Florence, August 22, 2009

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

Dear Editor of HESSD,

We sincerely thank for the constructive comments.

The original comments from Referees have been reproduced below, interspersed with our italicized responses and referring to the revised version of the manuscript.

The paper has been revised and improved: upgraded data analysis with new figures have been added, the discussion and conclusions sections have been expanded and bibliographical references have been integrated to support the above.

We hope that now the paper is suitable for publication in HESS.

We remain at your disposal for any further requests.

Best regards,

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Review of: Root reinforcement and slope bioengineering stabilization by Spanish Broom (Spartium junceum L.)

by F. Preti and F. Giadrossich

Submitted to HESS

Anonymous Referee #1

This manuscript presents a complete overview on the biotechnical characteristics of the root system of Spanish Broom in the context of slope stability and erosion. In particularly, the authors focus on the vertical distribution of Root Area Ratio for the quantification of root reinforcement. The authors rely on new data of laboratory tensile tests for the mechanical characterisation of mechanical root parameters and use them for the calculation of root reinforcement. The authors use the Wu approach (1979) for the calculation of the root reinforcement and implement it in an 2D-infinite slope method for the calculation of the Safety factor of the slope. Moreover, the authors discuss the influence of different type of plant propagation and plantation on the stabilisation effects of the plants. Comparing vertical root distribution data of transplanted and spontaneous plants the authors conclude that spontaneous plants are more efficient in stabilisation then transplanted plants. Finally, the authors tested the rooting ability of stem cuttings in order to evaluate the applicability of this technique for the recover unstable slopes.

Although, the analysis would constitute an interesting contribution to the topic, it is questionable if it would be the case to take in consideration more advanced approaches for the calculation and discussion of root reinforcement (Pollen et al., 2005) and slope stability (Schmidt et al., 2001).

1) We took in consideration more advanced approaches in another paper (Schwarz al., 2009); in the present paper our aim is to compare Spanish Broom reinforcement calculated as in other studies (e.g. Tosi 2007). See also answers to Referee#2.

2) Our equation is basically equal to Schmidt (2001) formula reported below. With few mathematical passages it is possible to verify that the two formulae analytically coincide. Schmidt formula neglects the overload due to the vegetation, while our formula neglects the lateral cohesion. Considering the overload equal to zero in our formula, and the lateral cohesion equal to zero in Schmidt formula, the results obtained are the same (as accurately proved).

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

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' = friction angle

$\gamma = \gamma_{sat} - \gamma_w$ "submerged" bulk unit weight [kN/ m3]
γ_{sat} = saturated bulk unit weight [kN/m3]
Wv = overload due to vegetation [kPa]

From Schmidt (2001) text:

The shear stress, τ, acting over the basal area of the landslide, A_b, is represented by

$$[7] \qquad \tau = A_b \rho_s g z \sin\theta \cos\theta$$

where ρ_s is the saturated sediment bulk density, z is the vertical colluvium thickness, and θ is the ground surface slope. Expanding on eq. [1], the resisting force is approximated as

$$[8] \qquad S_{sr} = c_l A_l + c_b A_b + A_b(\rho_s - \rho_w M) g z \cos^2\theta \tan\phi'$$

where c_l is the sum of the effective soil cohesion (c_{sl}') and the root cohesion (c_{rl}) along the perimeter with lateral area A_l, c_b is the basal cohesion comprised of the sum of effective soil cohesion (c_{sb}') and the root cohesion (c_{rb}), ρ_w is the bulk density of water, and M is the ratio of the height of the piezometric surface above the base of the colluvium (h) to the total vertical colluvium thickness (z). This approach neglects lateral earth pressure and the frictional components of resistance along A_l. At a factor of safety of unity, $\tau = S_{sr}$ and landsliding occurs. Solving for the critical proportion of saturated regolith necessary to trigger landsliding, M_c, yields

$$[9] \qquad M_c = \frac{c_l A_l + c_b A_b + A_b \rho_s g z_s \cos^2\theta \tan\phi' - A_b \rho_s g z \sin\theta \cos\theta}{A_b \rho_w g z \cos^2\theta \tan\phi'}$$

Gathering similar terms results in

$$[10] \qquad M_c = \frac{c_l A_l + c_b A_b}{A_b \rho_w g z \cos^2\theta \tan\phi'} + \frac{\rho_s}{\rho_w}\left(1 - \frac{\tan\theta}{\tan\phi'}\right)$$

The following are more detailed comment for the revision:

- Please number the equations reported and use the number as reference in the text.

  Amended

- P.3994,line 24,"….less suitable for soil bio-engineering or for triggering natural plant succession.": Where is it discussed in the text? Didn't you show that, even if less than natural plants, transplanted plants (like used in Bio-engineering) increase considerably slope stability? Is it not to early to take conclusion on the influence on natural plant succession? Please, rethink this sentence or explain better.

  The phenomenon of the Spanish Broom dense covering is well known and evident in spontaneous Spanish Broom stands which grow on hills or on low mountains on the driest slopes. The planting distance of transplanted Brooms is about 50 cm on a square layout. As we expected, also on our study slope, seven years after the planting, there is no sigh of other species, because of the dense covering. We already remarked this fact in the paper P.4009 L.23. See also answers to Referee#2.

- P. 3995, line 16, “Authors studied…hills.”: please reformulate the sentence or use a table.

  Amended

- P. 3996, line 3, “As far as fine roots are….land surface.”: This sentence is not clear to me. What you mean?

  This sentence has been deleted

- P. 3996, line 5:To me, is not clear the meaning of this sentence. Resistance to what? Which is the connection whit the previous sentence? Please explain better.
  and
- P. 3996, line 6: sentence is not complete “…cross section unit area”

  Modified as:” Moreover, they increase the resistance of top-soil to erosion and finer roots have a higher tensile strength per cross section unit area (Gray and Leiser 1982; Operstein and Frydman 2000)”

- P. 3996, line 13, “…, with regard to the spatial distribution of roots”: tensile strength or distribution of roots? Do you mean different root diameter classes? Please explain better.

  The literature also reports that as root tensile strengths are usually measured in tens or hundreds of megapascals and soil shear strengths are normally in the range of tens of kilopascals, interspecies differences in the tensile strength of living roots are probably less significant to slope stability than are interspecies differences in root distribution.

- P.3996, line 20, “….influence the results of tensile tests..”. Insert ”results”.

  Amended

- P. 3996, line 27, “…,except for species and soil conditions.”: Which is the meaning of this statement? Please explain better.

  Amended: deleted “except for species and soil conditions”.

- P. 3997, line 2, “…recover badlands ().”: give literature references.

  Literature references are done at the end of paragraph: Leopardi 1845; Bagnaresi et al. 1986; La Mantia and La Mela Veca 2004; Tosi 2007

- P. 3997, line 10 “…can develop quite satisfactory…”: this sentence is too qualitative and it is not clear to what is refereed. To which kind of root system? Please explain better.

  The sentence is clear in our opinion and it is refered to the studies of Laranci et al. (2004), as you can read at the beginning of the paragraph.

- P. 3997, lines 20-29: It looks like you anticipate a summary of methods in the Introduction. This is good in the abstract, but I think should be removed here.

  Amended: the paragraph has been moved on the materials and methods section and we added an outline of the paper at the and of the introduction section.

- P. 3998, line 9: more information would be helpful: age of the transplanted plants at the moment of transplantation, provenience of the transplanted plants, geometry of the plantation, and so on.
  and
- P. 3998, lines 13-14:This sentence should come before, in line 9.

  Amended: we have given more information.

- P. 3998, line 21: modify the sentence in "… of rain events a (Table 1).", and I would give the link of the data at the beginning of the sentence.

  Amended.

- P. 3999, line 7: specify the type of test: drained-undrained, saturated-unsaturated.

  Amended, specified drained-saturated in the text.

- P. 3999, line 25, "The direct calculation..": calculation or measurements? Wasn't it in the field? This sentence confuse, please explain better.

  Amended: the correct word is measurements.

- P. 4000, line 10: Ds, the largest soil diameter explored by the roots, how is it estimated or measured? How is the inter-distance between neighbour plants taken in account? How is it than considered for the estimation of root reinforcement at the stand scale? Are the root systems overlapping?

  For the RAR calculation, the measured largest soil diameter explored by the root system was considered constant (cylindrical rooted volume is assumed) for the whole soil depth explored by roots (new Fig 2b). Considering that the plants on the artificial slope were planted on a square layout with a 50 cm side, the mean soil diameter explored by the root system slightly overlaps (new Fig. 2b). In order to compare to a stand scale the RAR we calculated the average RAR of the eight plants for every layer depth cross section (as we said, 5 cm deep). The largest soil diameter explored by the roots was measured (now specified in the text); we considered an average RAR, as explained in the text.

- P.4001, line 10: a index is missing: (Mu-Mo)/Mo.

  Amended (it was an editing mistake)

- P. 4001, lines 21-24: This statement in not true. Is it know (Waldron and Dakessian, 1977; Pollen et al., 2005) that so-calculated cohesion values can not be use to rank species because it depend on the root diameter distribution. Different distributions leads to different maximal root reinforcement, thus the variability is not due only to the RAR and the maximal tensile strength.
  We know that variability is not due only to the RAR and to the maximal tensile strenght; we did not use to rank to mean classify, but to mean "compare", in order to compare the data with Tosi (2007).

- P. 4002, line 5: equation is not correct. Add brackets,
  $F_s =$ [illegible]

  Amended (it was an editing mistake)

- P. 4002, line 10: Z=vertical depth of the failure plane.

  Amended

- P. 4004, line 14: Soil analysis, and not analisys.

  Amended

- P. 4006, line 20: you calculated, somehow, the vertical distribution of the RAR for each single plant. How did you upscale the root reinforcement to the entire stand? How did you consider the distance between the plants?

  See answer P. 4000 Line 10. In order to upscale to the stand scale the RAR, we calculated the average for the eight analysed plants.

- P. 4006, lines 26-27: how are the hydrological thresholds calculated? Saturate or unsaturated flow? Which equation did you use?
  and
- P. 4009, lines 5-7: This conclusion can not be evaluated. It is not explained how you calculate the estimated occurrence of the return time. Please, explain better the method and how you get to the conclusions.

  The assumption is soil saturated according to P.4002 L.16; P.4006 L.26; P.4010 L.3. In eq. [3] porosity = 0.42, runoff coefficient = 0.52-0.66 concentration coefficient = 10. Rainfall Intensity-Duration-Frequency data gives the curve equation I = a'Tr^mD^(n-1)= 21,65Tr^0,18D^(0,21-1), where I = rainfall intensity [mm/h], Tr = return time interval [years], D = rainfall duration [h], according to the classical rainfall duration curve rainfall duration curve h = a'Tr^mD^n , where h = rainfall [mm])

- P. 4007, lines 11-15: as mentioned before, this method need to be better explained and some arguments of the discussion need to be revisited.
  and

- Figure 4: I suggest to replace it with the results of a chi squared test.

  The indirect method and its application are better explained in Dani and Preti 2007 and Preti et al., 2009. However in this paper we used directly measured data when available.

- P. 4009, line 5:It is not possible to evaluate the statement just on the base of fig 1. A better description of the slope failure is needed: dimensions, geometry, type of failure.

  We added geometric data and a picture of the landslide (Fig. 2a).

- P. 4009, line 2: Expand the discussion, considering that the methods you used are not the state of the art. Wu method versus Fiber bundle model, infinite slope method versus finite element method or discrete element methods.

  The discussion has been expanded. See also answer p.4001, line 20 to Referee#2.

- P. 4010, line 26, "The root tensile strength is significant." What does it mean? Refereed to what?

  The sentence has been modified.

- Figure 5: What do the bars mean? Quantile, confidence interval?

  Amended: the bars show the Standard Deviation.

- Figure 9: Add literature data as comparison (Operstein, Tosi, DeBeats)

  We added a new picture (Fig. 8) with literature data as comparison referring only to Spanish Broom studies.

The manuscript presented could be published in HESS with a minor revision, following the indicated modifications and expanding the discussion section 4.3.

Anonymous Referee #2

Received and published: 24 July 2009

This manuscript presents results of investigations into the root architecture and tensile strength characteristics of Spanish Broom, and its potential benefits for stabilizing Mediterranean soils. The paper is well structured and shows that the authors have collected a fairly extensive data set, using appropriate field and laboratory techniques, which are described in very good detail in the paper. The analysis of the data, however, is less clear, as is the basis for the conclusions reached. With additional information regarding how the field data were used to obtain Cv and Fs values, and a greater discussion of these values in the text, comparing them to other literature values for root-reinforcement, this paper could be suitable for publication in this journal. Additionally, more discussion of fiber bundle models versus the Wu eqn, and the potential magnitude of overestimation using the Wu equation can lead to should be added (more in specific notes below). Finally, results and values should be mentioned and discussed in the text and the reader should not simply be referred to a figure to find the values for RAR, Cv, Fs etc.

1) upgraded data analysis with new figures have been added in the revised manuscript;
2) in the root cohesion formula (Waldron, 1977; Wu et al., 1979) the K coefficient is usually assumed equal to 1.2, even if this value is known to lead to possible overestimation (more than 200%) of the actual root reinforcement, according to, for instance, Pollen and Simon (2005), Preti (2006), De Baets et al. (2008), and Mickowski (2008), Preti et al., 2009; Schwarz al., 2009. In the present study other data are provided for the calculation of root reinforcement also with alternatives methods as in Schwarz et al. 2009 (Fig. 5 of the revised paper). As answered to the Reviewer 1, the aim of the present paper is to compare Spanish Broom reinforcement calculated as in other studies (e.g. Tosi 2007); *we used more advanced approaches in another papers (Preti et al., 2009; Schwarz al., 2009)*;
3) The Discussion and Conclusions sections have been expanded in the revised manuscript. Bibliographical references have been integrated to support the above.

Specific comments are listed below (Several editorial comments have been made by the first reviewer so these comments concentrate on additions/ clarifications needed in the text):

p.3999, line 13: Bohm (1979) is the original reference for the trench-profile method and should be mentioned here.

Amended

p.4000, line 1: by only measuring above 0.5mm aren't you missing a lot of the fine roots - other studies (eg Pollen and Simon, 2005) have gone down to 0.1mm. Can you explain how/why you picked this lower limit?

Measuring the roots diameters we did not pick any limits. As shown in Table 5, 0.3 and 0.5 , respectively for transplanted and spontaneous plants, are the minimum diameters that we have found. Only in rooted cuttings we found adventitious roots (Fig. 11 in the revised manuscript) with lower diameters.

p.4001, line 20: The most important assumption made in the Wu eqn, and the one that leads to the most overestimation of root-reinforcement values, is the assumption that all of the roots break simultaneously and at their peak strength. This assumption should be mentioned here along with the magnitude of potential estimation discussed in several papers including but not limited to Pollen and Simon (2005).

In the revised manuscript we clarified this point, according to some sentences from our recent paper Schwarz et al. 2009:

"*A growing number of models are employed for quantifying root reinforcement however, direct comparisons between model predictions and data remain sketchy. Recently, the application of the Fiber Bundle Model (FBM) for the estimation of root reinforcement proposed by Pollen and Simon (2005) has emerged as a useful representation of mechanical and geometrical characteristics of plant root systems. The model has previously been used extensively in engineering and material sciences to study the breakdown of complex heterogeneous materials (Peires, 1926; Kun et al., 2007). In addition to other well-known methods and techniques used to study root reinforcement (e.g., shear, pull-out, or centrifuge tests) (Anderson et al., 1989; Zhou et al., 1998; Fan and Su, 2008), back analysis offers a useful approach to understanding the potential contribution of root reinforcement to mechanical stability of a natural slope.*

…

Additional studies by Waldron and Dakessian (1981) and others advanced the understanding of the mechanisms for root reinforcement in soils. Incorporating these concepts into simple factor of safety calculations reveal consistent overestimation of the role of root reinforcement of soils based on Wu's model (e.g. Pollen and Simon, 2005; De Baets et al., 2008; Docker and Hubble, 2008; Fan and Su, 2008; Mickowski et al., 2008). A summary of various experimental studies is presented in Table 1 showing the magnitude of the overestimation. A "correction factor" (frequently denoted as k") emerged from comparison of experimental data with model predictions and the average value of this factor is about 0.4 (Preti, 2006; Preti and Schwarz, 2006). The "correction factor" is calculated as the quotient between the measured data value and the estimated value. This overestimation is attributed primarily to Wu's assumption that all roots break at the same time regardless of their diameters. The introduction of the FBM to quantify root reinforcement (Pollen and Simon, 2005) allows for incorporation of differential mechanical contributions of different root diameters and improves understanding of how a bundle of roots with varying mechanical properties breaks

…

The introduction of the FBM concept for the quantification of root reinforcement in soils (Pollen and Simon, 2005) improved our understanding of the mechanical behaviors of rooted soils during failure. The FBM (Kun et al., 2007) used in this work gives results in accordance with data from literature for the quantification of the correction factor k" (Tab. 1). A longstanding issue for the application of this approach to slope stability is limited availability of root distribution data. Field estimation of root distribution on vegetated slopes is difficult and better techniques are needed."

In the present study other data are provided for the calculation of root reinforcement also with alternatives methods as in Schwarz et al. 2009 (Fig. 5 of the revised paper).

p.4005: change root average number to average root number throughout text. Also, what is the plant density (# of roots per plant are shown in Fig. 5 but how do you get from # of roots per plant to the number of roots crossing a square meter of the shear surface so you can calculate root-reinforcement?

The text was modified, according to the answer to Referee #1 at P4000 L10, as follows:.
"The spatial distribution of the Spanish Broom roots was evaluated digging out.by hand, starting from the collar, removing the soil and exposing the root system. As far as the horizontal distribution is concerned, the plants were planted in the artificial slope with a square layout with sides about 50 cm long (Fig. 2b): the mean soil diameter explored by the root system slightly

superimposes. As far as the vertical distribution is concerned, for every plant (transplanted and spontaneous) we measured the number and the diameter of those roots which go through a horizontal section for each depth level (5 cm intervals). Furthermore we measured the maximum distance reached by the roots with reference to the collar.

…

In our case the excavated plants were brought to our laboratory while they were still fresh. The rooted area (Ar) for each depth level was calculated by summing the areas of the single cross sections roots."

p.4006: State and discuss the values in Figs 10 and 11, rather than just referring the reader to the figures. The Cv values for the Spanish Broom seem very high, especially for a shrub type species, and compared to values published by others for Cv of a range of species. Granted the Wu eqn can overestimate significantly but even reducing the values by an appropriate reduction factor of approximately 50% these values would still be very high. The tensile strength values seem within an acceptable range, as do the RAR values, but without knowing what plant density/ how many roots we assumed to cross the shear plane in your analysis, it is not possible to tell if these calculations are correct. Also, the section on Fs values needs to be greatly expanded. It is not clear at all how the values in Fig 10 were used to get the Fs values in Fig 11, and none of these values are even discussed in the text. In Fig.11 how are Fs values calculated for different depths? Surely Fs is calculated for a given slope not a point within a slope, and Fs is based on a failure plane and failure block not a point? This figure and how the values were obtained definitely needs clarification. In addition, a note that if the Cv values are overestimated by using the Wu eqn, then similarly the Fs values will be overestimated and overly conservative, should be added.

and

p.4008. tensile strength values seem reasonable based on species I have tested in the past. In fact exponents seem on the low end of the range I have seen, further questioning the final root-reinforcement values calculated.

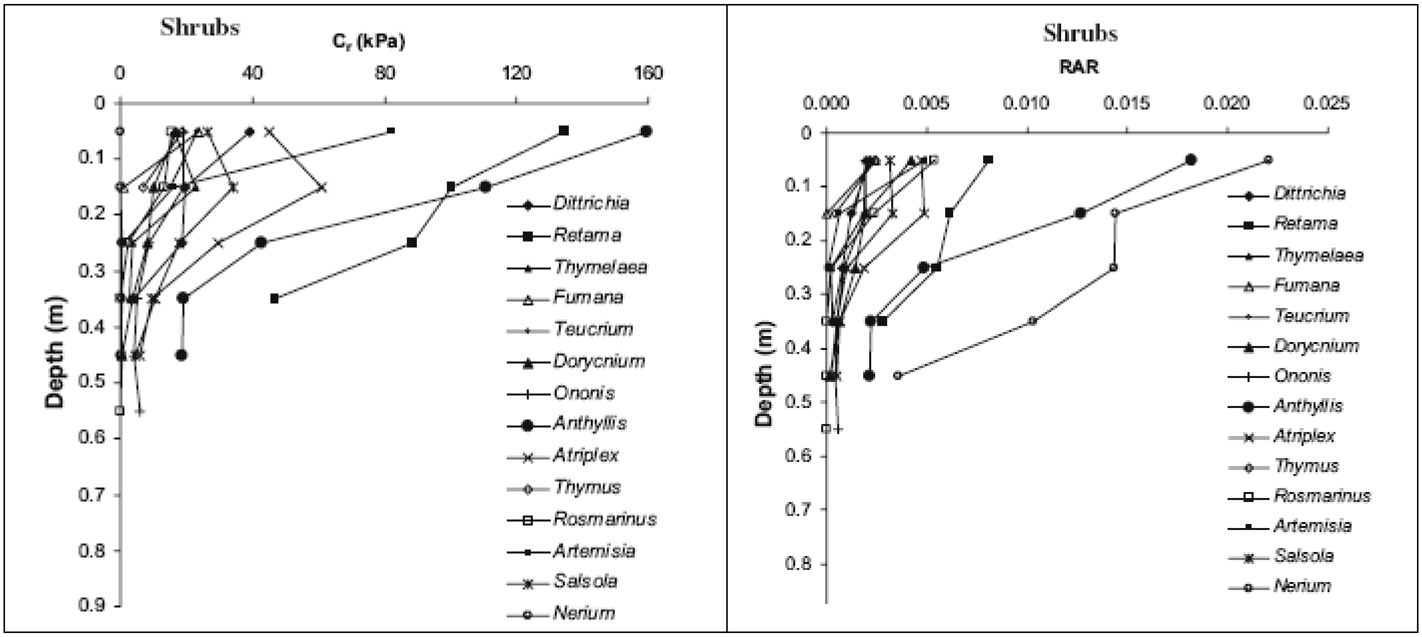
and

p.4009. State the range of values in the text not just the figure.

and

p.4010: conclusions: the RAR and tensile strength seems similar to other plants. Rooting depth is also similar to other Mediterranean species. The benefit of this plant in terms of bioengineering, in particular then, seems to lie in its ability to spread and establish quickly, rather than it's root properties. Cv values should be checked as they do seem high based on the RAR and Tr values given. This may be explained by a very high rooting density/ plant density, but the data to show that are not given here. Also, the root diameter distribution can have a big effect on calculated Cv values and this may also be causing the values to be high, but again, the root diameter distribution measured from field data and used in the data analysis is not given. Some comparison of values with other literature values at some point in the discussion or conclusions would be useful, especially a comparison with the values for 25 Mediterranean spp studied by deBaets et al. (2008) who I believe included Spanish Broom in their study.

The text was modified and revised, taking the comments into consideration.
Comparing our results for RAR and Cv with the following taken from De Baets et al. 2008, they seems correct.



The measured tensile strength is in agreement with other studies (added in the table of Fig. 8 of the revised paper Laranci et al. 2004)

	Samples	Diameter	Tr [MPa] Ø 1 mm	Exp	Tr [MPa] Average
(1)	98	0.70-9.90	37,7	-0,306	31,9
(2)	48	0.65-9.35	36,6	-0.341	30,3
(3)	24	0.44 - 2.68	56.4	-0.239	44,6
(4)	-	-	-	-	17,0

"… what plant density/ how many roots we assumed to cross the shear plane in your analysis" is better explained in the revised manuscript according to the previous answer.

"Surely Fs is calculated for a given slope not a point within a slope, and Fs is based on a failure plane and failure block not a point":
yes, as well explained in the revised manuscript as follows: "Fs was calculated for every 5 cm soil layer, considering the RAR at the stand scale and the value of Tr referred to the diameter of every root (from the equation in fig. 8) which crosses the horizontal plane at that given depth, and considering the deriving Cv

The note that if the Cv values are overestimated by using the Wu eqn, then similarly the Fs values will be overestimated and overly conservative, has been added.

In the case of transplanted plants the value of Fs is affected by the limited depth reached by the roots and shows its effect only in the first 35-40 cm. Still the presence of many roots in a limited soil thickness and the presence of many plants covering the slope create a considerable protection of the soil. The covering offered by the crown with the current square layout is 100% and the plants reach the height of 2 mt after about six years since the planting. The analysed spontaneous plants have deeper roots and also the horizontally explored surface is larger.but the *density lower. This is probably due to the minor competition and to the growth in a natural soil since the first years of life. We can state that on a natural slope continuos covering of Spanish Broom, as we can find in the Apennines, a high additional cohesion is provided to the soil (Fig.10).*

De Baets et al. (2008) did not study Spanish Broom.

Fig 6: x axis - do you mean mean root diameter?

Amended in the new Fig. 5b.

Fig 9: to compare against other studies it would be better to plot tensile strength (MPa) against root diameter (mm) showing the power law relation.

Also other authors use the graphs of tensile strength [kN], like Schmidt et al. (2001) and Tosi (2007). The equations that refer to tensile strength are quoted, for various authors allowing comparison, in the new Fig. 8.

Fig. 12: might not need this figure.

Ok

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 classic tensile strength–diameter relationships. Analysis 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 propoagation 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 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.

Keywords

Spanish Broom (*Spartium junceum* L.), Root reinforcement, Root Area Ratio, Root tensile strength, Slope stability, Agamic propagation, Stem cuttings, Soil bio-engineering.

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 in 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.

As one can see in Table 1, some Mediterranean species were subjected to root tensile strength, shear stress and/or pull-out tests, and also the architecture of their rooting system grown on slopes was studied. Spanish Broom (*Spartium junceum* L.) has been studied by Chiatante et al. 2001, 2003a, b 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 (if we consider the stem). This is a characteristic that guarantees the stability of the plant (Chiatante et al. 2001, 2003a, b; Di Iorio et al. 2005). Also Norris and Greenwood (2003), Laranci et al. (2004) and Tosi (2007) have studied Spanish broom.

In general, 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. Moreover, they increase the resistance of top-soil to erosion and finer roots have a higher tensile strength per cross section unit area (Gray and Leiser 1982; Operstein and Frydman 2000). On the other hand, thicker roots can be likened to biological nails, which probably tend more to pull out than to break (Coppin and Richards 1990; Greenwood 2005); thicker roots 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 as root tensile strengths are usually measured in tens or hundreds of megapascals and soil shear strengths are normally in the range of tens of kilopascals, interspecies differences in the tensile strength of living roots are probably less significant to slope stability than are interspecies differences in root distribution. (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 1984 a, 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. 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).

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 in 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 paper is structured as follows: in Materials and methods Section we describe the study area,, (hydrology, soils), and plants investigated (roots distribution, lab tensile tests, root reinforcement and plant propagation). The obtained results are presented and finally, these results are discussed and conclusions drawn.

Materials and methods

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 above mentioned 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).

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 were 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. The plants had grown in a local nursery and had been transplanted with their root balls, when the slope was being restored. The plantation is square with sides about 50 cm long. Eleven plants were sampled, eight from the artificial slope and three from spontaneously-growing plants in nearby areas (Gabbiola and Spedaletto sites are ex-agricultural areas colonised by natural shrubs 300 m away from Gentilino area), Fig. 1 and Table 3. All the plants (from the nursery and the spontaneous ones) were of the same age, about seven years old.

In 2007 a small landslide occurred at the foot of the slope in an area without vegetation. Fig. 2a shows the geometry of the landslide; the scarp was about 120 cm high for a front lenght of 6-7 meters.

Hydrology

The climate of the study area is Mediterranean (Köppen classification). Data for the rainfall as well as the maximum, average and minimum temperatures (<http://agrometeo.arsia.toscana.it/>) gives the daily average potential evapotranspiration *Tp*, the rainfall frequency λ_0, and the average rain events intensity. α (Table 2). Rainfall Intensity-Duration-Frequency data gives the curve equation $I = 21,65Tr^{0,18}D^{(0,21-1)}$, where I = rainfall intensity [mm/h], Tr = return time interval [years], D = rainfall duration [h], and the runoff coefficient value ranges from 0.52 to 0.66 according to previous studies on Flood Regionalization (Regione Toscana, 2007).

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 drained-saturated CD tests were carried out with loads of 50, 100, 150 and 200 Kpa.

Root distribution and estimation of Root Area Ratio (RAR)

The spatial distribution of the Spanish Broom roots was evaluated digging out.by hand, starting from the collar, removing the soil and exposing the root system. As far as the horizontal distribution is concerned, the plants were planted in the artificial slope with a square layout with sides about 50 cm long (Fig. 2b): the mean soil diameter explored by the root system slightly superimposes. As far as the vertical distribution is concerned, for every plant (transplanted and spontaneous) we measured the number and the diameter of those roots which go through a horizontal section for each depth level (5 cm intervals). Furthermore we measured the maximum distance reached by the roots with reference to the collar.

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 in counting roots using a profile trench (Bohm 1979). 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). In our case the excavated plants were brought to our laboratory while they were still fresh. The rooted area (Ar) for each depth level was calculated by summing the areas of the single cross sections roots. The

RAR of all samples was calculated with the direct method assuming a constant radius (specific for every plant) equal to the maximum distance reached by the roots with reference to the collar (Fig. 2b). 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 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 and we counted and measured the diameter of the roots using AutoCAD^{tm} (Dani and Preti 2007, Fig. 3).

The formula we used to estimate RAR was the following:

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

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

m = number of roots at z depth.

In order to upscale to the stand scale the RAR, we calculated the average for the eight analysed plants.

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 seconds in the Amsler machine, while breaking time ranged from 150 to 300 seconds on the Remo-Mat, due to the different method of control, the first being analogue while 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 hours later, were used to determine moisture content with reference to the dry weight (M.C.=(Mu–Mo)/Mo where Mu is the weight at the moment of the test while Mo is the dry weight).

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:

$$C_v(z) = K \sum_{j=1}^{n} Tr(z)_j \cdot RAR(z)_j \qquad [2]$$

where:

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

n = number of diameter classes at z depth.

One of the most important assumption made in the eq. [2] is that all of the roots break simultaneously and at their peak strength. According to Pollen and Simon (2005), Preti (2006) and De Baets et al. (2008), Preti et al. (2009), Schwarz et al. (2009), the Wu and Waldron model overestimates (more than 200%) root cohesion values (by putting only K = 1.2 as standard, root cohesion values could be considered maximum values). Cv was calculated for each cross section depth, applying to every root the tensile strenght value Tr referred to its diameter. (Fig. 8). In doing so, the contribution of each root was taken into account.

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):

$$F_s = \frac{(c' + c'_v)}{(\gamma_{sat} \cdot z \cdot \cos\beta + W_v) \cdot \sin\beta} + \frac{(\gamma \cdot z \cdot \cos\beta + W_v)}{(\gamma_{sat} \cdot z \cdot \cos\beta + W_v)} \cdot \frac{\tan\phi}{\tan\beta} \qquad [3]$$

where:

Fs = Factor of safety

c' = soil cohesion [kPa]

c'_v = root cohesion [kPa],

z = vertical depth of the failure plane [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] γ_{sat} = 20 kN m^{-3} (porosity 0.42), water unit weight γ_w = 9.8 kN m^{-3}, slope angle β = 26.5°, soil friction angle φ' = 20°, soil cohesion = 1 kPa. The surcharge on the soil slope owing to the presence of plants (Wv) was calculated on the basis of both the average weight of the Spanish Broom transplanted and spontaneous plants and their density (50 x 50 cm), giving a value of 20-40 kg/mq, which is equivalent to 0.196-0.4 kPa, respectively.

Fs was calculated for every 5 cm soil layer, considering the RAR at the stand scale and the value of Tr referred to the diameter of every root (from the equation in fig. 8) which crosses the horizontal plane at that given depth, and considering the deriving Cv

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 lays 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 4) 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 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 4).

Results

Soil analysis

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 3. 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 present.

Root distribution analysis

The average root number of transplanted and spontaneous plants, at the various depths (Fig. 4) shows slight differences in the first 10 cm and we find a high Standard Deviation in the superficial soil layers. The distribution of the roots was obtained by counting the number of roots in the 1 mm diameter classes and by determining the values for each vertical soil level explored (Fig. 5a). This graph shows only transplanted plants, which are more interesting as they form a continuous vegetated slope, suited to compare the cohesion data to a stand scale. Fig. 5b shows the comparison between average root diameter of transplanted and spontaneous Spanish Broom plants. Considering the percentage number of roots at different depths, it is noted that (Fig.6) at a depth 20 cm we find 90% of the transplanted plants roots and 65% of the spontaneous plants roots. At a depth of 40 cm there are almost all the roots of all the plants, with the exception of the spontaneous plants top-roots, representing only 10%.

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.

For transplanted plants the maximum distance reached by a root with reference to the collar is about 50 cm, while for the spontaneous plants is about 60 cm. Table 5 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 in spontaneous and transplanted plants. 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.

Tensile strength tests

The regression curves obtained for tensile force *tr* versus diameter (Schmidt el al. 2001) were as follows (Fig. 8): $tr=0.0203d^2+0.0062d$ $R^2=0.94$ SD=0.287 for all 98 samples, tr=0.0233

d^2+0.0034d R^2=0.93 SD=0.334 for the data obtained by the Amsler, and tr=-0.0176d^2+0.0241d 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%.

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. 8) for each root at the horizontal cross section of soil. Consequently, ,the variation in Cv depending on depth is shown in Fig. 9.

Fs on saturated soil at various depths is shown in Fig. 10 for different scenarios: unvegetated soil, transplanted stand and natural slope. The presence of roots significantly increases the stability factor, with a maximum value at that depth which includes 90% of roots, both for transplanted and spontaneous plants. The stability of the unvegetated slope is 1 with a slope of about 50% at a depth of 20 cm. This value increases at 35 cm with transplanted plants and reaches the maximum value with spontaneous plants, which have a deeper tap-root, of 65 cm.

Considering the above-mentioned rainfall-duration curve ($h = a'Tr^{m}D^{n}$) and the saturated landslide depth, the return time Tr of the hydrological instability threshold can be calculated. We obtained an Tr ~ 10 years for a rainfall duration of 24 hours by considering the known runoff coefficient value and the estimated upslope contributing area (connection with the urbanized area in Fig. 1 with concentration coefficient equal to 10).

Spanish Broom propagation

Surveys on vegetative conditions were conducted in February, March and June. Almost two year after planting, all the root-ball plants had rooted, 93.4% of stem cuttings without hormone treatment had died, and 92.3% of stem cuttings with hormone treatment had died. Of the stem cuttings planted in pots, the survival rate was 5%. As shown in Fig. 11, roots (about 20 cm long) developed only from the deeper regions of the stem cutting (October 2007 planting).

Discussion

Root distribution

The analyzed root systems did not show substantial differences in their architecture: they have always a tap-root and a high concentration of roots in the first 10 cm of soil. There are however some differences between the growth of spontaneous and transplanted plants, as shown in the following paragraphs. The root distribution of the transplanted plants (Figg. 5, 6, 7, 8) could be due to plant origin and growth and soil condition (in pot , nursery and natural soils). 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). It can be noticed that transplanted plants are effective for slope stabilization at soil depth up to 40 cm, while natural plants up to 70 cm. Transplanted plants have a high concentration of roots in the first centimeters of soil as shown by the very high number of roots (Fig. 4, Fig. 5a and Fig 6) and RAR (Fig.7). The average root diameter at various depths is similar for transplanted and spontaneous plants as shown in Fig. 5b. The percentage distribution of the roots is almost uniform on the whole profile and could be the consequence of the growing conditions mentioned above. Considering that the age of the transplanted and of the spontaneous plants is almost the same, the provenance from the nursery, and consequently the growth in the pot during the first years, could have negatively affected the roots distribution. The. differences in roots distribution are destined to decrease in time. Roots number variability (Fig. 4) decreases as depth increases. At depths between 0 and 40 cm the root system branches off, while at depths exceeding 40 cm, it is basically only the tap-root that contributes to the RAR. In transplanted plants the development of the tap-root is limited, but there are more roots on the surface.

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 2002b, Laio et al. 2006, Preti et al. 2009).

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

The photogrammetric method (indirect method) used to assess RAR was comparable with the direct type of measurement (Fig. 3) 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.

Tensile strength tests

Fig. 8 shows 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 $Tr=37.605d^{-0.306}$ 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 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).

Root reinforcement and hydrological conditions

A stability analysis was performed using the infinite slope model (Fig. 10) in order to compare our results with those of other authors who have studied the Spanish Broom (e.g. Tosi 2007). In the present study other data are provided for the calculation of root reinforcement also with alternatives methods as in Schwarz et al. 2009 (Fig. 5).

The slope stability considerably increases with the presence of Spanish Broom. It is to be noticed that the Cv values are overestimated by using eq. [2], then similarly the Fs values could be overestimated. In the case of transplanted plants the value of Fs is affected by the limited depth reached by the roots and shows its effect only in the first 35-40 cm. The analysed spontaneous plants have deeper roots and also the horizontally explored surface is larger.but the density lower. This is probably due to the minor competition and to the growth in a natural soil since the first years of life. We can state that on a natural slope continuos covering of Spanish Broom, as we can find in the Apennines, a high additional cohesion is provided to the soil (Fig.10). The Fs values obtained in saturated conditions harmonized satisfactorily with the measured landslide scarp (Fig. 2) and with Tosi's results (2007) from the clay slopes of the Apennines. We obtained satisfactory agreement between the statistically estimated occurrence return time of the rainfall event occurred and the calculated one by means of the stability model.

The presence of many roots in a limited soil thickness and the presence of many plants covering the slope create a considerable protection of the soil. The covering offered by the crown with the current square layout is 100% and the plants reach the height of 2 mt after about six years since the planting. 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).

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. Root-ball plants gave excellent results and created dense land cover. 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. 11). 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. 11 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. 11 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).

Conclusions

The measurement and calculation of mean root number, mean root diameter, RAR, tensile strength, 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 Spanish Broom is a species capable of adapting to types of soil characterized as dry and 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 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 two year after planting, 92.7 stem cuttings 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 – Specie mediterranee studiate da altri autori.

Table 2 – Daily rainfall data parameters at Sambuca and Ponte a Moriano measured by rainfall gauges: Tp = potential evapotranspiration, λ *= rainfall frequency,* α *= average rainfall intensity.*

Table 3 – Soil sample characteristics.

Table 4 – Number of planted stem cuttings for different experimental conditions.

Table 5 – Root diameter of transplanted and natural plants.

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. 2a – Land slide occurred in December 2007 on the experimental slope with the Spanish Broom *stand.*

Fig. 2b – Experimental slope layout of transplanted plants: square sides about 50 cm and horizontal section at 5 cm step. The mean soil diameter explored by the root system slightly superimposes (adapted from Chiatante et al. 2003b).

Fig. 3 – RAR estimation (four Spanish Broom *specimens) using the direct and indirect method.*

Fig. 4 – Average root number with SD bars versus depth of transplanted and spontaneous Spanish Broom plants. All plants are about seven years old.

Fig. 5a – Vertical distribution of transplanted plant root number: root diameter classes per every cross section depth (5 cm step).

Fig. 5b – Average root diameter of transplanted and spontaneous Spanish Broom plants.

Fig. 6 – Percentage roots distribution: at a depth of 20 there are 90% of transplanted plants roots and 65% of natural plants; at 40 cm there are respectively 100% and 90% of roots.

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

Fig. 8 – Tensile force [kN] tr versus root diameter of Spanish Broom. The line shows the second order polynomial regression curves fitted to the experimental data: $tr = 0.0203d^2 + 0.0062d$ $R^2 = 0.94$. The regression equation of tensile strength [MPa] Tr versus root diameter [mm] of Spanish Broom curve is (1) $Tr = 37.605\ d^{-0.306}$ $R^2 = 0,29$. Comparison between literature data: (2) Tosi, 2007; (3) Laranci et al., 2004; (4) Norris and Greenwood, 2003.

Fig. 9 – Root cohesion Cv versus depth of transplanted, spontaneous and all Spanish Broom plants: la RAR considerata nel calcolo è quella riferita a un metro quadrato. Per ogni singola radice è stato applicato il valore di Tr riferito al suo diametro, come da Fig. 8.

Fig. 10 – Factor of safety (Fs) versus depth in unvegetated soil, transplanted stand or natural slope under the following conditions: saturated bulk unit weight [kN/m3], $\gamma_{sat} = 20$ kN m^{-3}, water unit weight $\gamma w = 9.8$ kN m^{-3}, slope angle $\beta = 26.5°$, soil friction angle $\varphi' = 20°$, soil cohesion = 1 kPa, surcharge Wv = 0 – 0.196 – 0.4 kPa respectively. .Cv (z) as in Fig. 9 and Fig. 5.

Fig. 11 – Specimen of rooted cutting of Spanish Broom 1 year after plantation.

Table 1

Autors	*Studied plants*
Operstein and Frydman (2000)	*Medicago sativa, Rosmarimus officinalis, Pistacia lentiscus e Cistus* (all dicotyledonous shrub species)
Gallotta et al., (2000 and 2003)	*Cupressus, Crataegus, Juglans, Prunus, Pyrus, morus, tamarix*
Amato et al., (1997 and 2000)	*Citrus sinensis, Prunus avium, Ailanthus altissima, Castanea sativa, Ficus carica, Pinus, Quercus pebescens, Prunus, Arundo, Festuca, Poa, Dactylis, Trifolium, Cyclamen, Brassica and Rubus frutticosus*
Mattia et al. (2005)	*Lygeum spartum* L. (herb), *Atriplex halimus* L. and *Pistacia lentiscus* L. (shrub)
De Baets et al. (2008)	*Atriplex halimus* (shrub), *Salsola genistoides* (shrub), *Brachypodium retusum* (grass), *Thymelaea hirsuta* (shrub), *Phragmites australis* (reed) *Limonium supinum* (herb), *Tamarix canariensis* (tree), *Artemisia barrelieri* (shrub), *Stipa tenacissima* (grass), *Juncus acutus* (rush), *Fumana thymifolia* (shrub), *Dorycnium pentaphyllum* (shrub), *Teucrium capitatum* (shrub), *Dittrichia viscosa* (shrub), *Thymus zygis* (shrub), *Lygeum spartum* (grass), *Plantago albicans* (herb), *Rosmarinus officinalis* (shrub), *Helictotrichon filifolium* (grass), *Piptatherum miliaceum* (grass), *Avenula bromoides* (grass), *Nerium oleander* (shrub), *Ononis tridentata* (shrub), *Anthyllis cytisoides* (shrub), *Retama sphaerocarpa*
Laranci et al. (2004)	*Phillirea latifolia, Rhamnus alaternus, Viburnum tinus, Euonymus europaeus, Coronilla emerus, Pistacia terebinthus, Acer campestre* and ***Spartium junceum***
Tosi (2007)	*Rosa canina, Inula viscosa and* ***Spartium junceum***
Chiatante et al., 2001, 2003a, b)	architecture of the ***Spartium junceum*** L. rooting system grown on slopes

Table 2

		Summary climate parameters			
Gauge	Experimental Site	Tp [mm/d]	λ [event/d]	α [mm/event]	Time series data
Sambuca 1680260 E 4829130 N	San Casciano in Val di Pesa (Florence)	2.189	0.374	5.284	2001–2006

Table 3

	Clay	Silt	Sand	Porosity	Classification USDA
Site A $_{\textbf{cuttings}}$	44.0%	46.4%	9.6%	56.0%	Silty Clay
Site A $_{\alpha}$	51.0%	41.5%	7.5%	50.0%	Silty Clay
Site A $_{\beta}$	18.3%	48.5%	33.2%	38.7%	Loam
Site A $_{\rho}$	31.1%	56.8%	12.1%	35.5%	Silty Clay Loam
Site A $_{\varphi}$	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 $_{\textbf{landslide}}$	28.7%	34.2%	37.2%	42.0%	Clay Loam
Site Cs $_{\textbf{landslide}}$	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 4

	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**

Table 5

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

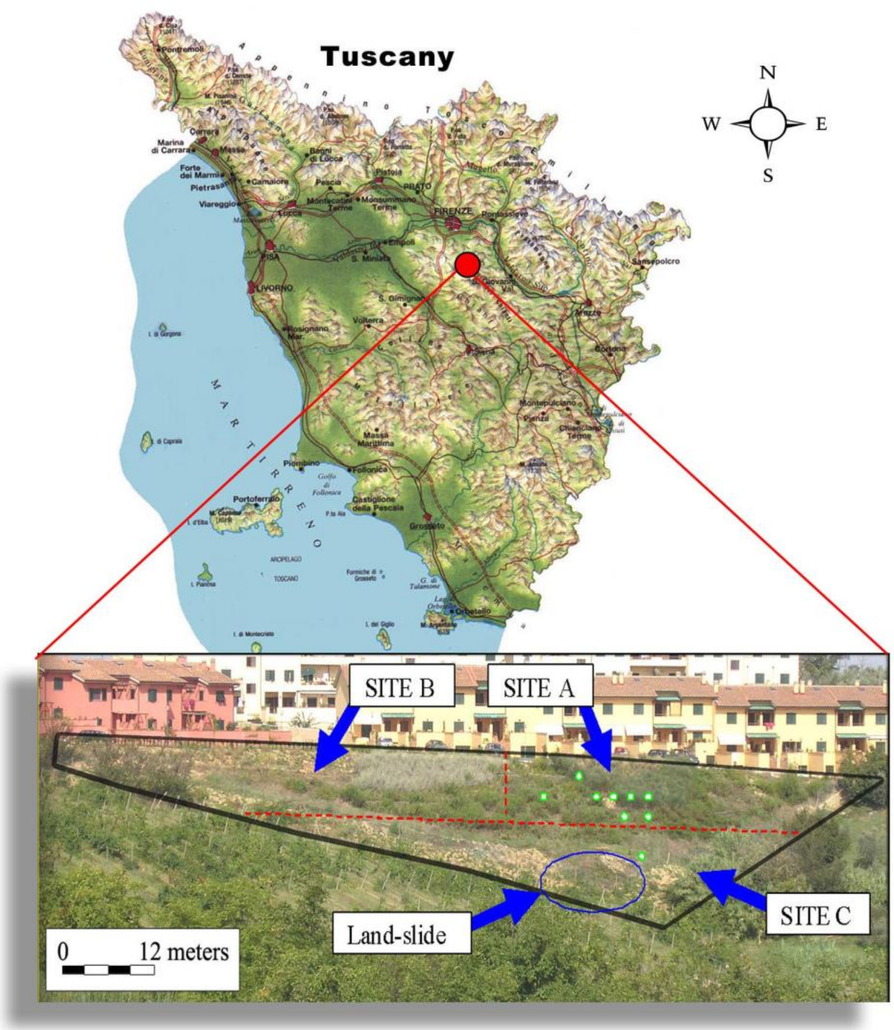


Fig. 1

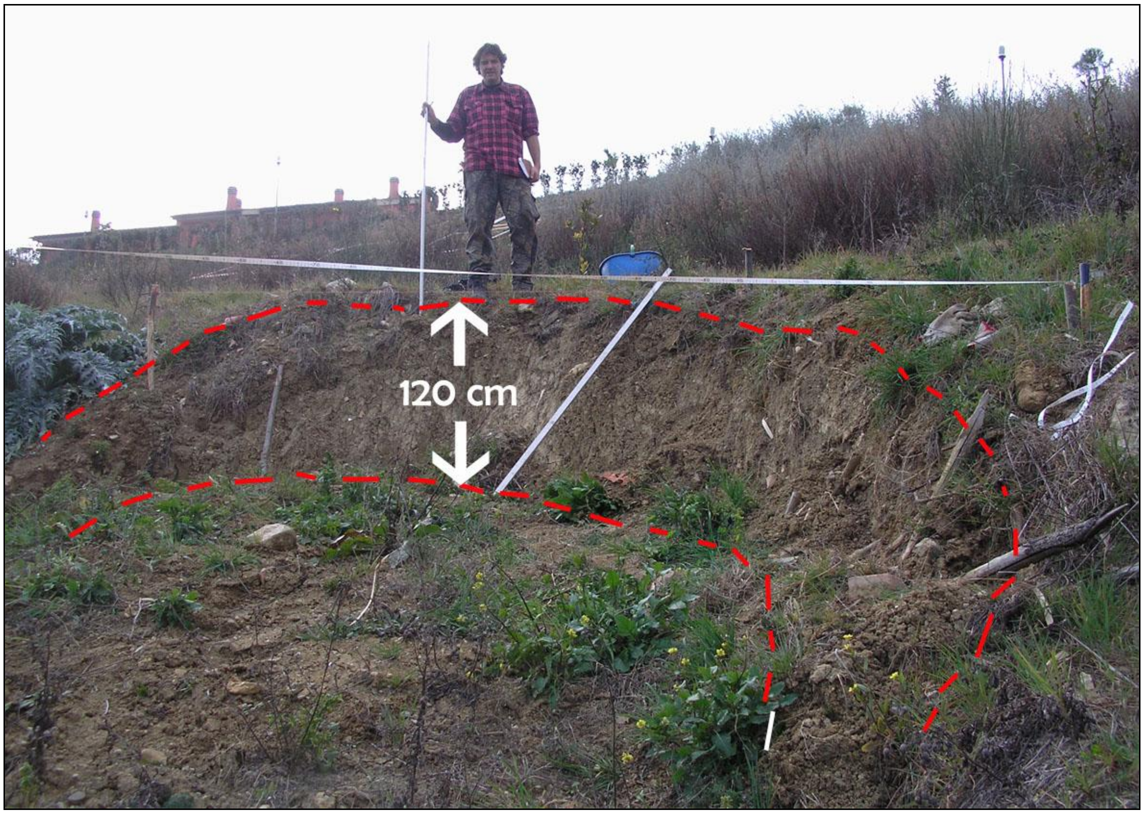


Fig. 2a

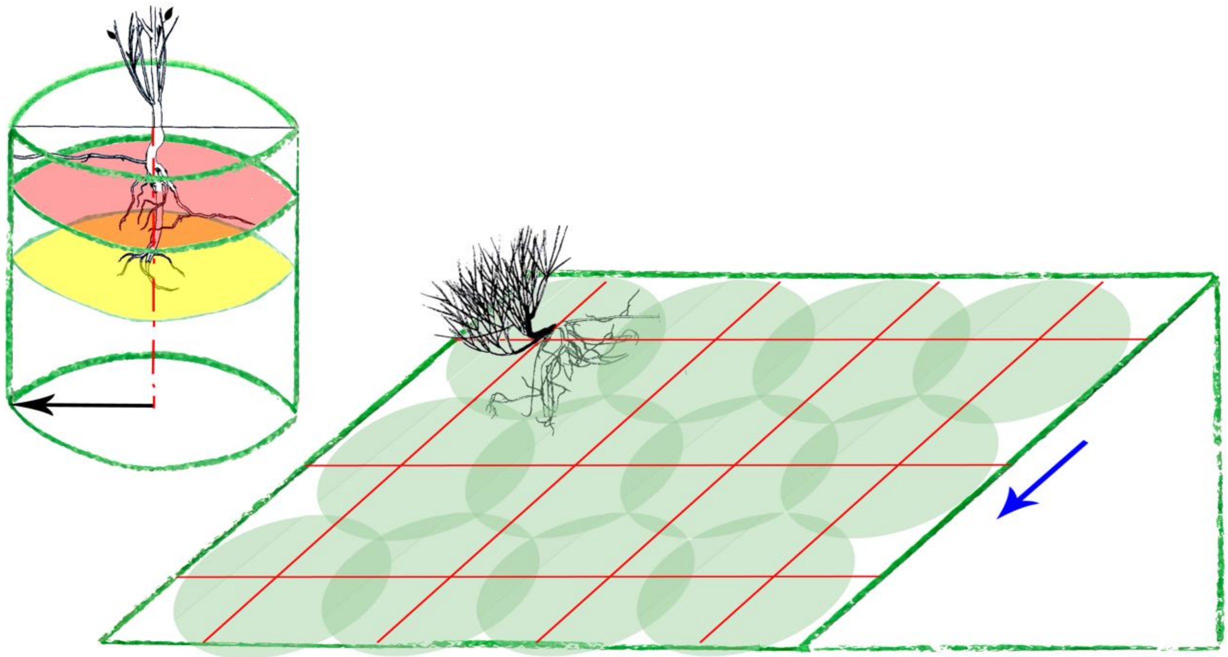


Fig. 2b

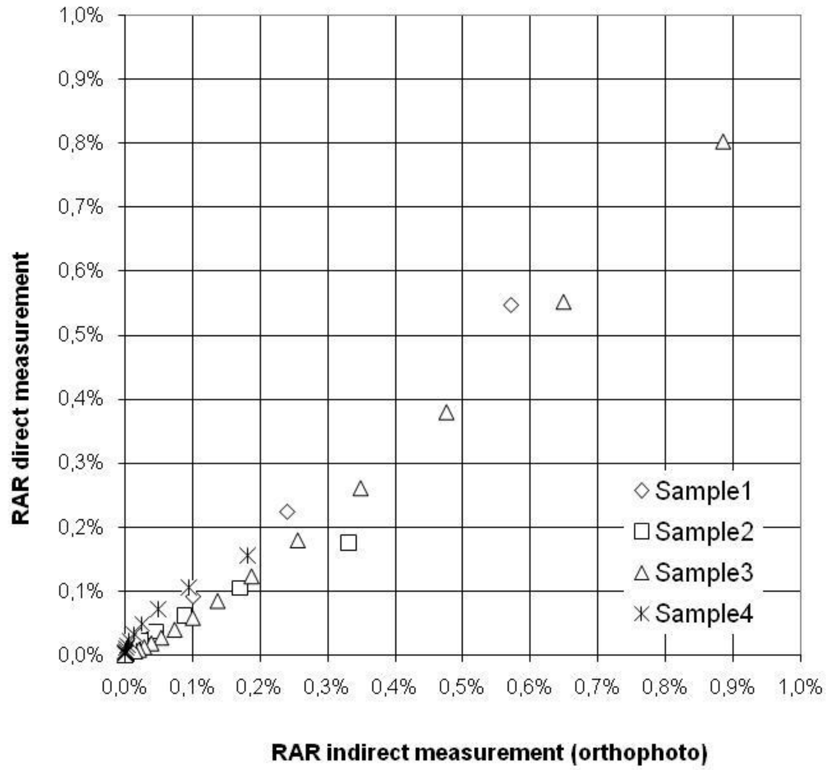

1,0%
0,9%
0,8%
0,7%
0,6%
0,5%
0,4%
0,3%
0,2%
0,1%
0,0%
RAR direct measurement
0,0% 0,1% 0,2% 0,3% 0,4% 0,5% 0,6% 0,7% 0,8% 0,9% 1,0%
RAR indirect measurement (orthophoto)
Sample1
Sample2
Sample3
Sample4

Fig. 3

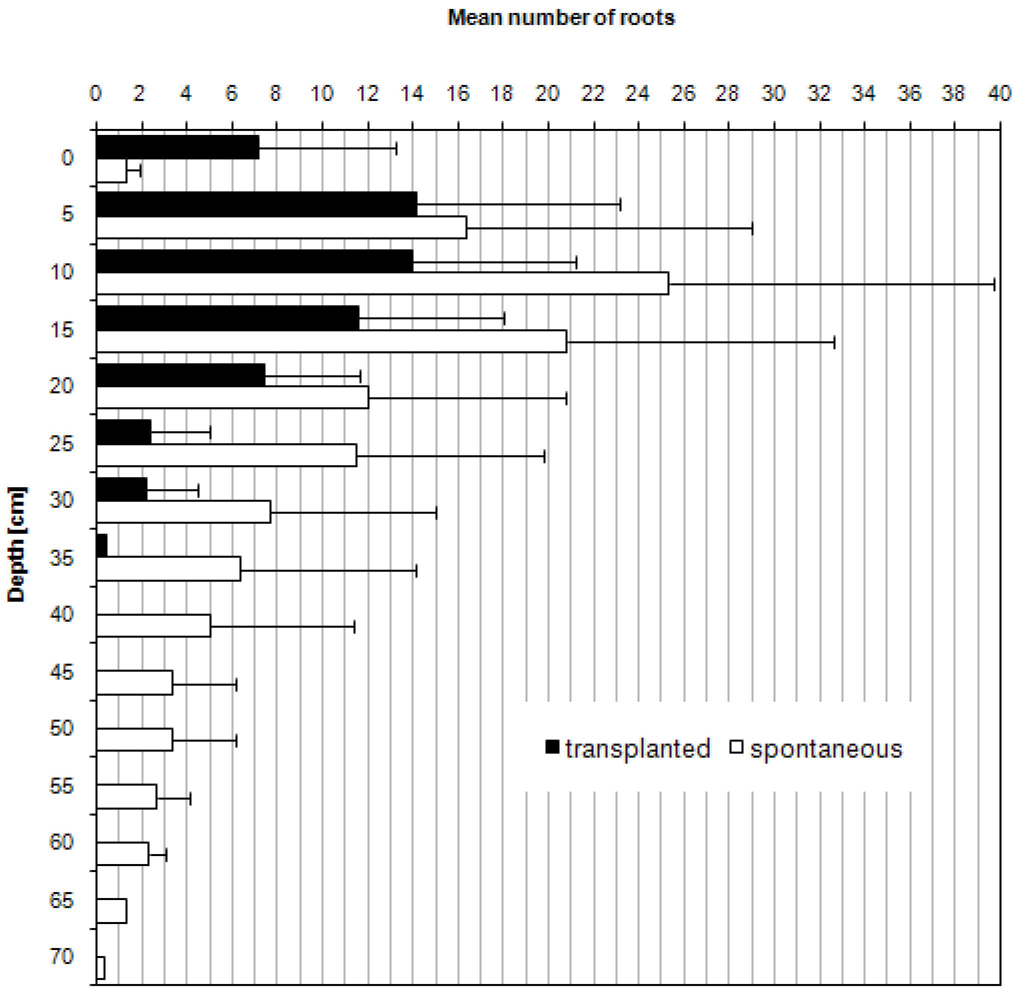
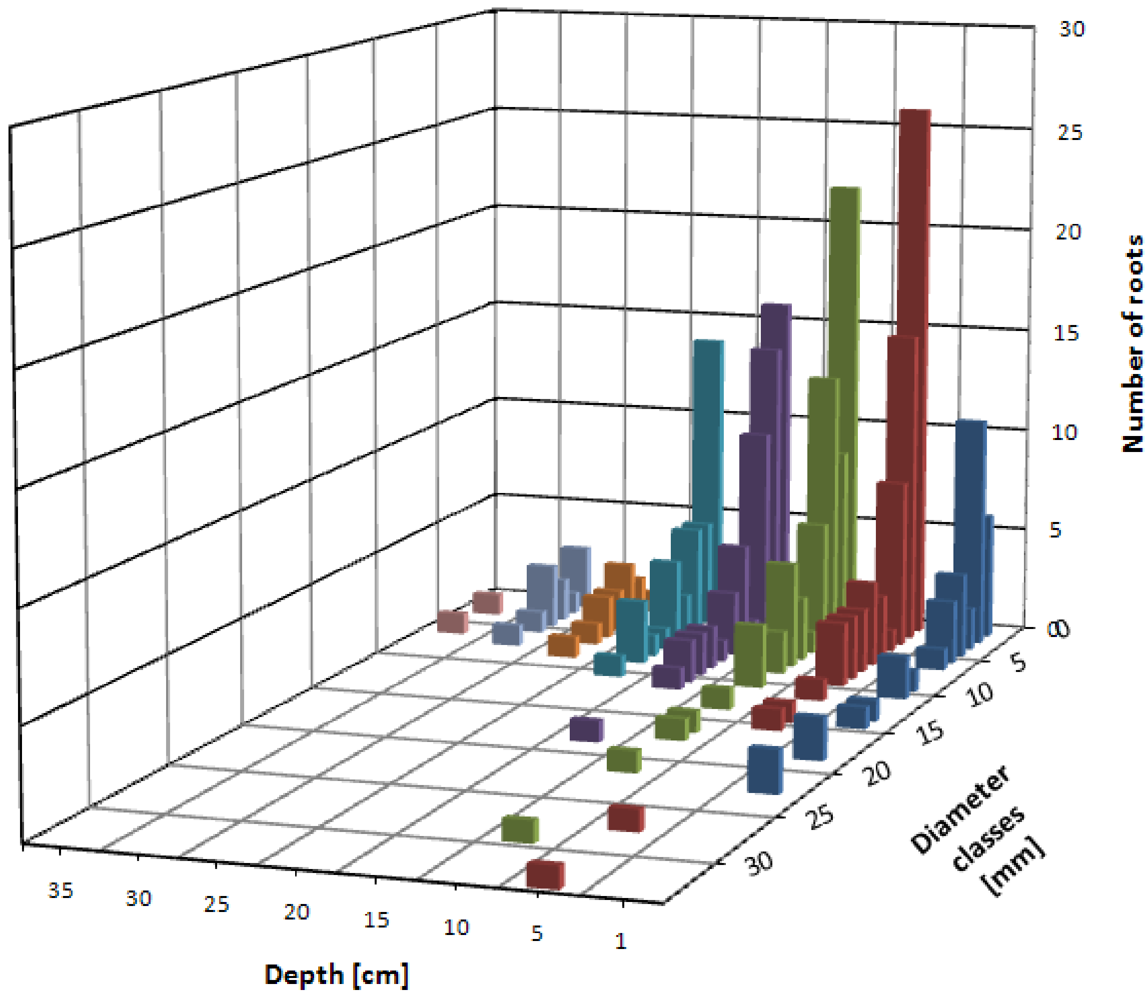

Mean number of roots
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
Depth [cm]
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
transplanted
spontaneous

Fig. 4



30
25
20
15
10
5
0
Number of roots
5
10
15
20
25
30
Diameter classes [mm]
35
30
25
20
15
10
5
1
Depth [cm]

Fig. 5a

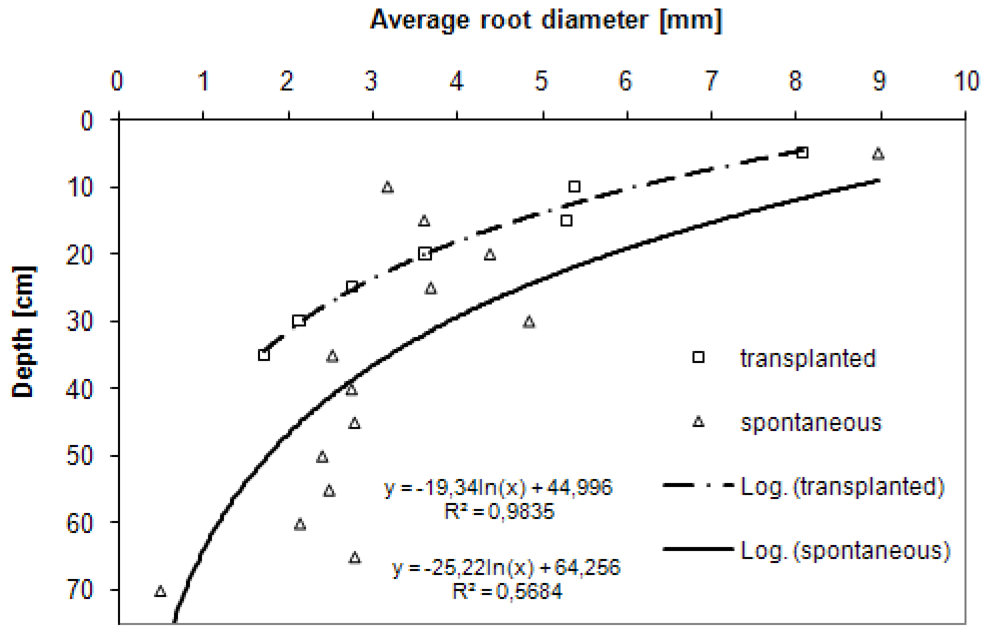

Average root diameter [mm]
0
1
2
3
4
5
6
7
8
9
10
Depth [cm]
0
10
20
30
40
50
60
70
transplanted
spontaneous
Log. (transplanted)
Log. (spontaneous)
y = -19,34ln(x) + 44,996
R² = 0,9835
y = -25,22ln(x) + 64,256
R² = 0,5684

Fig. 5b

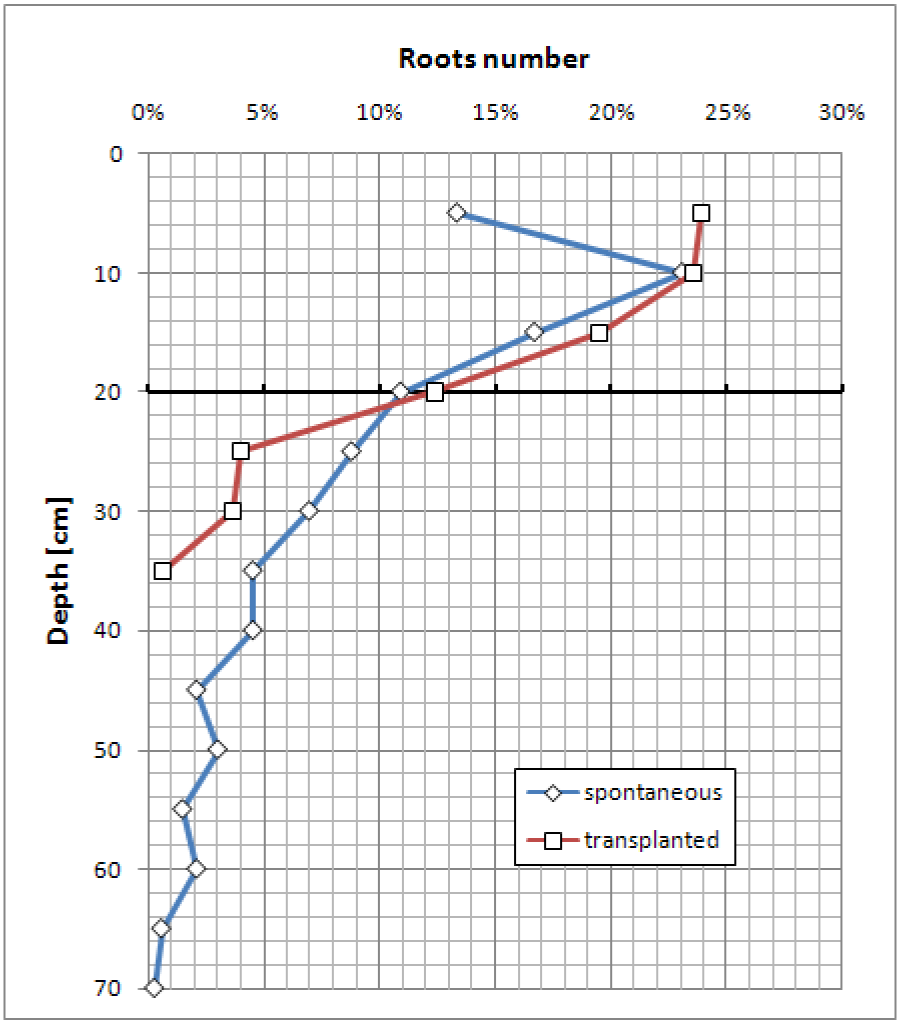

Roots number
0%
5%
10%
15%
20%
25%
30%
0
10
20
30
40
50
60
70
Depth [cm]
spontaneous
transplanted

Fig. 6

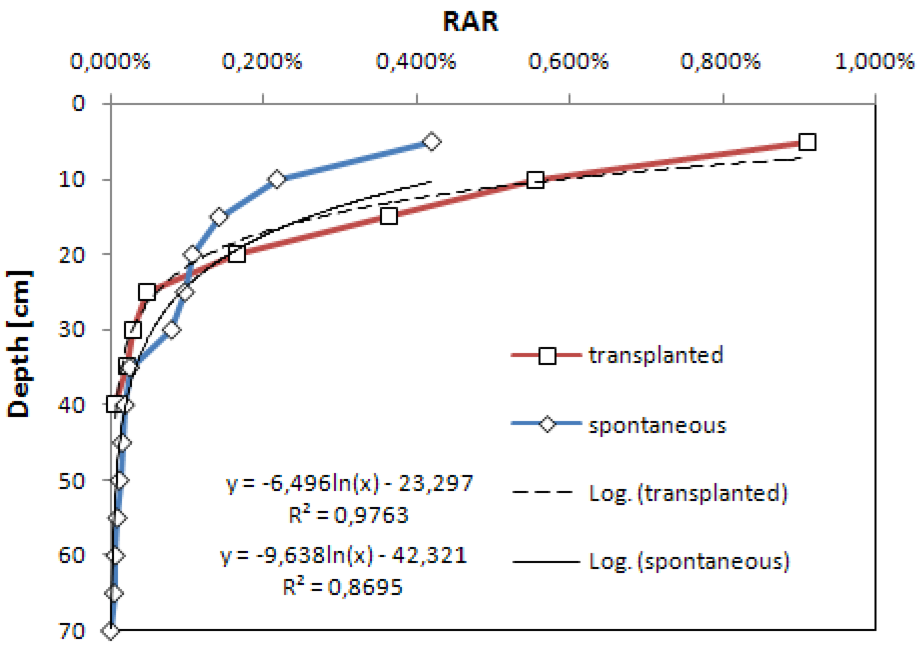
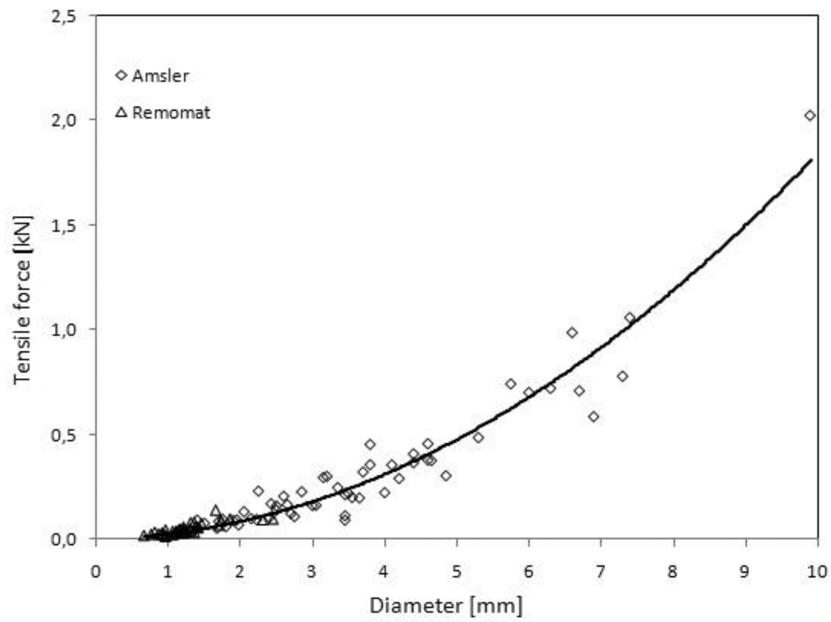

RAR
0,000%
0,200%
0,400%
0,600%
0,800%
1,000%
Depth [cm]
0
10
20
30
40
50
60
70
transplanted
spontaneous
Log. (transplanted)
Log. (spontaneous)
y = -6,496ln(x) - 23,297
R² = 0,9763
y = -9,638ln(x) - 42,321
R² = 0,8695

Fig. 7



	Samples	Diameter	Tr [MPa] Ø 1 mm	Exp	Tr [MPa] Average
(1)	98	0.70 - 9.90	37,7	-0,306	31,9
(2)	48	0.65 - 9.35	36,6	-0.341	30,3
(3)	24	0.44 - 2.68	56.4	-0.239	44,6
(4)	-	-	-	-	17,0

Fig. 8

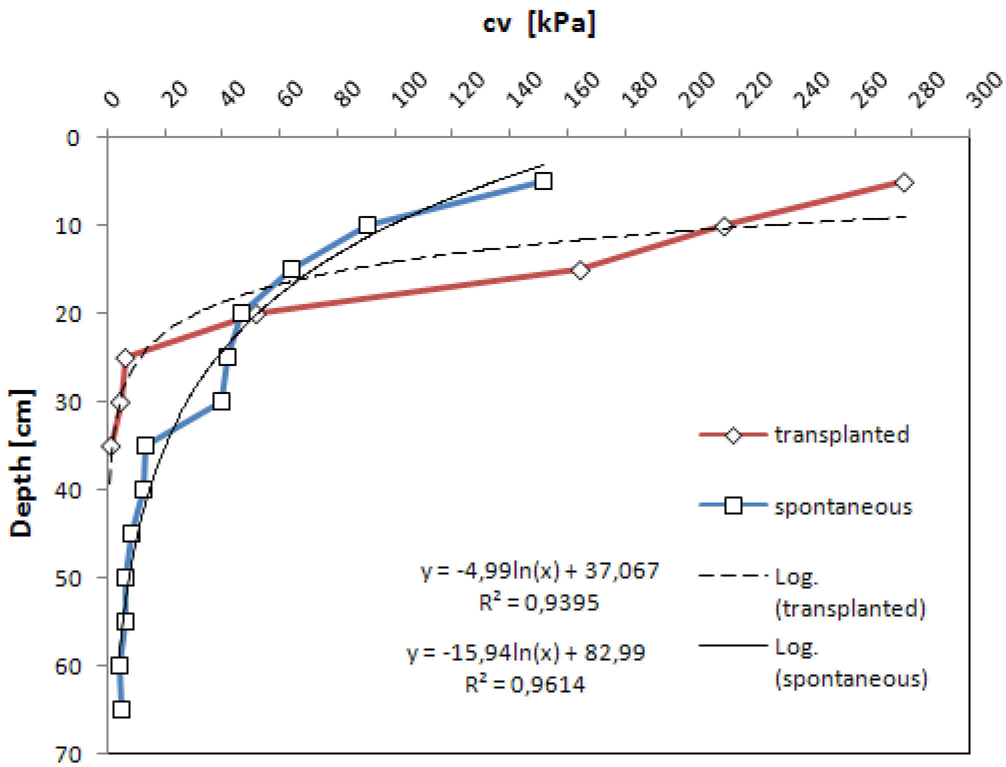

cv [kPa]
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
Depth [cm]
0
10
20
30
40
50
60
70
transplanted
spontaneous
Log. (transplanted)
Log. (spontaneous)
y = -4,99ln(x) + 37,067
R² = 0,9395
y = -15,94ln(x) + 82,99
R² = 0,9614

Fig. 9

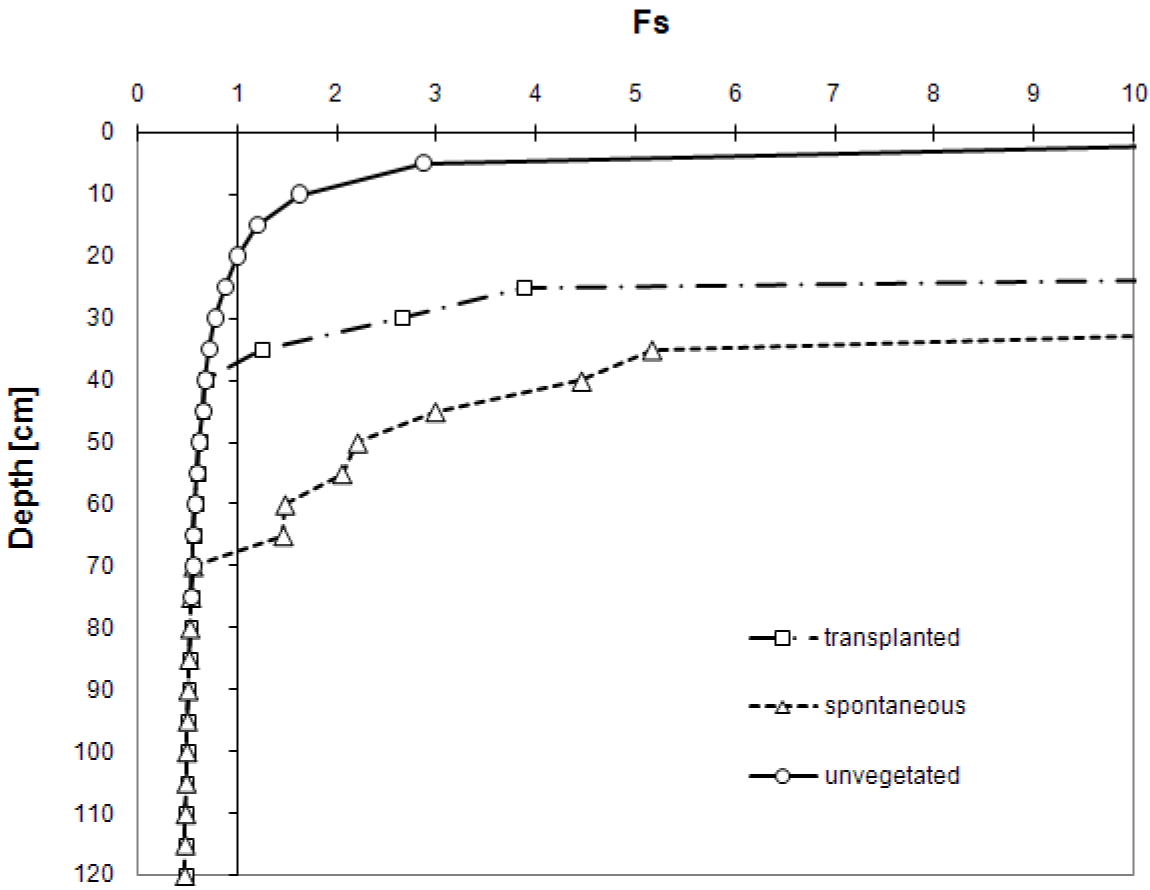

Fs
0
1
2
3
4
5
6
7
8
9
10
0
10
20
30
40
50
60
70
80
90
100
110
120
Depth [cm]
transplanted
spontaneous
unvegetated

Fig. 10

Fig. 11