# Soil reinforcement by the root system of six dominant species on eroded mountainous marly slopes (Southern Alps, France)

M. Burylo, C. Hudek, Rey F Nom_exemple

Elsevier Editorial System(tm) for Catena
Manuscript Draft

Manuscript Number: CATENA2467R3

Title: Soil reinforcement by the roots of six dominant species on eroded mountainous marly slopes (Southern Alps, France)

Article Type: Research Paper

Keywords: marls; root area ratio; root tensile strength; root system; erosion; soil reinforcement

Corresponding Author: Miss Melanie Burylo,

Corresponding Author's Institution: Cemagref Grenoble

First Author: Melanie Burylo

Order of Authors: Melanie Burylo; Csilla Hudek; Freddy Rey

Abstract: In marly catchments of the French Southern Alps, the development of plant root systems is essential to increase slope stability and mitigate soil erosion, prevalent in this area. In a context of land restoration, it is important to be able to evaluate plant efficiency for soil reinforcement. This paper presents the results of investigations carried out on six dominant species from marly gullies. It aims to compare the additional soil cohesion they provide at the early stages of their development. The six following species were collected: two tree species, Pinus nigra and Quercus pubescens, two shrubby species, Genista cinerea and Thymus serpyllum, and two herbaceous species, Achnatherum calamagrostis and Aphyllantes monspeliensis. For each of them, we measured root tensile strength and root area ratio in order to calculate the potential root reinforcement and to compare species suitability to prevent shallow mass movements. Results showed significant differences between species. The herbaceous species Aphyllantes monspeliensis and the shrubby species Genista cinerea provided the highest increase in soil shear strength while the tree species, Pinus nigra and Quercus pubescens were the least efficient. These results, along with the knowledge on vegetation dynamics and species response to erosive constraint, allow us to better evaluate land vulnerability to erosion and the efficiency of restoration actions in eroded marly lands.

## COMMENTS FROM EDITORS AND REVIEWERS:

All the minor remarks have been included in the new revised manuscript.

**Research highlights:**

- Juvenile plant species increase soil cohesion by root reinforcement.
- Root reinforcement depends on species and root system type.
- Grasses and shrubs provide higher increase in soil shear strength than young trees.

# Soil reinforcement by the roots of six dominant species on eroded mountainous marly slopes (Southern Alps, France)

**M. Burylo[1*], C. Hudek[2], F. Rey[1]**

[1] Cemagref Grenoble, UR EM, 2 rue de la papeterie, BP 76, 38402 Saint Martin d'Hères Cedex, France

[2] Corvinus University of Budapest, Faculty of Horticultural Science, Department of Soil Science and Water Management, 29-43 Villányi út, 1118 Budapest, Hungary.

## Abstract

In marly catchments of the French Southern Alps, the development of plant root systems is essential to increase slope stability and mitigate soil erosion, prevalent in this area. In a context of land restoration, it is important to be able to evaluate plant efficiency for soil reinforcement. This paper presents the results of investigations carried out on six dominant species from marly gullies. It aims to compare the additional soil cohesion they provide at the early stages of their development. The six following species were collected: two tree species, *Pinus nigra* and *Quercus pubescens*, two shrubby species, *Genista cinerea* and *Thymus serpyllum*, and two herbaceous species, *Achnatherum calamagrostis* and *Aphyllantes monspeliensis*. For each of them, we measured root tensile strength and root area ratio in order to calculate the potential root reinforcement and to compare species suitability to prevent shallow mass movements. Results showed significant differences between species.

* corresponding author. Tel. (+33).4.76.76.28.11; fax. (+33).4.76.51.38.03; E-mail address: melanie.burylo@cemagref.fr

The herbaceous species *Aphyllantes monspeliensis* and the shrubby species *Genista cinerea* provided the highest increase in soil shear strength while the tree species, *Pinus nigra* and *Quercus pubescens* were the least efficient. These results, along with the knowledge on vegetation dynamics and species response to erosive constraint, allow us to better evaluate land vulnerability to erosion and the efficiency of restoration actions in eroded marly lands.

**Keywords:** marls, root area ratio, root tensile strength, root system, erosion, soil reinforcement

## Introduction

Soil erosion by water is a hazard that affects both natural and cultivated lands all over the world and causes considerable soil losses. In the French Southern Alps, marly lands are subjected to severe erosion, leading to high soil erosion rates (e.g. 1.5 $cm.yr^{-1}$ in Descroix, 1994; 3.5 $cm.yr^{-1}$ in Lecompte et al., 1998), considerable soil losses (100 $tons.ha^{-1}.yr^{-1}$ reported in Mathys et al., 2003) and highly unstable soils. These lands are subjected to intense gullying, ending in the formation of badlands (Poesen et al., 2003). On gully walls, the bedrock is overlain by a very loose regolith layer, composed of disintegrated marl particles, which can be transported down the slopes during intensive rainfall events and which lead to increased gullying. These shallow mass movements, described by Oostwoud Wijdenes and Ergenzinger (1998) as miniature debris flows, consist of a mixture of coarse marl fragments within a silty matrix, moving down slope as slides, gravity and fluid driven flows. Shallow landslides are a widespread erosional process in mountainous areas where conditioning factors, such as steep slopes, high weathering rates due to severe climatic conditions or lack of vegetation, often accumulate. Relatively similar soil slippage problems have been described previously in other mountainous regions (e.g. Abe and Ziemer, 1991; Schmidt et al., 2001; Schwarz et al., 2009). Nevertheless, the phenomenon we discuss here describes surficial landslides (< 1 m deep) and will be refered to as miniature debris flows (MDF) hereafter.

On slopes prone to instability, it is widely recognized that vegetation can significantly reduce erosion (Thornes, 1990; Morgan, 1995; Gray and Sotir, 1996). For the last 130 years, the protective role of vegetation has been extensively studied and applied to mitigate soil erosion through restoration operations on marly badlands using ecological engineering principles (Mitsch and Jørgensen, 2003; Odum and Odum, 2003). In the French Southern Alps, at the end of the 19th century, huge surface areas underwent massive afforestation, primarily with Austrian Black pine (*Pinus nigra* Arn. subsp. *Nigra*), which is now a dominant species in the local flora (Vallauri et al., 2002). Recently, local scale actions, consisting of bioengineering works installed in the gullies, have been used successfully for water erosion control (Rey, 2009). After restoration operations, spontaneous vegetation growing on these marly slopes is mainly composed of juvenile individuals of trees, shrubs and grasses (Rey et al., 2005). However, locally, this vegetation can remain limited. Managing degraded lands and evaluating their vulnerability to soil slippage thus implies combining knowledge on species dynamics (Rey et al., 2005; Burylo et al., 2007) and species biomechanical characteristics such as resistance to erosive forces (Burylo et al., 2009) and potential for preventing soil slippage. Until now, few investigations have been carried out on marly soils stability (e.g. Mickovski and van Beek, 2009), or on the effects of grasses and young shrubs for improving slope stability (e.g. Operstein and Frydman, 2000; Mattia et al., 2005; De Baets et al., 2008). As a consequence, further investigations on the effect of plant roots in preventing shallow mass movements, especially at the early stages of development, where plants offer the lowest protection and where soil should be the most vulnerable, are of major interest.

Plants can substantially improve slope stability and prevent soil slippage in two ways, through hydrological mechanisms lowering pore water pressure (Greenway, 1987; Gyssels et al., 2005) and through mechanical reinforcement of soil by roots (Waldron, 1977; Ziemer, 1981; Nilaweera and Nutalaya, 1999). However, in temperate regions, it is believed that root reinforcement contributes much more to shallow soils stability than hydrological factors (Gray and Sotir, 1996; Stokes et al., 2009). Plant roots provide additional cohesion to the soil and root-permeated soils are thus much stronger than soils alone to withstand soil erosion processes such as mass movements (e.g. Ziemer, 1981; Operstein and Frydman, 2000; Mickovski and van Beek, 2009). The extent to which roots reinforce the soil depends on several variables (Loades et al., 2009; Stokes et al., 2009) including root system morphology, such as root biomass, root number, root diameter or rooting depth (Wu et al., 1979), root system architecture (Stokes et al., 1996; Dupuy et al., 2005; Mickovski et al., 2007; Reubens et al., 2007), and root system mechanical properties such as root tensile strength (Wu et al., 1979; Operstein and Frydman, 2000) and pullout resistance (Nilaweera and Nutalaya, 1999; Norris, 2005).

During the past thirty years, many authors made an attempt to connect root system characteristics to erosion processes and slope stability. Given the complexity of root-soil interactions, modelling and quantifying root reinforcement has remained challenging. In the late seventies, pioneering modelling contribution was provided by Wu et al. (1979) and

Waldron and Dakessian (1977). Their perpendicular model is based on the Coulomb equation (1) extended to root-permeated soil by introducing increased shear strength due to roots (2).

$$\mathbf{S = C + \sigma_N . \tan\phi} \qquad \textbf{(1)}$$

$$\mathbf{S = C + \Delta S + \sigma_N . \tan\phi} \qquad \textbf{(2)}$$

where S is soil shear strength, C is soil cohesion, $\sigma_N$ the stress normal to shear plane, $\phi$ the angle of internal friction and ΔS the increase in soil shear strength due to the presence of roots. In this model, the evaluation of ΔS (in kPa) simply depends on root tensile strength ($T_R$ in MPa) and on the cross-sectional area of roots in the shear plane (RAR):

$$\mathbf{\Delta S = K.\ T_R .\ RAR = 1.2\ T_R .\ RAR} \qquad \textbf{(3)}$$

where K is a factor accounting for the decomposition of $T_R$ according to a tangential and normal component on the shear plane. From laboratory and field investigations, Wu et al. (1979) observed that K generally ranges from 1.0 to 1.3 and selected a constant value of 1.2 (3).

This model relies on the assumptions that all roots are fully mobilized during soil shearing and that all roots break at the same time, whereas in reality, roots break progressively. Consequently, it estimates maximum and potential values of ΔS, and was found to overestimate root reinforcement (Operstein and Frydman, 2000; Pollen and Simon, 2005; Mickovski et al., 2009). Fiber bundle models, such as the RipRoot model (Pollen and Simon, 2005) consider that roots within the soil break progressively during soil failure and load is redistributed to the remaining intact roots. Comparative analysis showed that the RipRoot approach provided better root reinforcement estimations (Pollen and Simon, 2005; Mickovski et al., 2009). Greenwood (2006) developed the computer program SLIP4EX which calculates the slope factor of safety using different methods of analysis and which includes both the mechanical and hydrological changes due to vegetation. Although the Wu and Waldron model is not the most accurate and realistic one, it remains one of the most widespread model for preliminary root reinforcement assessment. Because it is simpler and requires less input data than the above-mentioned models, it was used in the present study to rank species according to their soil stabilization potential and to compare species suitability for soil protection against shallow mass movements (e.g. Bischetti et al., 2005; Mattia et al., 2005; Tosi, 2007; De Baets et al., 2008; De Baets et al., 2009).

The aim of this paper is to evaluate and compare the suitability for preventing MDF of six dominant species at the juvenile stage, growing on marly slopes. Juvenile individuals of each species were collected on site and we measured root tensile strength and root system distribution with depth. Their contribution to slope stability was calculated using Wu's reinforcement model and their suitability for erosion control was assessed.

## Materials and methods

### *Study site*

The study site is located in the Saignon catchment, situated in North-East of Sisteron (Alpes-de-Haute-Provence department, France), a 400-ha gully catchment on marls (Figure 1). The climate on the test site is mountainous sub-Mediterranean, characterised by summer droughts (on average 168 mm from June to August) interspersed with intense storms. The mean annual rainfall is 787 mm and the mean annual temperature is 10.2°C with 4-5 cold months (Rey, 2002). The sampling area is South-West oriented, its altitude is about 800 m and mean slope of gully sides is 33° (Rey, 2002).

The local vegetation is dominated by *Pinus nigra* Arn. *ssp. nigra* introduced at the beginning of the last century for erosion control purposes. The other dominant tree species are *Acer opalus* Mill., *Quercus pubescens* Wild., and *Robinia pseudoacacia* L. also introduced in the 19th century. The shrubby layer mainly consists of a mixture of *Ononis fruticosa* L. and *Genista cinerea* Vill., and the grass layer of *Achnatherum calamagrostis* L. (Vallauri, 1997).

*Soil*

The soils in the study area are derived from Jurassic black marls (Callovian and Bathonian). Weathering of black marls results in extended gullied areas called badlands. The soils on gully slopes consist of superimposed layers with different structure and compaction (Maquaire et al., 2002):

- 0 to 50-100 mm depth: loose detrital cover sensitive to erosion made of structureless marl fragments and colluvial materials
- 50-100 to 450 mm depth: regolith of marls consisting of marl fragments whose compaction increases with depth (Oostwoud Wijdenes and Ergenzinger, 1998)
- > 450 mm depth: the bedrock, compact, structured and cohesive.

The detrital and regolith layers are partially removed by erosion processes, including shallow mass movements, causing further decompression of the underlying bedrock.

On marly sites similar to the sampling area, Maquaire et al. (2003) measured relatively low carbonate content (from 20 to 35%) which explains the susceptibility of the soil to weathering processes. Moreover, shear tests performed on weathered material showed that effective cohesion ranged from 6 to 12 kPa (Antoine et al., 1995; Maquaire et al., 2003).

*Species studied*

Six species, among the most dominant in the local vegetation, were chosen for the present study: *Pinus nigra* Arn. *ssp. nigra*, *Quercus pubescens* Wild., *Genista cinerea* Vill., *Thymus serpyllum* L., *Achnatherum calamagrostis* L. and *Aphyllantes monspeliensis* L. P. Beauv.. These species represent three different vegetation growth forms: tree, shrubby and herbaceous plants. In the Saignon catchment, *P. nigra* and *Q. pubescens* are tree species commonly found at all the stages of their development, including the juvenile stage. At this stage, these two species show a fast growing and deeply penetrating taproot system with thin lateral roots. *G. cinerea* is a widespread shrub in the area. It develops a deep tap root with long lateral roots which generate a large root system both in depth and in width. *T. serpyllum* presents a shallower root system with a relatively short tap root and longer lateral roots (see Burylo *et al.*, 2009 for more details on root system description of woody species). *A. calamagrostis* and *A. monspeliensis* are two herbaceous species. *A. calamagrostis* is a perennial grass while *A. monspeliensis* is a perennial dicotyledonous plant. However, both show a graminoid shape, with tillers packed into tussocks and a heart root system where many fibrous roots develop from the plant base (Rameau, 1993). In the study area, the two species can be found as isolated tussock, with a diameter ranging from 15 to 30 cm.

*Species sampling*

Between 5 and 10 individuals of each plant species were sampled from the marly slopes in the study area. Isolated juvenile plants, with no neighbours within a 300 mm radius, were selected to limit plant-plant interactions which can dramatically affect root system development and makes sampling easier. As plant age could not be determined accurately, small plants were chosen within each species. Threshold values of 20 mm and 100 mm in basal diameter were selected for woody and herbaceous species respectively, and for all species, plants less than 300 mm high were sampled. *P. nigra* and *Q. pubescens* seedlings of similar shapes and surrounding environments were collected from the same area. For the two shrubby and two herbaceous species, age determination was difficult, therefore individuals were chosen by their height and diameter. Because of the lack of soil cohesion at our study site, we could not use the traditional 'trench wall' method described by Böhm (1979). Therefore, each plant was carefully excavated by hand to keep the root system intact, up to a depth of 60 mm depending of the species. Photos of the different steps of the excavation process were taken for further measurements as well as lateral spreading of the root system. Plants were then put in plastic bags and transported to a cold room (5°C) until laboratory measurements that took place during the following week.

*Root distribution and root area ratio measurements*

During the week after the harvest, roots were cleaned from the remaining soil particles with a hand water jet so that we could measure root characteristics. For each plant, root area ratio (RAR) was estimated following the method described by Mattia et al. (2005). Using photos of the plant root system, the spatial distribution of roots was recreated in the laboratory and the diameter of all the roots was measured every 50 mm up to the maximum rooting depth of the plant. For each depth level, the roots were then divided into diameter classes of 0.25 mm.

Finally, RAR was calculated every 50 mm as the ratio of root surface area ($A_R$ in mm²) calculated from root diameters) to the surface area of the root-permeated soil (A in mm²). A was calculated from the measurements of maximum lateral spreading of the root system. Hence, A differs for each plant sample but we used the same value for all RAR calculations within a plant.

*Root tensile strength measurements*

After the RAR measurements, all roots were cut off and conserved in a 15% alcoholic solution following Bischetti et al. (2005). Root tensile strength ($T_R$) tests were performed with a device built by the Institute of Agricultural Hydraulics of the University of Milan (Italy) and previously used in similar studies (Bischetti et al., 2005; Mattia et al, 2005). Before testing, roots were inspected and damaged roots were removed from the study. Root samples of approximately 200 mm were selected for testing and root diameter was measured at three points along root length. For woody species, root bark, when observed, was conserved for the tests. The two root ends were fixed to the clamps of the machine, of which one can move at a constant speed of 10 mm.min$^{-1}$ to apply a tensile force to the root. A load cell continuously registered the force applied to the root and we measured $T_R$ (MPa) as:

$$T_R = F_{max} \Big/ \pi\left(\frac{D}{2}\right)^2 \qquad (4)$$

where $F_{max}$ is the maximum tensile force (N) registered before breaking and D is the average diameter (mm) of the root being tested. For each species, at least 15 roots with diameters ranging from 0.15 to 5 mm were tested.

*Comparison of species suitability for soil reinforcement*

To evaluate the potential increase in soil shear strength due to roots ($\Delta S$ given in equation (3)), the static perpendicular model described by Wu et al. (1979) was used. In order to account for root diameters variability, equation (3) has to be written as follows, taking into account $T_R$ and RAR for different diameter classes:

$$\Delta S = 1.2 \sum_{i=1}^{N} T_{Ri} \cdot A_{Ri} / A \qquad (5)$$

where $T_{Ri}$ (in MPa) and $A_{Ri}$ (in mm²) are $T_R$ and $A_R$ values for diameter class i, and N is the number of classes.

$\Delta S$ was thus calculated for each plant sample and used to compare species efficiency for soil reinforcement.

*Data analysis and statistics*

According to many authors (Norris et al., 2008), $T_R$ decreases with increasing root diameter following a simple power law equation of the form:

$$T_R = \alpha \cdot D^{-\beta} \qquad (6)$$

where $\alpha$ and $\beta$ are empirical values depending on species. The power relationship between $T_R$ and root diameter was tested and an analysis of covariance (ANCOVA) with root diameter as a covariate, was performed to test for significant differences between species and growth forms (Tukey HSD procedure). $T_R$ values were log-transformed before analysis to meet the assumption of normal distribution.

RAR and ΔS differences between species were investigated with Kruskal-Wallis nonparametric test as sample number is low and data are not normally distributed. All the analyses were carried out with STATISTICA (version 7.1 for Windows, Statsoft 1984).

## Results

### *Root distribution and root area ratio*

All species showed similar root distribution, with a decreasing number of roots with depth (Table 1) and the largest part of root system biomass being observed in the upper 200 mm of soil.

Root distribution within diameter classes is highly variable between species and growth forms. For grasses, which present a fibrous root system, the majority of the roots consisted of roots smaller than 1 mm in diameter and no roots larger than 2 mm were observed. Root systems of tree species comprised very few roots, representing root morphology at the juvenile stage, made of a vigorous tap root and few laterals. Shrubby species showed a third morphological type, with about half a dozen coarse roots (diameter > 1 mm) and many fine roots (diameter < 1 mm).

RAR significantly decreases with depth as revealed by the Kruskal-Wallis test (Table 2). RAR distribution with depth also revealed differences between species regarding rooting depth and RAR values (Fig. 2). RAR for *G. cinerea* ranges from 0.053 % at the soil surface to 0 % at 600 mm soil depth, while RAR for *P. nigra* reaches 0.015 % at the soil surface and 0% at a depth of 400 mm.

Nevertheless, there were large standard errors in RAR measurements and the Kruskal-Wallis test showed that RAR values were not significantly different either between species or between growth forms (Table 3).

*Root tensile strength*

The results of the tensile strength tests are given in Figure 3. As expected, there was a decrease of $T_R$ with increasing root diameter following the power relationship given by Eq. 7. Values of α, β and of the statistical significance of the relationships are given in Table 4. This relationship was observed for all species except for *G. cinerea* for which no correlation between $T_R$ and diameter could be observed.

The results of the ANCOVA showed that root tensile strength differed significantly between species (D: F=28.8, $p$<0.0001; $T_R$: F=14.3, $p$<0.0001) and between growth forms (D: F=18.5, $p$<0.0001; $T_R$: F=17.8, $p$<0.0001 – Table 5). The roots of the tree species (*P. nigra* and *Q. pubescens*) were less resistant to tension than the shrubby and herbaceous species. The shrub *G. cinerea* and the two herbaceous species (*A. calamagrostis* and *A. monspeliensis*) had the strongest roots. However, $T_R$ values of the two latter species decreased quickly with increasing root diameter (high values of the decay coefficient *β*) and were similar to the other species above diameters of 1 mm. The shrub *T. serpyllum* had intermediate values of root strength.

*Root reinforcement*

By applying Eq. 6 to the data, we calculated ΔS, the increase of soil cohesion induced by plants roots. $T_R$ values were re-calculated for each root diameter class (0.25 mm step) using the parameters of the power relationship given in Table 4. As for *G. cinerea* the strength-diameter relationship was not clear, ΔS was calculated from mean values of $T_R$. The results (Fig. 4) showed that the shrub *G. cinerea* and the herbaceous species *A. monspeliensis* could provide the highest increase in soil cohesion. Calculated ΔS values exceeded 5 kPa in the first 200 mm of soil and were significantly higher for these two species (see Table 3 for the results of the Kruskal-Wallis test). As for root tensile strength, the tree species *P. nigra* and *Q. pubescens* were the least efficient for soil reinforcement with ΔS values ranging between 0.5 and 1 kPa in the upper soil layers. Root reinforcement decreased quickly with increasing soil depth for all species, and below 300 mm, ΔS values were not significantly different between species (Table 3).

**Discussion**

Root area ratio measurements showed a high variability within species which resulted in high standard errors and no significant differences between species, as revealed by the Kruskal-Wallis test (Table 3). This variability can be explained by several reasons, first and foremost, environmental heterogeneity. Many environmental factors have a strong influence on root architecture (Coutts et al., 1999). Soil properties, such as soil bulk density (Goodman and Ennos, 1999), soil moisture and fertility (Fitter & Stickland, 1991; Taub and Goldberg, 1996; Hodge, 2004), or natural obstacle like stones or stumps (Quine et al., 1991), can dramatically affect root system development. Plant-plant interactions, especially competition, also modify root growth (e.g. Craine, 2006). Root system development also depends on the genetic variability of the species. On the other hand, variability in RAR may be due to sampling and errors in measurements in the laboratory. Moreover, when measuring RAR, it was sometimes difficult to replace the root system in the original position it had in the field.

Nevertheless, species showed more differences in root number distribution within diameter classes reflecting differences in root system types (Table 1): tap-like root system with a vigorous main root, tap-like root system with many laterals and coronal root system (Fig. 5).

The values of RAR measured in the present study, with root cross-sectional areas representing less than 0.05% of the reference areas of soil, were in the same order of those reported by De Baets et al. (2008), who studied comparable species. Other authors found higher RAR values (e.g. Abernethy and Rutherfurd, 2001; Bischetti et al., 2005) but plant development and methods of measurements were different.

Tensile strength tests confirmed that there exists a power relationship between $T_R$ and root diameter. This well-known relationship (e.g. Bischetti et al., 2005; Mattia et al., 2005; Norris et al., 2005) reveals that thin roots are more resistant to tensile stresses than thick roots. However, this relationship has not been observed for *G. cinerea*. As for root architecture variability, many factors can influence root tensile strength, among which soil properties, root age, root bark or root structure (Genet et al., 2005). In our study, as individuals of *G. cinerea* were sampled from the same site, a few meters apart from each other, soil and environmental characteristics may not be the cause of the lacking $T_R$-root relationship for *G. cinerea*. Variations in root age would more likely explain this result, as well as the low number of tests and the range of diameters tested for each species (0.3 to 3 mm), which may not have been sufficient enough. Microscopy observations on root cross sections or cellulose content measurements would help discussing on this result.

The values of $\alpha$ (scale factor) and $\beta$ (decay coefficient) generally fall in the range of values already found in previous studies. Several grasses have been characterized by low scale factors and decay coefficients higher than 1 (Mattia et al., 2005; De Baets et al., 2008). For shrubby species, values of $\alpha$ and $\beta$ ranging from 4.4 to 91.2 and from -0.52 to -1.75 respectively, have been reported (Operstein and Frydman, 2000; Bischetti et al., 2005; Mattia et al., 2005; De Baets et al., 2008). De Baets et al. (2008) studied two shrubby species (*Rosmarinus officinalis* and *Thymus zygis*) belonging to the same plant family as *T serpyllum* (Lamiaceae) and found $\alpha$ and $\beta$ values very similar to ours (12.9 and 19.3 for $\alpha$ and -0.77 and -0.73 for $\beta$). For tree species, decay coefficients found in literature (Bischetti et al., 2005; Genet et al., 2005) ranged from -0.52 to -1.11 but higher scale factors were reported (from 18.4 to 60.15) compared to our measurements (12.41 and 17.37). The analysis of covariance revealed that the roots of shrubs and herbaceous species were the most resistant to tensile stresses. De Baets et al. (2008) studied the root tensile strength of 25 Mediterranean species, mostly shrubs and herbs, and found no significant strength differences between the two growth forms. Generally speaking, species which have the strongest roots are those with high values of $\alpha$ and low values of $\beta$. This observation might be attributed to differences in root structure between species. Genet et al. (2005) showed that cellulose concentration influenced root strength properties, higher cellulose concentrations resulting in stronger roots. Moreover, lignin concentrations also strongly determine root tensile strength. Hathaway and Penny (1975) demonstrated that Young's modulus decreased with increasing lignin/cellulose ratio. Therefore, it can be assumed that roots of tree species are weaker in tension than fibrous roots because of higher lignin content in fibrous root systems.

The values of root reinforcement calculated with assumed parameters in Wu's model generally ranged between 0 and 10 kPa in the upper 20 cm of soil and fell under 5 kPa in the deeper soil layers. These values are in the same order of magnitude of the values reported in Mattia et al. (2005), but lower than the ones reported by De Baets et al. (2008). Again, the analysis showed that herbaceous and shrubby species provide more soil reinforcement than tree species. For example, at 10 cm depth, the additional cohesion provided by the roots of *A. monspeliensis* and *G. cinerea* is respectively 14 and 15 times greater than that of *P. nigra* and respectively 6.5 and 7 times greater than that of *Q. pubescens*. De Baets et al. (2007) follow this idea as they found that the increase in soil cohesion due to roots was significantly higher for soils permeated with fibrous roots of grasses than for soils permeated with tap-like root systems.

Nevertheless, the results of the present study must be analyzed with caution. Values were calculated with a perpendicular static model designed on the basis of assumptions leading to important simplifications of the process. An important assumption is that all roots are mobilized in tension when the soil shears, and reach their maximum tensile strength at the same time before breaking. Such models give potential maximum root reinforcement and overestimate the additional soil cohesion provided by roots (Operstein and Frydman, 2000; Pollen and Simon, 2005; Mickovski et al., 2009). Thus, the values of soil reinforcement calculated in the present work must be regarded as relative values allowing species comparison according to their efficiency for soil stabilization and not as absolute values.

The results of the present study suggest that shrubs and herbaceous species, in particular *G. cinerea* and *A. monspeliensis*, are the most efficient for soil reinforcement. These growth forms have either fibrous root systems with many fine roots resistant to tension (*A. monspeliensis*) or tap-like root systems with a mixture of woody coarse roots and many fine and strong roots (*G. cinerea* – Fig. 4). Both species have a significant protective effect against MDF, reinforcing the soil to a depth corresponding to the plant rooting depth (up to 550 mm on individuals tested).

Combined with the knowledge on vegetation dynamics and ecological site properties, these results can help in evaluation the vulnerability of degraded lands to erosion or the efficiency of restoration actions. Previous studies have demonstrated that after environmental disturbance or land restoration, herbaceous species first recolonize the substrate (Cammeraat et al., 2005; Burylo et al., 2007). Then, vegetation cover evolves and the proportions of shrubby and tree species slowly increase. In particular, in marly gullies of the French Southern Alps, *A. monspeliensis* and *A. calamagrostis* represent an important part of the colonizing vegetation (Rey et al., 2005). Therefore, vegetation that colonizes marly lands soon after restoration could quickly and efficiently stabilize shallow soil layers, thereby increasing the effects of restoration works. Then, the growth of tree seedlings, shown to be less efficient in the first years of development than herbaceous species and shrubby species, could fix the upper layers of soil to the bed rock by penetrating into the underlying bedrock (Styczen and Morgan, 1995). Moreover, tree roots can penetrate into bedrock discontinuities and act as restraint piles firmly anchoring the root-permeated soil to the bedrock (Fig. 6).
Evaluating the suitability of species for erosion control should also include knowledge on species resistance to different erosion processes (De Baets et al., 2009). Erosive constraints can be seen as environmental filters that determine which species from the regional pool can persist (Keddy, 1992), and thus actually prevent shallow mass movements. Burylo et al. (2009) studied the resistance to uprooting of 12 species growing in eroded marly lands, among which *P. nigra*, *Q. pubescens*, *G. cinerea* and *T. serpyllum*. These four species showed contrasting anchorage strengths. *G. cinerea* was found to be one of the most resistant while

*P. nigra* was among the least resistant species. *T. serpyllum* and *Q. pubescens* had intermediate anchorage strengths.

Therefore, global species suitability to prevent MDF can be specified by taking into account species resistance to uprooting. *P. nigra*, used for massive afforestation at the beginning of the last century, proved not to be the most efficient species for root reinforcement of soils. On the other hand, *G. cinerea* would be very interesting both for sustainable land colonization, due to its high resistance to uprooting, and for soil stabilization. *T. serpyllum* and *Q. pubescens*, respectively post-pioneer and late succession species, would have an intermediate efficiency to prevent soil slippage. These two latter species could be interesting when erosion is already partially controlled, for example to restore soil structure. The anchorage strength of *A. monspeliensis* and *A. calamagrostis* has not yet been evaluated, but uprooting tests on Vetiver grass showed that this graminaceous species possessed the root strength to withstand torrential runoff (Mickovski et al., 2005). In addition, the grass *A. calamagrostis*, known for its rusticity, its important expansion by vegetation reproduction, and which is currently used in land restoration (Barrouillet, 1982), is suggested to be very resistant as well.

## Conclusion

Measurements of RAR and root tensile strength were conducted on six species growing on eroded marly lands to evaluate root reinforcement of soil using Wu's perpendicular model and to compare species efficiency to prevent MDF. The results presented here expand the knowledge on the biomechanical characteristics of grasses and woody species growing on mountainous marly lands. Results confirmed that thin roots can resist higher tensile stresses than thicker roots, although roots with larger diameters need higher tensile forces to break. Furthermore, this study concluded that grasses and shrubs provided higher increase in soil shear strength in the topsoil than tree species in the early stages of their development. Combined with the knowledge on vegetation dynamics, ecological site properties and species resistance to erosion, these results can help in evaluating land vulnerability to erosion and the efficiency of restoration actions in eroded marly lands.

**Acknowledgements**

We thank the Istituto di Idraulica Agraria for the use of their device for root tensile strength tests. We also thank Pr. Gian battista Bischetti and Enrico Chiaradia for helpful discussions on methodological problems.

**References**

Abe, K., Ziemer, R.R., 1991. Effect of tree roots on a shear zone: modeling reinforced shear stress. Canadian Journal of Forest Research, 21: 1012-1019.

Abernethy, B., Rutherfurd, I.D., 2001. The distribution and strength of riparian tree roots in relation to riverbank reinforcement. Hydrological processes, 15: 63-79.

Antoine, P., Giraud, A., Meunier, M., Van Asch, T., 1995. Geological and goetechnical properties of the "Terres noires" in southeastern France: weathering, erosion, solid transport and instability. Engineering Geology 40, 223-234.

Barrouillet, J., 1982. La revégétalisation dans les Alpes du Sud: choix et emploi des espèces herbacées et arbustives. Cemagref, Grenoble, 143 p.

Bischetti, G.B., Chiaradia, E.A., Simonato, T., Speziali, B., Vitali, B., Vullo, P., Zocco, A., 2005. Root strength and root area ratio of forest species in Lombardy (Northern Italy). Plant and Soil, 278: 11-22.

Böhm, W., 1979. Methods of Studying Root systems, Ecological Series No. 33. Springer-Verlag, Berlin.

Burylo, M., Rey, F., Delcros, P., 2007. Abiotic and biotic factors influencing the early stages of vegetation colonization in restored marly gullies (Southern Alps, France). Ecological Engineering, 30: 231-239.

Burylo, M., Rey, F., Roumet, C., Buisson, E., Dutoit, T., 2009. Linking plant morphological traits to uprooting resistance in eroded marly lands (Southern Alps, France). Plant and Soil, 324: 31-42.

Cammeraat, E., Kooijman, A., Van Beek, R., 2005. Vegetation succession and its consequences for slope stability in SE Spain. Plant and Soil, 278 (1-2): 135-147.

Craine, J., 2006. Competition for nutrients and optimal root allocation. Plant and Soil 285: 171-185.

Coutts, M.P., Nielsen, C.C.N., Nicoll, B.C., 1999. The development of symmetry, rigidity and anchorage in the structural root system of conifers. Plant and Soil 217, 1-15.

De Baets, S., Poesen, J., Knapen, A., Galindo, P. 2007. Impact of root architecture on the erosion-reducing potential of roots during concentrated flow. Earth Surface Processes and Landforms 32, 1323-1345.

De Baets, S., Poesen, J., Reubens, B., Wemans, K., De Baerdemaeker, J., Muys, B., 2008. Root tensile strength and root distribution of typical Mediterranean plant species and their contribution to soil shear strength. Plant and Soil, 305: 207-226.

De Baets, S., Poesen, J., Reubens, B., Muys, B., De Baerdemaeker, J., 2009. Methodological framework to select plant species for controlling rill and gully erosion: application to a Mediterranean ecosystem. Earth Surface Processes and Landforms 34, 1374-1392.

Descroix, L., 1994. L'érosion actuelle dans la partie occidentale des Alpes du Sud. Ph.D. Thesis, Lyon, France.

Fitter, A.H., Stickland, T.R., 1991. Architectural analysis of plant root systems 2. Influence of nutrient supply on architecture in contrasting plant species. New phytologist, 118: 383-389.

Genet, M., Stokes, A., Mickovski, S.B., Fourcaud, T., Salin, F., Dumail, J.-F., Van Beek, R., 2005. The influence of cellulose content on tensile strength in tree roots. Plant and Soil, 278: 1-9.

Goodman, A.M., Ennos, A.R., 1999. The Effects of Soil Bulk Density on the Morphology and Anchorage Mechanics of the Root Systems of Sunfower and Maize. Annals of Botany, 83: 293-302.

Gray, D.H., Sotir, R.B., 1996. Biotechnical and sol bioengineering slope stabilization: a practical guide for erosion control. John Wiley and Sons.

Greenway, D.R., 1987. Vegetation and slope stability Slope stability. John Wiley & Sons.

Greenwood, J.R., 2006. SLIP4EX – A program for routine slope stability analysis to include the effects of vegetation, reinforcement and hydrological changes. Geotechnical and Geological Engineering, 24: 449-465.

Gyssels, G., Poesen, J., Bochet, E., Li, Y., 2005. Impact of plant roots on the resistance of soils to erosion by water: A review. Progress in Physical Geography, 29: 189-217.

Hathaway, R.L., Penny, D., 1975. Root Strength in Some Populus and Salix Clones. New Zealand Journal of Botany, 13: 333-344.

Hodge, A., 2004. The plastic plant: Root responses to heterogeneous supplies of nutrients. New Phytologist 162, 9-24.

Keddy, P., 1992. Assembly and response rules: two goals for predictive community ecology. Journal of Vegetation Science 3, 157-164.

Lecompte, M., Lhenaff, R., Marre, A., 1998. Huit ans de mesures du ravinement des marnes dans les Baronnies méridionales (Préalpes françaises du sud). Géomorphologie : relief, processus, environnement, 4: 351-374.

Loades, K.W., Bengough, A.G., Bransby, M.F., Hallett, P.D., 2009. Planting density influence oon fibrous root reinforcement of soil. Ecological Engineering, *In press*.

Mathys, N., Brochot, S., Meunier, M., Richard, D., 2003. Erosion quantification in the small marly experimental catchments of Draix (Alpes de Haute Provence, France). Calibration of the ETC rainfall-runoff-erosion model. Catena, 50: 527-548.

Mattia, C., Bischetti, G.B., Gentile, F., 2005. Biotechnical characteristics of root systems of typical Mediterranean species. Plant and Soil, 278: 23-32.

Maquaire, O., Ritzenthaler, A., Fabre, D., Ambroise, B., Thiery, Y., Truchet, E., Malet, J.-P., Monnet, J., 2002. Caractérisation des profiles de formations superficielles par pénétrométrie dynamique à énergie variable: application aux marnes noires de Draix (Alpes-de-Haute-Provence, France). C.R. Géosciences 334, 835-841.

Maquaire, O., Malet, J.-P., Remaître, A., Locat, J., Klotz, S., Guillon, J., 2003. Instability conditions of marly hillslopes: towards landslidong or gullying? The case of the Barcelonnette basin, South East France. Engineering Geology 70, 109-130.

Mitsch, W.J., Jørgensen, S.E., 2003. Ecological engineering: A field whose time has come. Ecological Engineering, 20 (5): 363-377.

Mickovski, S.B., van Beek, L.P.H., 2009. Root morphology and effects on soil reinforcement and slope stability of young vetiver (*Vetiveria zizanioides*) plants grown in semi-arid climate. Plant and Soil 324, 43-56.

Mickovski, S.B., van Beek, L.P.H., Salin F., 2005. Uprooting resistance of vetiver grass (*Vetiveria zizanioides*). Plant and Soil, 278: 33-41.

Mickovski, S.B., Bengough, A.G., Bransby, M.F., Davies, M.C.R., Hallett, P.D. 2007 Material stiffness, branching pattern and soil matric potential affect the pullout resistance of model root systems. European Journal of Soil Science 58, 1471-1481.

Mickovski, S.B., Hallett, P.D., Bransby, M.F., Davies, M.C.R., Sonnenberg, R., Bengough, A.G., 2009. Mechanical reinforcement of soil by willow roots: impacts of root properties and root failure mechanism. Soil Science Society of America Journal, 73: 1276-1285.

Morgan, R.P.C., 1995. Soil erosion and conservation - Second edition Longman.

Nilaweera, N.S., Nutalaya, P., 1999. Role of tree roots in lope stabilization. Bulletin on Engineering Geology and the Environment 57, 337-342.

Norris, J.E., 2005. Root reinforcement by hawthorn and oak roots on a highway cut-slope in Southern England. Plant and Soil, 278: 43-53.

Norris, J.E., Stokes, A., Mickovski, S.B., Cammeraat, E., van Beek, R., Nicoll, B.C., Achim, A., 2008. Slope stability and erosion control: Ecotechnological solutions. Springer, Dordrecht.

Odum, H.T., Odum, B., 2003. Concepts and methods of ecological engineering. Ecological Engineering, 20 (5): 339-361.

Oostwoud Wijdenes, D.J., Ergenzinger, P., 1998. Erosion and sediment transport on steep marly hillslopes, Draix, Haute-Provence, France: An experimental field study. Catena, 33: 179-200.

Operstein, V., Frydman, S., 2000. The influence of vegetation on soil strength. Ground Improvement, 4: 81-89.

Poesen, J., Nachtergaele, J., Verstraeten, G., Valentin, C., 2003. Gully erosion and environmental change: Importance and research needs. Catena, 50: 91-133.

Pollen, N., Simon, A., 2005. Estimating the mechanical effects of riparian vegetation on streambank stability using a fiber bundle model. Water Resources Research, 41:1-11.

Quine, C.P., Burnand, A.C., Coutts, M.P., Reynard, B.R., 1991. Effects of mounds and stumps on the root architecture of *Sitka spruce* on a peaty gley restocking site. Forestry 64, 385-401.

Rameau, J.C., Mansion, D., Dumé, G., 1993. Flore forestière française, Tome 2 Montagnes. Institut pour le développement forestier.

Reubens, B., Poesen, J., Danjon, F., Geudens, G., Muys, B., 2007. The role of fine and coarse roots in shallow slopes stability and soil erosion control with a focus on root system architecture: a review. Trees 21, 385-402.

Rey, F., 2002. Influence de la distribution spatiale de la vegetation sur la production sédimentaire de ravines marneuses dans les Alpes du sud. Ph.D. Thesis, Grenoble, France.

Rey, F., 2009. A strategy for fine sediment retention with bioengineering works in eroded marly catchments in a mountainous Mediterranean climate (Southern Alps, France). Land Degradation and Development, 20: 1-7.

Rey, F., Isselin-Nondedeu, F., Bédécarrats, A., 2005. Vegetation dynamics on sediment deposits upstream of bioengineering works in mountainous marly gullies in a Mediterranean climate (Southern Alps, France). Plant and Soil, 278: 149-158.

Schmidt, K.M., Roering, J.J., Stock, J.D., Dietrich, W.E., Montgomery, D.R., Schaub, T., 2001. The variability of root cohesion as an influence on shallow landslides susceptibility in the Oregon Coast Range. Canadian Geotechnical Journal, 38: 995-1024.

Schwarz, M., Preti, F., Giadrossich, F., Lehmann, P., Or, D., 2009. Quantifying the role of vegetation in slope stability: a case study in Tuscany (Italy). Ecological Engineering *In press*

Stokes, A., Ball, J., Fitter, A.H., Brain, P., Coutts, M.P. 1996. An Experimental Investigation of the Resistance of Model Root Systems to Uprooting. Annals of Botany 78, 415-421.

Stokes, A., Atger, C., Glyn Bengough, A., Fourcaud, T., Sidle, R.C., 2009. Desirable plant root traits for protecting natural and engineered slopes against landslides. Plant and Soil, 324: 1-30.

Styzcen, M.E., Morgan, R.P.C., 1995. Engineering properties of vegetation. In R.P.C. Morgan, R.J. Rickson (Editors). Slope stabilization and erosion control: a bioengineering approach. E and FN SPON, London, pp. 5-58.

Taub, D.R., Goldberg, D., 1996. Root system topology of plants form habitats differing in soil resource availability. Functional Ecology 10, 258-264.

Thornes, J.B. (1990) Vegetation and erosion, Processes and environments John Wiley & Sons.

Tosi, M., 2007. Root tensile strength relationships and their slope stability implications for three shrub species in the Northern Apennines (Italy). Geomorphology, 87: 268-283.

Vallauri, D., 1997. Dynamique de la restauration forestière des substrats marneux avec *Pinus nigra* J.F. Arnold *ssp. nigra* dans le secteur haut-provençal. PhD thesis, Cemagref, Grenoble, France.

Vallauri, D.R., Aronson, J., Barbero, M., 2002. An analysis of forest restoration 120 years after reforestation on badlands in the Southwestern Alps. Restoration Ecology, 10 (1): 16-26.

Waldron, L.J., 1977. The shear resistance of root-permeated homogeneous and stratified soils. Soil Science Society of America Journal, 41: 843-849.

Waldron, L.J., Dakessian, S., 1981. Soil reinforcement by roots: calculation of increased soil shear resistance from root properties. Soil Science, 132: 427–435.

Wu, T.H., McKinnell III, W.P., Swantson, D.N., 1979. Strength of tree roots and landslides on Prince of Wales Island, Alaska. Canadian Geotechnical Journal, 16: 19-33.

Ziemer, R.R., 1981. Roots and the stability of forested slopes. Erosion and sediment transport in Pacific rim steeplands. International Associated Hydrological Science Publications, 132, 343-361.

**Table 1**
Click here to download Table: Table 1.doc

Table 1: Root number distribution with depth and within diameter classes. Values are mean root number in each diameter class and depth. Growth forms are tree (T), shrubs (S) and grasses (G).

| | | | Depth (m) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Species | Growth form | Root diameter (mm) | 0.05 | 0.10 | 0.15 | 0.20 | 0.25 | 0.30 | 0.35 | 0.40 | 0.45 | 0.50 | 0.55 |
| *Pinus nigra* | T | <1 | | 2.2 | 4.8 | 2.6 | 0.8 | 0.4 | 0.6 | 0.2 | | | |
| | | 1-2 | | 0.6 | 0.8 | 0.8 | 0.4 | 0.2 | | | | | |
| | | > 2 | 1 | 0.8 | 0.2 | | | | | | | | |
| *Quercus pubescens* | T | <1 | 1.9 | 1.6 | 1.9 | 1.4 | 0.7 | 0.3 | 0.3 | 0.1 | 0.1 | 0.1 | |
| | | 1-2 | | 0.3 | 0.4 | 0.6 | 0.4 | 0.4 | 0.1 | 0.4 | | | |
| | | > 2 | 1 | 0.7 | 0.9 | 0.6 | 0.3 | | | | | | |
| *Genista cinerea* | S | <1 | 28.2 | 32 | 36.8 | 18.6 | 10.4 | 8.6 | 9.2 | 5.4 | 7.8 | 3.8 | 1.2 |
| | | 1-2 | 2.6 | 2 | 2.2 | 3.2 | 3.2 | 2 | 0.6 | 0.8 | 0.6 | 0.2 | 0.2 |
| | | > 2 | 3.8 | 0.6 | 0.8 | 1.2 | 0.4 | 0.4 | 0.69 | 0.2 | 0.2 | | |
| *Thymus serpyllum* | S | <1 | 116.5 | 46.8 | 26.5 | | | | | | | | |
| | | 1-2 | 6.3 | 2.3 | 2 | | | | | | | | |
| | | > 2 | 2.3 | 1.3 | | | | | | | | | |
| *Achnatherum calamagrostis* | G | <1 | 85.8 | 71.2 | 57.2 | 32.8 | 25.6 | 14.4 | 3.6 | 2.2 | 3 | | |
| | | 1-2 | 7.4 | 2.6 | 1 | 0.4 | 0.2 | | | | | | |
| | | > 2 | | | | | | | | | | | |
| *Aphyllantes monspeliensis* | G | <1 | 142.5 | 307.3 | 257 | 192.3 | 149.3 | 94.7 | 51.5 | 21.3 | | | |
| | | 1-2 | 7.7 | 1.7 | 2.2 | 1.3 | | | | | | | |
| | | > 2 | | | | | | | | | | | |

Table 2: Results of the Kruskal-Wallis test (test statistic H and probability value *p*) for root area ratio (RAR) differences with depth within each species. RAR significantly decreases with depth for all investigated species.

| | *Pinus nigra* | *Quercus pubscens* | *Genista cinerea* | *Thymus serpyllum* | *Achnatherum calamagrostis* | *Aphyllantes monspeliensis* |
|---|---|---|---|---|---|---|
| H | 25.5 | 31.05 | 25.7 | 6.72 | 22.3 | 27.2 |
| *p* | <0.000 | <0.000 | 0.007 | 0.034 | 0.004 | <0.000 |

Table 3

Click here to download Table: Table 3.doc

**Table 3:** Results of the Kruskal-Wallis test (test statistic H and probability value *p*) for root area ratio (RAR) and root reinforcement (ΔS) differences between the six species studied (*P. nigra*, *Q. pubescens*, *G. cinerea*, *T. serpyllum*, *A. calamagrostis* and *A. monspeliensis*) and between growth forms (trees, shrubs and grasses).

| | Depth (m) | 0.05 | 0.10 | 0.15 | 0.20 | 0.25 | 0.30 | 0.35 | 0.40 |
|---|---|---|---|---|---|---|---|---|---|
| RAR | | | | | | | | | |
| Species | | | | | | | | | |
| | H | 5.81 | 7.31 | 1.92 | 8.88 | 8.31 | 5.31 | 6.40 | 2.40 |
| | *p* | 0.32 | 0.19 | 0.86 | 0.064 | 0.08 | 0.25 | 0.17 | 0.66 |
| Growth form | | | | | | | | | |
| | H | 2.65 | 2.12 | 0.34 | 3.43 | 0.99 | 3.51 | 4.90 | 2.29 |
| | *p* | 0.26 | 0.34 | 0.84 | 0.18 | 0.61 | 0.17 | 0.08 | 0.32 |
| ΔS | | | | | | | | | |
| Species | | | | | | | | | |
| | H | 20.49 | 20.14 | 17.89 | 18.42 | 14.93 | 10.28 | 8.24 | 7.2 |
| | *p* | 0.001 | 0.001 | 0.003 | 0.001 | 0.004 | 0.035 | 0.08 | 0.125 |
| Growth forms | | | | | | | | | |
| | H | 17.30 | 14.30 | 12.86 | 15.64 | 12.85 | 9.44 | 7.21 | 6.82 |
| | *p* | 0.000 | 0.000 | 0.001 | 0.000 | 0.001 | 0.008 | 0.027 | 0.033 |

Table 4: Parameters of the power law relationship between root tensile strength and root diameter. Significance levels: ns nonsignificant, *$p$<0.05, **$p$<0.001, ***$p$<0.0001. N is the number of valid tests.

| Species | N | $\alpha$ | $\beta$ | $R^2$ | $p$ |
|---|---|---|---|---|---|
| *Pinus nigra* | 25 | 12.41 | 0.69 | 0.50 | *** |
| *Quercus pubescens* | 14 | 17.37 | 0.63 | 0.73 | *** |
| *Genista cinerea* | 35 | - | - | - | ns |
| *Thymus serpyllum* | 23 | 14.67 | 0.76 | 0.58 | *** |
| *Aphyllantes monspeliensis* | 30 | 16.57 | 1.02 | 0.75 | *** |
| *Achnatherum calamagrostis* | 31 | 17.59 | 1.22 | 0.86 | *** |

Table 5

Click here to download Table: Table 5.doc

Table 5: Root tensile strength differences between species and growth form (ANCOVA, Tukey HSD test, α=0.05). Growth forms are tree (T), shrubs (S) and grasses (G). Letters indicate significant differences between species (column 2) and between growth forms (colum 4)

<table>
<tr><th>Species</th><th colspan="4">Significant differences</th><th>Growth form</th><th colspan="2">Significant differences</th></tr>
<tr><td>Pinus nigra</td><td>A</td><td></td><td></td><td></td><td rowspan="2">T</td><td rowspan="2">A</td><td></td></tr>
<tr><td>Quercus pubescens</td><td>A</td><td>B</td><td></td><td></td><td></td></tr>
<tr><td>Genista cinerea</td><td></td><td></td><td></td><td>D</td><td rowspan="2">S</td><td></td><td rowspan="2">B</td></tr>
<tr><td>Thymus serpyllum</td><td></td><td>B</td><td>C</td><td></td><td></td></tr>
<tr><td>Achnatherum calamagrostis</td><td></td><td></td><td>C</td><td>D</td><td rowspan="2">H</td><td></td><td rowspan="2">B</td></tr>
<tr><td>Aphyllantes monspeliensis</td><td></td><td></td><td></td><td>D</td><td></td></tr>
</table>

**Captions**

**Figure 1**: Localization map of the experimental site.

**Figure 2:** Root area ratio (RAR) distribution with depth for the six species studied.

**Figure 3:** Relationship between root tensile strength ($T_R$, MPa) and root diameter (D, mm) for the six species studied. Points represent the measured values of $T_R$ and curves represent the predicted $T_R$ from the parameters $\alpha$ and $\beta$ given in Table 4.

**Figure 4:** Soil reinforcement (Calculated ΔS in kPa) provided by the roots of the six species studied. Points represent the mean values of calculated ΔS at each depth.

**Figure 5:** Schematic representation of the three types of root systems studied. (A) Tap-like root system of juvenile trees (*P. nigra* and *Q. pubescens*) with a vigorous central vertical root and few fine laterals, (B) Tap-like root system of shrubby species (*G. cinerea* and *T. serpyllum*) with an identifiable larger central root and many thinner laterals and (C) heart root system of graminoïd-shaped herbaceous species (*A. calamagrostis* and *A. monspeliensis*) with many fibrous roots.

**Figure 6:** Schematic representation of the combined effect of trees, shrubs and herbaceous species for shallow slope stabilization at the early stages of plant development.

**Figure 1**

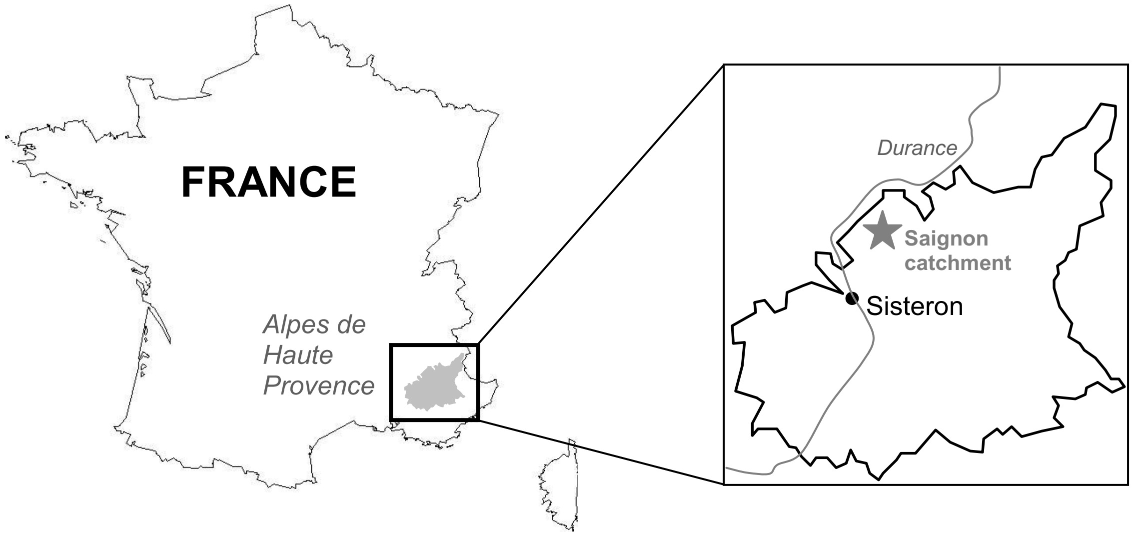

FRANCE
Alpes de
Haute
Provence
Durance
Saignon
catchment
Sisteron

**Figure 2**

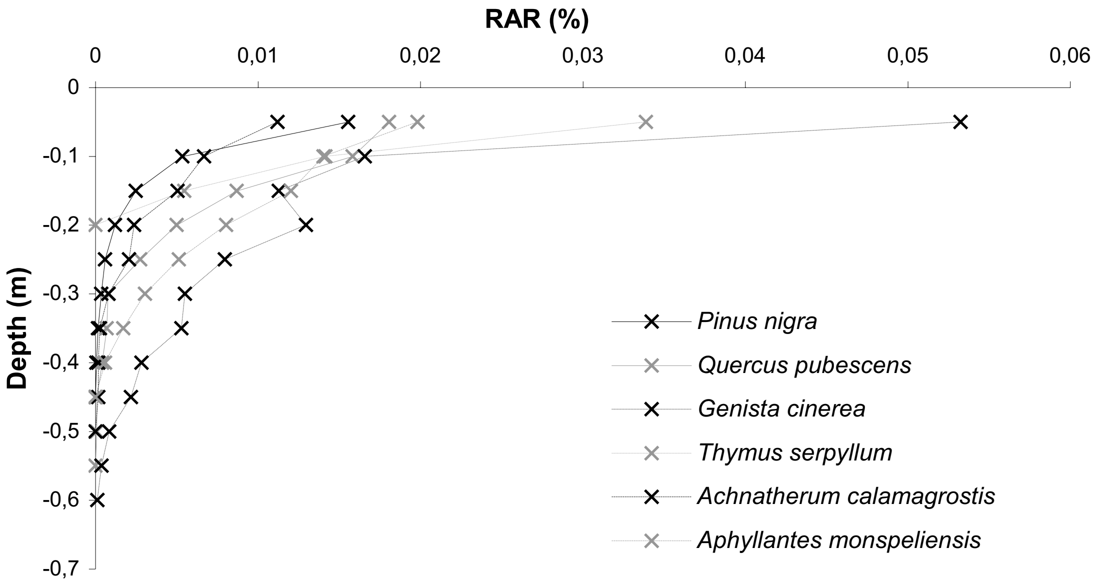
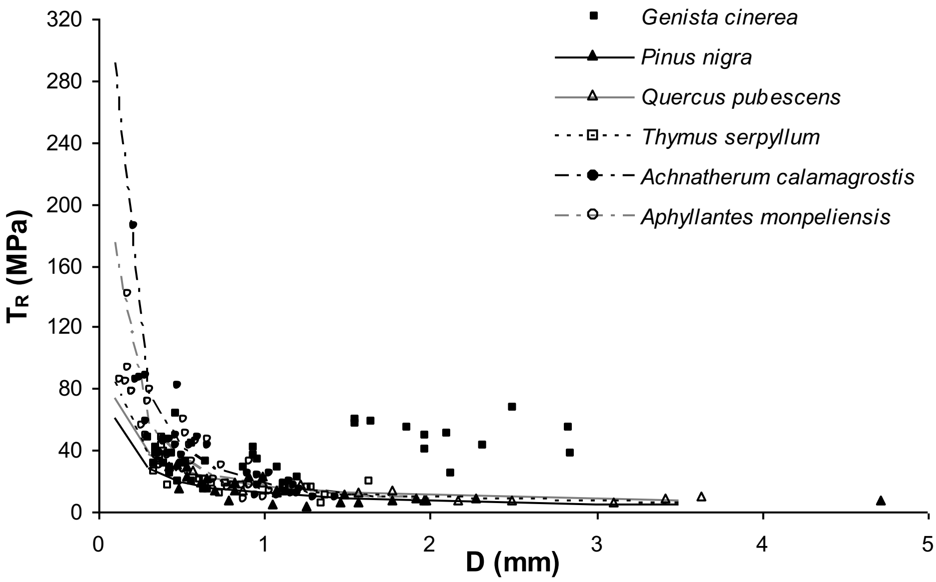

RAR (%)
0
0,01
0,02
0,03
0,04
0,05
0,06
Depth (m)
0
-0,1
-0,2
-0,3
-0,4
-0,5
-0,6
-0,7
Pinus nigra
Quercus pubescens
Genista cinerea
Thymus serpyllum
Achnatherum calamagrostis
Aphyllantes monspeliensis

**Figure 3**



Genista cinerea
Pinus nigra
Quercus pubescens
Thymus serpyllum
Achnatherum calamagrostis
Aphyllantes monpeliensis
T_R (MPa)
D (mm)
0
40
80
120
160
200
240
280
320
0
1
2
3
4
5

**Figure 4**

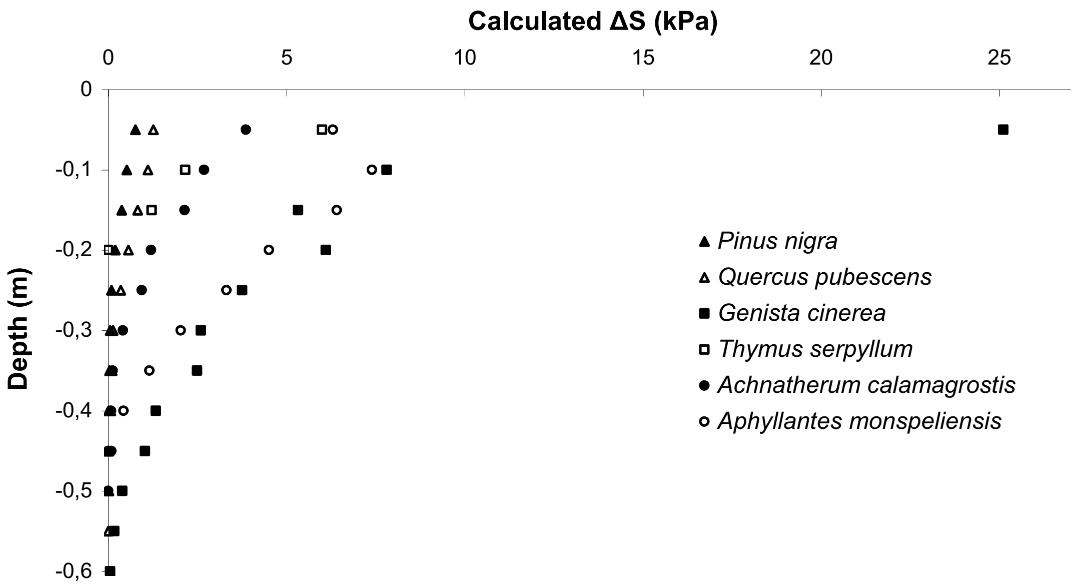

Calculated ΔS (kPa)
0
5
10
15
20
25
0
-0,1
-0,2
-0,3
-0,4
-0,5
-0,6
Depth (m)
Pinus nigra
Quercus pubescens
Genista cinerea
Thymus serpyllum
Achnatherum calamagrostis
Aphyllantes monspeliensis

**Figure 5**

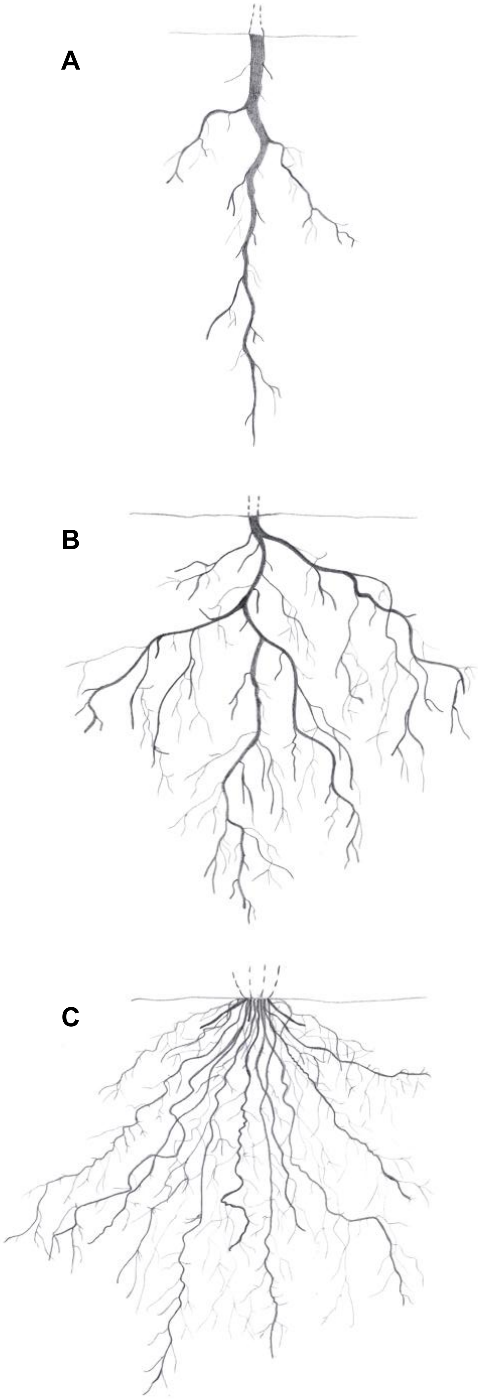
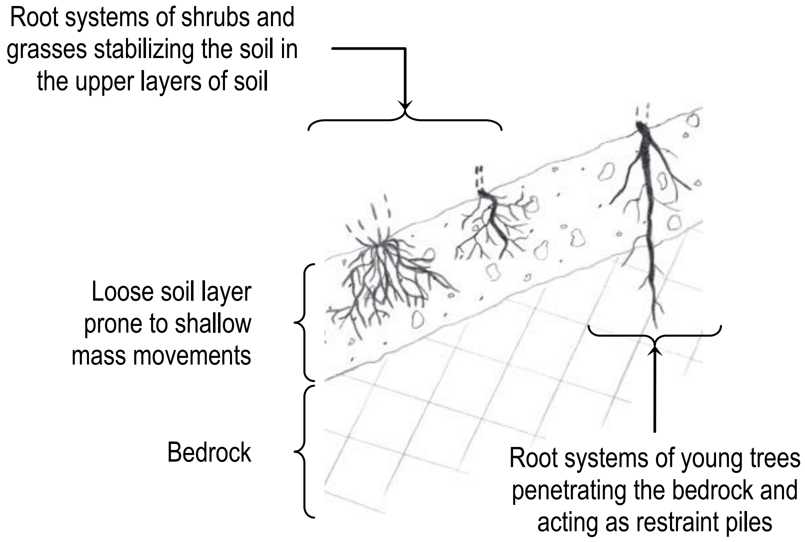


**Figure 6**



Root systems of shrubs and grasses stabilizing the soil in the upper layers of soil
Loose soil layer prone to shallow mass movements
Bedrock
Root systems of young trees penetrating the bedrock and acting as restraint piles