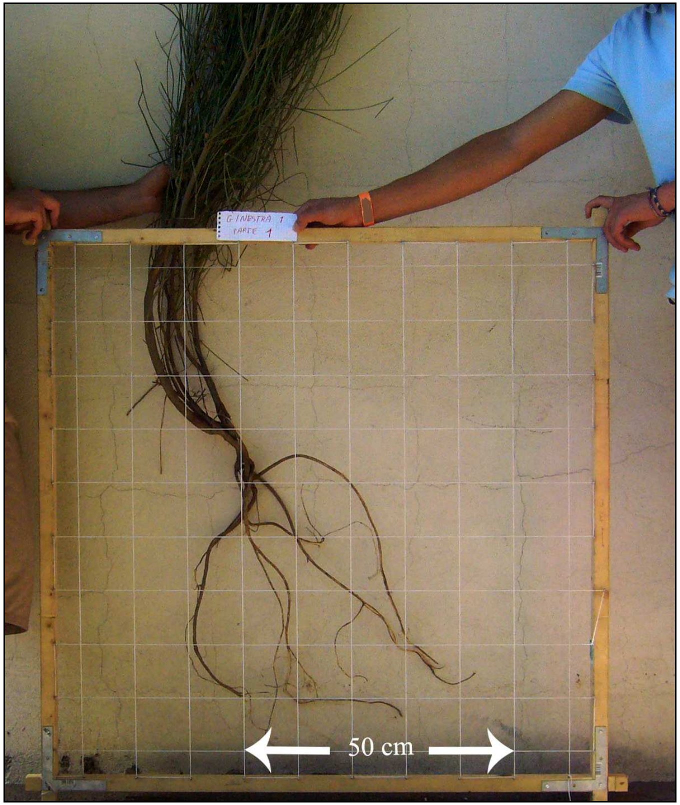

Fig. 2. Specimen of naturally grown Spanish Broom (square grid size 10 cm).

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Fig. 3. Specimen of rooted cutting of Spanish Broom.

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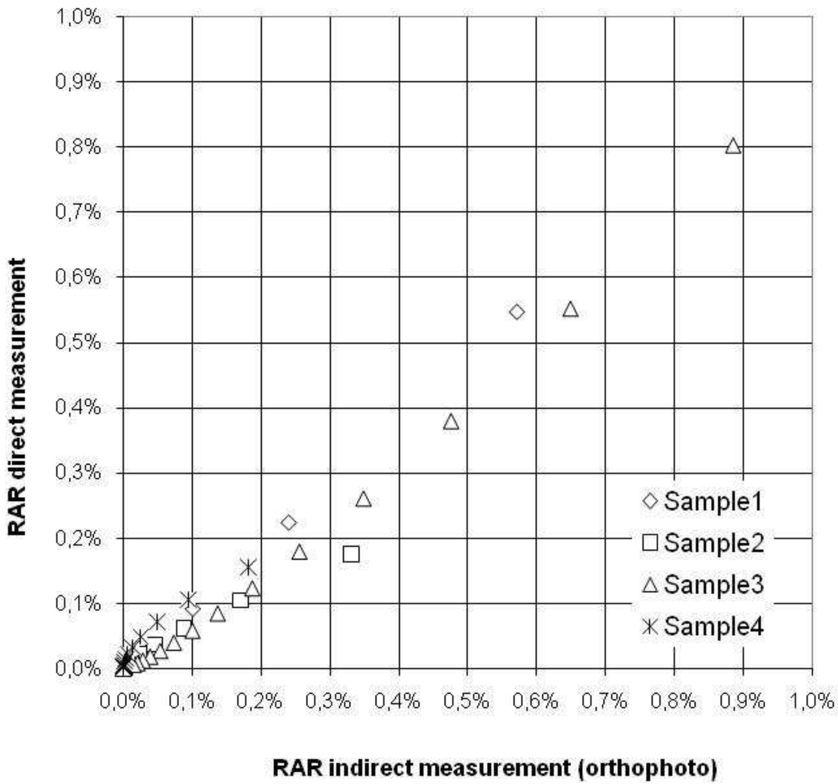

Fig. 4. RAR estimation (four Spanish Broom *specimens*) using the direct and indirect method.

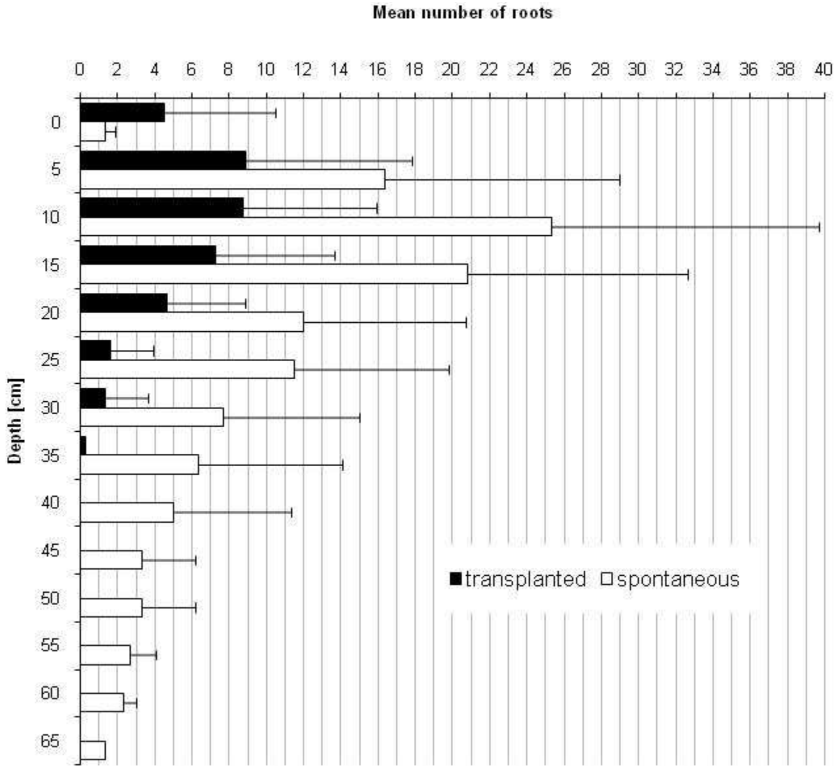

Fig. 5. Number of roots versus depth of transplanted and spontaneous Spanish Broom plants. All plants are about seven years old.

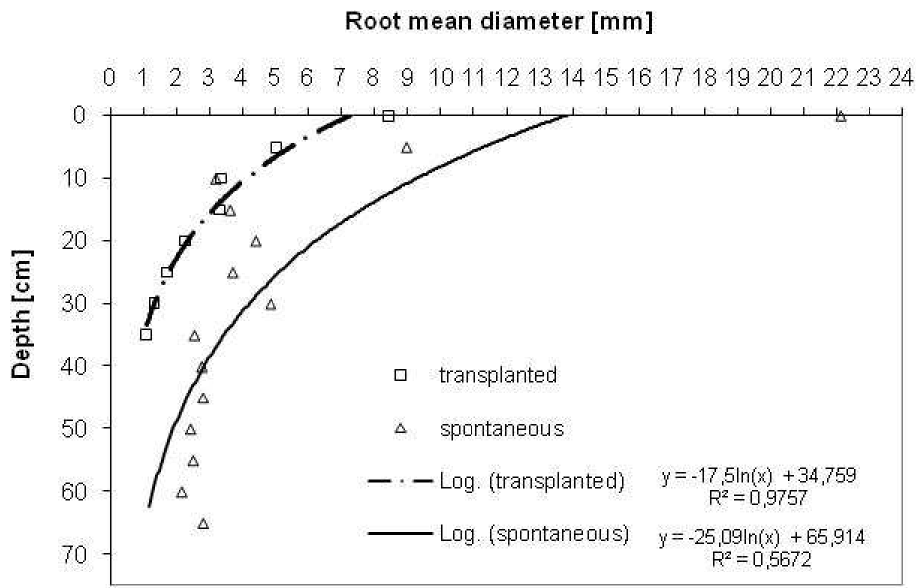

Fig. 6. Root mean diameter versus depth of transplanted and spontaneous Spanish Broom plants.

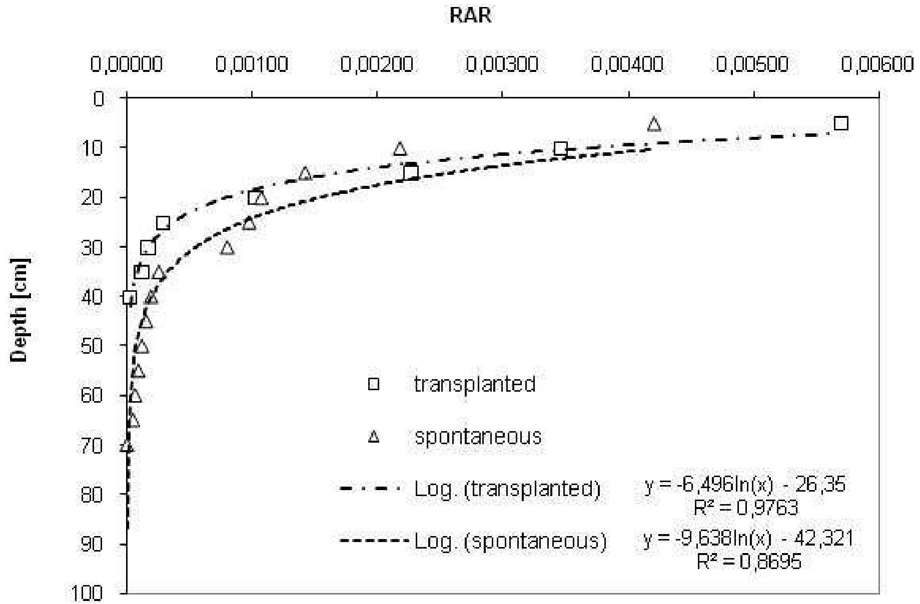

Fig. 7. RAR versus depth of transplanted and spontaneous Spanish Broom plants.

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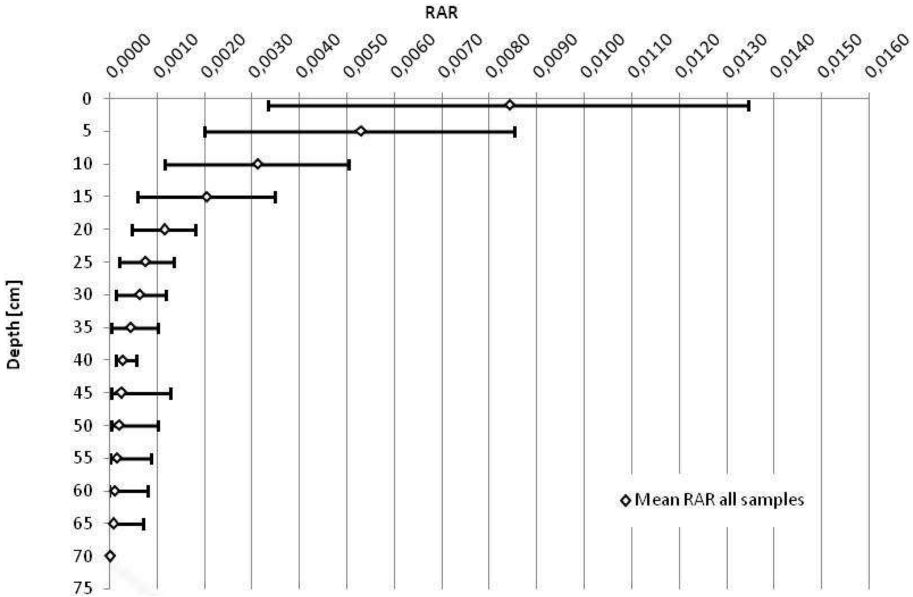

Fig. 8. 95% confidence limits of mean RAR% considering all samples of Spanish Broom.

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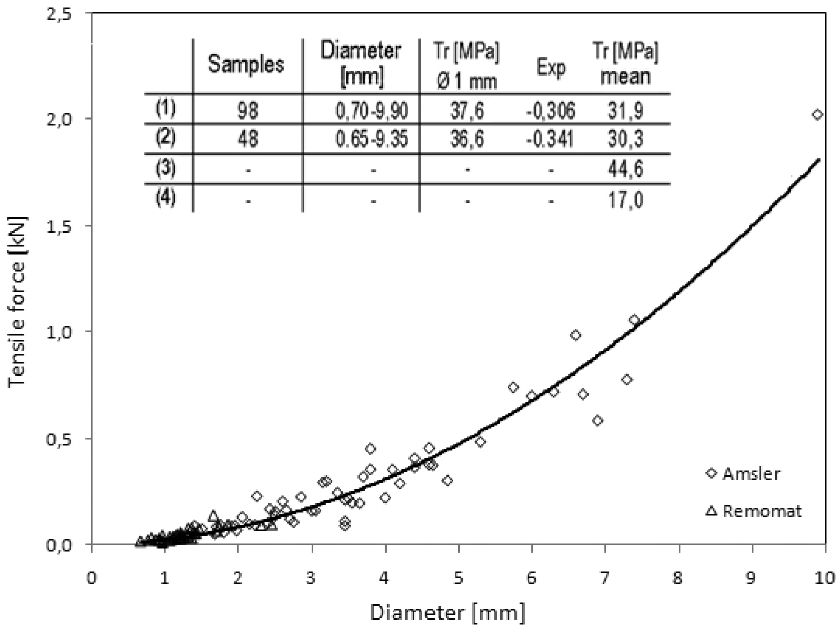

Fig. 9. Tensile force [kN] *tr* versus root diameter of Spanish Broom. The line shows the second order polynomial regression curves fitted to the experimental data: $tr = 0.0203\,\mathrm{d}^2 + 0.0062\,\mathrm{d}$ $R^2 = 0.94$. The regression equation of tensile strength [MPa] *Tr* versus root diameter [mm] of Spanish Broom curve is (1) $Tr = 37.605\,\mathrm{d}^{-0.306}$ $R^2 = 0.29$. Comparison between literature data: (2) Tosi (2007); (3) Laranci et al. (2004); (4) Norris and Greenwood (2003).

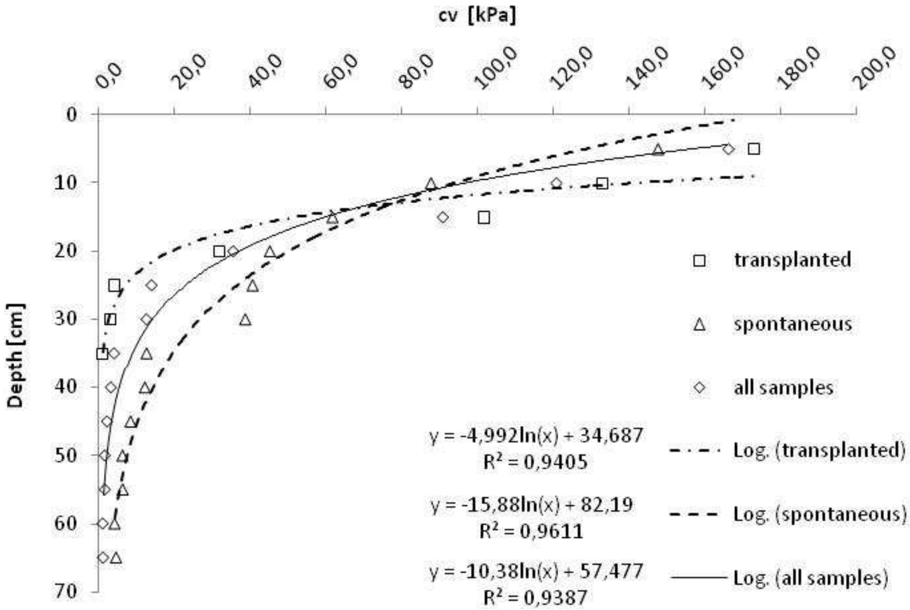

Fig. 10. Root cohesion *Cv* versus depth of transplanted, spontaneous and all Spanish Broom plants: the first line represents the plants transplanted in the study area (Gentilino); the second line represents the plants growing spontaneously in the neighboring area (Gabbiola and Spedaletto); the continuous line refers to all samples.

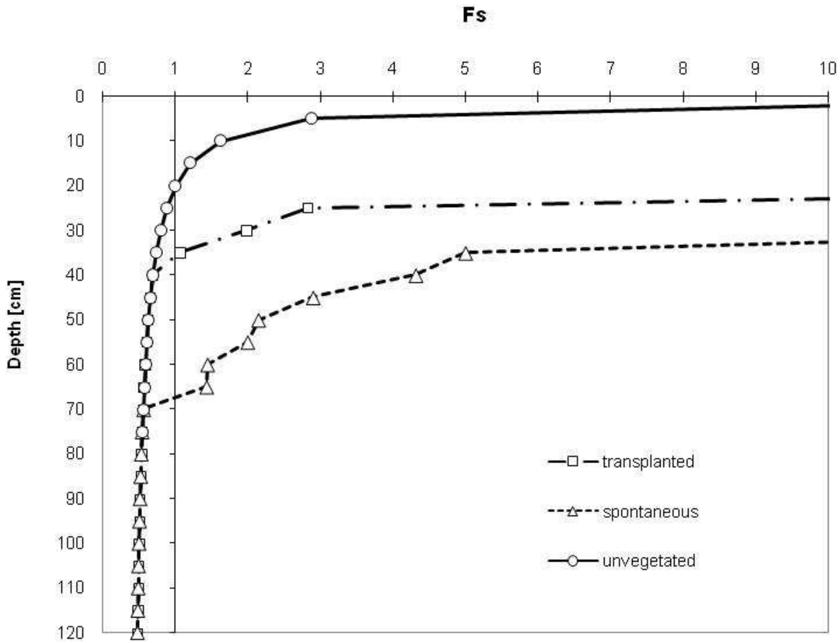

Fig. 11. Factor of safety (*Fs*) versus depth in unvegetated soil, transplanted stand or natural slope under the following conditions: saturated bulk unit weight [kN/m^3], $\gamma_{sat} = 20\,\mathrm{kN\,m^{-3}}$, water unit weight $\gamma_w = 9.8\,\mathrm{kN\,m^{-3}}$, slope angle $\beta = 26.5°$, soil friction angle $\phi' = 20°$, soil cohesion = 1 kPa, surcharge W_v = 0–0.196–0.4 kPa, respectively. *Cv(z)* as in Fig. 10. All plants are about seven years old.

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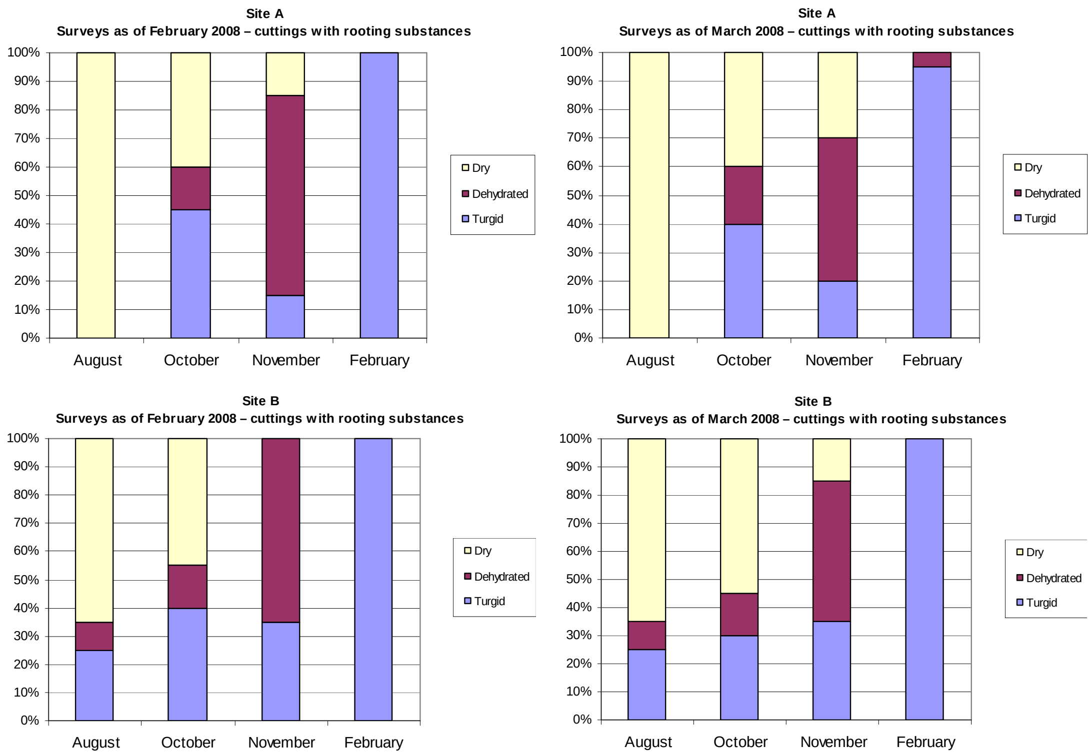

Fig. 12. Condition of cuttings as of February and March 2008 at sites A and B.

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