Root Characteristics of Herbaceous Species for Topsoil Stabilization in Restoration Projects

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Full title: Root characteristics of herbaceous species for topsoil stabilization in restoration projects

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Short title: ROOTS OF HERBACEOUS SPECIES FOR TOPSOIL STABILIZATION

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Abstract

Quarries are highly heterogeneous and constraining environments because of man-induced disturbances associated with soil erosion and shallow mass movements. Recognizing the importance of plant root systems to overcome stability problems, we investigated the contributions of three different herbaceous species typical of calcareous grasslands, i.e., *Anthyllis vulneraria*, *Bromus erectus* and *Stachys recta*, to the stability of the superficial layers of dump deposits at limestone quarries in the Botticino extractive basin (Lombardy, Italy). We analysed i) the root mechanical properties and root diameter distributions of the selected species and estimated ii) the lateral root reinforcement they can provide through the Fiber Bundle Model. To assess the effective contribution of a species to the topsoil stabilization, we implemented the results obtained in a stability model based on the ordinary method of slices. Our results showed that using species such as *B. erectus* and *S. recta* with a density of 100 plants/m^2 guarantees a better stability of the superficial layers.

Key words

Bromus erectus, *Anthyllis vulneraria*, *Stachys recta*, root reinforcement, topsoil stability

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1 Introduction

Landscape in limestone quarries affected by long-lasting extractive activities is often deeply altered and covered with only sparse vegetation. This pattern is especially true at the foot of quarry fronts where waste materials (mainly consisting of stone fragments) are dumped in inactive areas (Gentili *et al*., 2011; Gilardelli *et al*., 2015). Dump deposits usually deter the revegetation process and can remain bare for long periods of time because of their undesirable chemical and physical properties (Gilardelli *et al*., 2016b).

The question of surface stabilization after extractive activities has been previously considered in literature. Since the mid-1990s, the application of geomorphic principles to land reclamation after surface mining (Bugosh & Eckels, 2006) has been reported in the literature, mostly from Australia, Canada and the USA, as a suitable tool to control soil erosion in restoration project (Martín-Duque *et al.*, 2010; Espigares *et al*., 2011). In general terms, the geomorphological approach represents the best way to manage landscape reconstruction because it aims to reproduce the final step of the erosion/deposition process, when no more soil movement happens. At the same time, this approach is more difficult to be applied in practice because the complexity of the shape that would be achieved (Hancock *et al*., 2003). Traditional restoration strategies, instead, suggest to divide the slope in inclined surfaces separated by benches. This approach has the limit to generate high erosion rates and shallow soil stability problems, that must be taken into account during the restoration process.

The presence of vegetation can mitigate the erosion phenomena and improve the surface stability of banks. Various authors have in fact demonstrated that the root systems of herbaceous, shrub and tree species play a key role in both improving slope stability (Mafian *et al*., 2009; Simon & Collison, 2002; Rickson *et al*., 2006; Tosi, 2007; Burylo *et al*., 2011) and controlling erosion and biogeochemical cycles (Gyssels *et al*., 2005, De Baets *et al*., 2007; Carbutt & Edwards, 2015).

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Roots may influence the soil hydrological features by forming macropores within the soil and controlling the infiltration rate and movement of water; thus, the roots drive the soil moisture content (Ziegler & Giambelluca, 1998; Bernini *et al*., 2003; Vergani & Graf, 2015). Likewise, roots improve the soil structure and, thereafter, enhance the stability of soil aggregates: this effect is of upmost importance to limit the soil erosion and to allow the establishment of a permanent vegetation cover (Burri *et al*., 2009; Podwojewski *et al*., 2014).

Roots also affect the soil mechanical properties by forming a binding network within the soil layer and by anchoring the superficial unstable soil layer to the deeper, more stable layer or to the bedrock (Waldron, 1977; Schmidt *et al*., 2001; Gyssels *et al*., 2005). The way vegetation contributes to the soil stability depends on the development and structure of the root system and, accordingly, varies with the plant morphogenetic features and soil structure (Bischetti *et al*., 2009), as well as plant species and root size (Waldron, 1977; Norris *et al*., 2008).

The three main mechanisms by which roots can mechanically reinforce the soil (generally defined as "root reinforcement") have been defined by Giadrossich *et al*. (2013). The first, and most efficient, is the basal reinforcement that roots provide when they cross the basal slip surface of a shallow landslide and reach the underlying stable layer. When roots do not reach the failure plane, their contribution to stability is reduced, which depends on the dimensions of the potential shallow landslide (Schwarz *et al*., 2010a). In this case, roots stabilize the soil through the so-called lateral reinforcement, the mobilization of root tensile strength and the compression force at the lateral surface of the landslide (tension crack). The third stabilizing mechanism is the stiffening of the soil material due to the roots in the sliding mass: this process is relevant when there is a strong interaction of neighbouring root systems.

While Gilardelli *et al*. (2015) suggested that many common herbaceous species with fast growth rates and specific traits may be suitable candidates for substrate stabilization in quarry areas, their effectiveness has not yet been fully investigated from the slope stability point of view. The contributions of roots to the control of landslides, riverbank stabilization and bioengineering interventions have indeed been evaluated mostly for tree and shrub species, and information concerning native herbaceous species is limited (Simon & Collison, 2002; Mattia *et al*., 2005; De Baets *et al*., 2008). To our knowledge, no studies have investigated the role of herbaceous species on soil stabilization for the restoration of the highly disturbed environment of quarry areas. Knowledge of the root system characteristics of herbaceous species is crucial for identifying pioneer species that may effectively enhance revegetation processes and promote topsoil stabilization. The advantage of using herbaceous species rather than shrub and wood species, is that they grow and establish rather quick and hence can cover these soils quickly, favouring natural succession. It is well known the competence of herbaceous plants on shrubs and planted seedlings, which stops ecological succession (Moreno de las Heras *et al*., 2008). On the contrary shrub and wood species are subject to high mortality ratio due to stress or disturbance such as plant transplanting, water lack, disease, insects, slope stability, etc. (Martínez-Garza *et al*., 2011; Anton *et al*., 2015; Gilardelli *et al*., 2015). During restoration actions, herbaceous species can be established at relatively lower economic cost (Gilardelli *et al*., 2016b). The principal objective of the present study is to evaluate the ability to promote the superficial soil stabilization by three herbaceous species (*Bromus erectus* Huds., *Stachys recta* L. and *Anthyllis vulneraria* L.), which show different types of root systems. The applied objective is to promote the superficial soil stabilization of quarry dump deposits after their abandonment on the limestone quarries of the Botticino extractive basin (Lombardy, Italy).

In particular, we aim to answer the following questions: how do the differences in root characteristics of the three studied herbaceous species affect the soil reinforcement? and is the root reinforcement provided by the selected species effective for topsoil stabilization in restoration projects? Thus, we provide useful information to select the most suitable species for quarry restoration.

2 Materials and methods

2.1 Study area and selected species

The study area is located in the Botticino basin, in a hilly area (180-650 m a.s.l.) of the Brescia Province (Lombardy). This area represents the second most important extractive basin in Italy, containing over a hundred working quarries. The area is known worldwide for the extraction of the famous "Botticino Marble" limestone. The climate is continental, with cold and dry winters (mean annual temperature: 13.5°C) and rainy springs and autumns (mean annual precipitation: 1026.13 mm). The local lithology is composed of limestone and karst rocks of the "Corna" formation, with calcareous and breccia facies (Servizio Geologico d'Italia, 2008). The vegetation that grows in the surroundings of the quarries is mainly copse woodlands dominated by *Quercus pubescens* Willd; *Ostrya carpinifolia* Scop. and *Fraxinus ornus* L. are abundant. However, these native woodlands might be locally replaced by planted woodlands dominated by *Castanea sativa* Mill.

Most restoration projects for the quarries of the Botticino extractive basin include landform remodelling and soil preparation before the revegetation phase. Generally, a homogeneous topsoil with an average thickness from 50 cm to 1 m is created by using waste material deriving from local quarry activities. The target vegetation types during restoration refer to *Quercus pubescens* and *Ostrya carpinifolia* woodlands (*Quercetalia pubescentis)* as well as to natural/semi-natural arid grassland (*Festuco-Brometalia* community) for open stands. In the work of Giladelli *et al*. (2016b) several methods or revegetation applied in the Botticino extractive basin are described in detail: a) spontaneous succession (passive method); b) seeding of hayseed; c) seeding of commercial seed mixtures.

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In this study, the restored area was characterized by terraces where the flat surface was at a maximum of 5° slope between steep slopes up to 45° (Fig. 1).

To evaluate the contribution of the vegetation to the topsoil stabilization, we selected three herbaceous species with different types of root systems: *A. vulneraria*, *B. erectus*, and *S. recta*. All of them usually grow in arid and dry environments, including in the dump deposits of the Botticino extractive basin, where they characterize different phases of the spontaneous revegetation process (Table 1).

Anthyllis vulneraria (Fabaceae) is a perennial, short basal herb (H scap) of 8-40 cm that prefers arid and dry environments and basic or neutral-basic substrates, even nutrient-poor substrates, such as arid grasslands (Pignatti, 1982; Pignatti *et al*., 2005). Its root system consists of one main tap root and several thinner lateral roots, with some mycorrhizae. Within the Botticino extractive basin, it is usually absent during the initial and intermediate phases of recolonization; however, it is present in the last stage. This species is characteristic of the local grasslands and may be used as a reference for the success of restoration (Gilardelli *et al*., 2016a).

Bromus erectus (Poaceae) is a perennial tussock (H caesp) of 40-60 cm that develops in arid and dry environments on nutrient-poor calcareous substrates, such as arid grasslands (Pignatti, 1982; Pignatti *et al*., 2005). The root system is fasciculated and composed of thick, dense and fibrous primary roots. Within the Botticino extractive basin, it is usually present at later phases of recolonization, but it is a typical species of the local grasslands that can be used as a reference for the success of restoration efforts (Gilardelli *et al*., 2016a).

Stachys recta (Lamiaceae) is an erect, leafy, perennial herb (H scap) of 20-40 cm. It is found in arid and dry environments and highly basic substrates, even in nutrient-poor ones, such as rocks, heaps of stones and arid grasslands (Pignatti 1982; Pignatti *et al.*, 2005). The root system is characterised by a main tap root and several lateral roots. Within the Botticino extractive basin, it is present during all the phases of plant recolonization after extraction, especially on recent dump deposits abandoned in the previous 1-10 years (Gilardelli *et al.*, 2016a).

2.2 Modelling the stability of reconstructed slope

In civil engineering, the classical methods for slope stability analysis are based on the concept of "limit equilibrium" (Lu & Godt, 2013). A slope is stable if the shear stresses acting along a mass of soil over a sliding surface are less than the shear strengths (i.e., resisting forces). Otherwise, the slope collapses. The factor of Safety, FoS, defines this equilibrium as the following ratio:

— (1)

where τ_f is the shear strength, and τ_d is the shear stress. The shear strength behaviour of a slope is commonly modelled by the Mohr Coulomb failure criterion:

(2)

Eq. 2 means that the effective normal stress, σ', due, in first approximation, to the weight of the mobilized volume of soil generates shear strength through the soil. The effective cohesion, c', and the internal friction angle, ϕ', are two parameters that describe the geomechanical properties of soils (i.e., how they react to force solicitations).

The shear stress, instead, is related to the component of soil weight acting parallel to the sliding surface and is the driving force that induces the sliding phenomena.

In a two dimensional representation of the slope, defining the geometry of the sliding surface is the first step of the stability analysis. In most practical cases, the potential failure plan is circular. Then, the sliding area is divided into vertical slices of the same width, and the force analysis is applied (Fig. 2). Among the different methods currently available to consider for forces acting on the sliding volumes, the "ordinary method" (Fellenius, 1927) provides the most conservative factor of safety and, for that reason, can be used for a preliminary analysis under the design process (Burman *et al.*, 2015).

The factor of safety (FoS) is then evaluated as follows:

(3)

Where, l_n is the width of the slice, W_n is the weight of the slice, γ_w is the volumetric weight of the water, h is the local elevation of the water table with respect to the sliding surface, α is the local angle of the sliding surface, m is the total number of slices, and n is a counter.

The presence of vegetation is included in eq. 3 by the introduction of an additive term called "root reinforcement", c_r (originally named "root cohesion"; see Waldron, 1977; Wu *et al.*, 1976 and 1979). Root reinforcement can be estimated analysing the morphology and the mechanical properties of the root elements as explained in the following section.

2.3 Root reinforcement evaluation

Root reinforcement (C_r) can be estimated by the application of several models taking into account mainly 1) the root distribution along the soil profile and 2) the ultimate resisting force obtained before the rupture of each root (Wu *et al*., 1976; Waldron, 1977; Pollen & Simon, 2005; Schwarz *et al*., 2010b).

In this study, we chose the Fiber Bundle Model, FBM (Pollen & Simon, 2005) because it is considered a reference estimator of the mechanical contribution of plant roots (Docker & Hubble, 2008; Bischetti *et al*., 2009; Mickovski *et al*., 2009; Ji *et al*., 2012; Mao *et al.*, 2012). In addition, this model can be implemented in a simple way and only requires a small number of parameters to be calculated.

In the most simplified condition, when all the roots are assumed to break at the same time, according to Wu (1976) and Waldron (1977 and 1981), the C_r factor can then be determined as follows:

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(6)

where N is the total number of roots crossing the shear reference area *a*, and F_i is the maximum tensile force of each root. Note that F_i varies according to mechanical properties and diameter of each single root.

The condition of simultaneous breakage of all roots is poorly realistic, and the FBM approach (Pollen & Simon, 2005) was introduced to account for the progressive failure of roots. The method considers different increasing steps of load and removes from the list of the intact roots, those roots that have an ultimate stress at failure lower than the applied loading force. At each time, certain roots fail as their resistance threshold value is reached; the applied load is then redistributed to the remaining intact roots at the following time step, causing further root ruptures until the remaining root bundle reaches an equilibrium. At this point, an increment of load is applied, and the process repeats until the whole root bundle has broken.

The root reinforcement is exerted by roots that cross both the lateral and the basal surfaces of the sliding volume, which gives the lateral, c_{r_l}, and the basal, c_{r_b}, root reinforcement, respectively.

Due to the relatively shallow root systems of the considered herbaceous species (most of the roots are found in the first 30 cm of soil, Fig. 3), we consider here only the contribution of the lateral reinforcement and null basal reinforcement (Schwarz *et al*., 2012).

2.3.1 Sampling strategy to evaluate the root reinforcement

The root distribution and the root tensile force data, required to apply the FBM, were obtained for the three selected species, whose root systems are shown in Fig. 3.

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For each species, we collected 25 individuals for the root mechanical properties determination and 10 individuals with a soil parallelepiped that encompassed the majority of the root system (30 depth x 15 x 15 cm) for the root distribution determination, as 75% of the root biomass is commonly located in the first 30 cm of soil (Jackson *et al*., 1996). All sampling was conducted between July and August 2012 to avoid any effect of temporal variability. Before collection, we also counted or measured a) the number of stems, b) the number of rosettes, c) the number of mycorrhizae, c) the height of the stems, d) the number of leaves in each stem (for *B. erectus* and *S. recta*)/rosette (for *A. vulneraria*), e) the maximum depth of the root system (cm) and f) the maximum lateral extension of the root system. Individuals of *A. vulneraria* were collected from dump deposits of a working quarry (coordinates Gauss-Boaga: 1607763-5047960; altitude: 641 m a.s.l.; aspect: 69°; slope: 26°) characterized by high stoniness (50%, with stones of 1-60 cm). The vegetation at this location consisted of ruderal species that are typical of the pioneer phases of revegetation process, with a low vegetation cover (20%) consisting of only shrub (13%) and herb (7%) layers. Individuals of *B. erectus* and *S. recta* were sampled at similar dump deposits (coordinates: 1607763-5047960; altitude: 219 m a.s.l.; aspect: 212°; slope: 41°), with low stoniness (10%, with stones of 1-30 cm), high rockiness (50%) and low vegetation cover (20%) consisting of only shrub (8%) and herb (12%) layers.

2.3.2 Tensile strength tests

We gently separated the collected roots from the soil by hand. We repeatedly washed the roots with jets of water and stored them in a 15% alcohol solution to prevent the growth of mould and microbial degradation (Mattia *et al*., 2005). As soon as possible, we conducted 421 tensile force tests on 15-cm-long root samples after we measured the diameter at the midpoint and at the endpoints. We analysed 35 root samples of *A. vulneraria*, 262 samples of *B. erectus* and 124 samples of *S. recta*. Differences in the number of analysed samples depended on the different root architectures of the three species; when possible, roots were chosen according to the proportion of roots in each root diameter class. We performed these tests using the Stable Micro System TA Hd Plus apparatus (load cell of 500 N, noise of 0.01%) at the CIRA Laboratory of the University of Milan; two non-serrated clamps specifically developed by the Institute of Agricultural Hydraulics of the University of Milan were used.

Considering that the root tensile strength increases from 8% to 20% when the displacement rate is increased rapidly from 10 to 400 mm min^{-1} (Cofie & Koolen, 2001), we used a constant speed of 10 mm min^{-1}, according to previous studies (Mattia *et al*., 2005). We did not include the results for samples that broke in close proximity to the clamps (50 tests, i.e., 11.88% of the total tests) because these breaks were most likely associated with the presence of damage to the root structure (Cofie & Koolen, 2001; Mattia *et al*., 2005; De Baets *et al*., 2008).

Data were acquired at 200 Hz and then processed using the Texture Exponent 32 software (Stable Micro Systems, Vienna Court, UK).

The relationship between root tensile force F (N) and root diameter d (mm) can be expressed by a power law: $F = a\, d^b$ (Vergani *et al*., 2012).

We used the analysis of covariance (ANCOVA), with the root diameter as the covariant factor, to test the differences among the tensile forces between *S. recta* and *A. vulneraria*, as these roots have a broader range of diameters.

Before running the ANCOVA, we log-transformed the data. To test the normality of the data at the 1% significance level, we performed the Kolmogorov-Smirnov test (ks-test).

The tensile force of *B. erectus* was compared with the other species by considering the values in the classes of diameter < 0.5 mm and between 0.5 and 1 mm. As these data were not normally or log-normally distributed, a non-parametric test (Mann Whitney test) was used to compare the median value of tensile strength in each diameter class.

The mechanical properties of the selected species have also been expressed in terms of the tensile strength (Tr, Mpa) - diameter (d, mm) relationship: $Tr = a\ d^b$, to compare the results with the available literature (Table 3). The tensile strength can be obtained by dividing the root tensile force, F, by the root diameter, d.

All the analyses were performed with the open source software R (R Core Team, 2014).

2.3.3 Root diameters distribution characterization

We cleaned and photographed the root system of each plant using a white sheet as background. In order to reduce the distortion error of the different root pictures we rectified and scaled the pictures with a Geographic Information System, GIS (QGIS), using a graph paper square of 10 x 10 mm as a background reference (Fig. 3). The same software was used to digitize the roots. We recorded information about root diameters and their position along the explored soil profile. In particular, the diameter of roots at 5, 10 and 15 cm from the middle axes of the plant were used to evaluate the lateral root reinforcement.

We calculated the Root Area Ratio (RAR), which is defined as the ratio between the cross sectional area of all the roots intersecting the lateral surface and the area of the soil, for each species at each distance. This parameter provides a measure of the root density in the soil (Bischetti *et al*., 2005).

2.4 Application to a test case

To assess the effective contribution to the slope stability of the three species studied, we performed a stability analysis applied to a simplified topographic profile that reproduces the condition showed in Fig. 1. The "ordinary method of slices" model (Fellenius, 1927) was used to predict the stability of the slope under different conditions (see par. 2.2).

The analysed condition is represented by a bank of 45° slope and 5 m height. The soil properties were internal friction factor, ϕ', equal to 39.2°, the soil cohesion, c', equal to 0 kPa under the hypothesis of soil near to saturation along the sliding surface and soil density equal to 1579 kg/m^3.

Because the actual sliding surface was unknown, different centres and radii of the circular sliding surface were tested.

Different vegetation coverages were considered: 1) bare soil and 2) three monospecific stands of *A. vulneraria, B. erectus* and *S. recta* with a density of 100 plants/m^2 uniformly distributed over the surface.

3 Results

3.1 Root mechanical properties

The diameters of the tested roots as well as the number of valid tests are reported in Table 2. The root tensile force - diameter relationships for the three species are reported in Fig. 4. The root tensile forces of *A. vulneraria* and *S. recta* increased with the root diameters according to the power law curve (Fig. 4). Their root tensile forces were not found to be significantly different at the 0.5 level of significance (ANCOVA, p = 0.064). For *B. erectus*, all the root diameters were smaller than 1 mm; thus, even if the power law was still significant, extrapolating the values for higher diameter classes was misleading and illogical, as the range of diameters of this species' root system is extremely limited. *B. erectus* tensile force was significantly higher than the tensile forces of *S. recta* and *A. vulneraria* if we consider the diameter class 0-0.5 mm (Mann Whitney test, $p < 0.001$), while there were no significant differences for the diameter class 0.5-1 mm ($p > 0.1$).

3.2 Root diameters distribution

At a distance of 5 cm from the plant axis, *B. erectus* showed the highest number of roots (Fig. 5), closely followed by *S. recta*, whilst the lowest values were calculated for *A. vulneraria*. The fasciculate root system of *B. erectus* was mostly constituted by fine roots between 0.1 and 1.5 mm in diameter. *S. recta* was characterized by a large primary root (diameter >3 mm), and by secondary thinner roots with diameters between 0.1-2 mm. The root system of *A. vulneraria* was, in most cases, characterized by a tap root with few and thin lateral roots with diameters between 0.1 and 1 mm.

When further from the plant axis, i.e., from 10 cm to 15 cm from the plant axis (Table 4), *S. recta* had the highest number of roots because its root system is wider compared with the architecture of the other two species. This species is also the one that showed the highest number of roots with diameters higher than 1 mm, while the root system of the other two species mainly comprised roots smaller than 1 mm in diameter.

The Root Area Ratio (RAR, Table 3 and 4), was the highest for *Bromus erectus* at a distance of 5 cm and the highest for *Stachys recta* at distances of 10 and 15 cm.

3.3 Root reinforcement evaluation

At a 5 cm distance from the plant axis, *B. erectus* yielded the highest values of root reinforcement (0.00221 MPa) and *S. recta* the second highest (0.00213 MPa); in contrast, the degree of soil reinforcement provided by *A. vulneraria* was particularly low (0.00043 MPa). Considering a larger distance from the plant stem (10 and 15 cm), the reinforcement provided by *A. vulneraria* and *B. erectus* was negligible, while *S. recta* was still able to apply a certain degree of reinforcement (Table 4). It is important to note that the high value of reinforcement given by *A. vulneraria* at a distance of 15 cm (Table 4) was due to an outlier value of a single plant that had the tap root (diameter = 5 mm) intersecting the lateral area at 15 cm. The mean reinforcement value excluding this outlier would be zero.

3.4 Results from stability analysis

Under the condition of bare soil (i.e., without vegetation) and applying eq. 3, the results of the stability analysis are represented in Fig. 6A. Hypothetical sliding surfaces explore most of the bank section and reached a maximum depth of 18 m; however, instability conditions were concentrated in the most superficial part of the slope. The maximum depth of the unstable surface was between 0.06 m to 1.60 m, and the most unstable conditions were represented by the lowest FoS values that were obtained with the most superficial sliding surface (Fig. 6B). This result is in agreement with field evidence where soil movements were superficial (Fig. 1). The most unstable condition (FoS = 0.8) was, indeed, obtained with a maximum depth of 0.09 m.

By including the effect of vegetation, we considered that root reinforcement was bringing an additive cohesion to the soil. In the first case, we considered a uniform distribution of *A. vulneraria* plants with a distance between each plant of 10 cm (100 plants/m^2). This value is consistent with the density range reported for numerous herbaceous/grass species used in greening projects (Dunnet & Hitchmough, 2004) In this case, c_r was set to 0.43 kPa. This low reinforcement induces slow stability to the slope but the number of unstable sliding surfaces decreases by 37%, and the lowest FoS increases to 0.87.

If a uniform distribution of *B. erectus* was considered with the same distance between plants, as in case of *A. vulneraria,* the average root reinforcement was set to 2.21 kPa. The results of the stability analysis are shown in Fig. 6A. The number of unstable surfaces decreased significantly from 60 to 13 and the minimum FoS was equal to 0.94.

Finally, the effect of *S. recta* was considered. Under the same hypothesis as *B. erectus* and *A. vulneraria*, the root reinforcement was set to 2.13 kPa. The stability analysis showed a low number of critical sliding surfaces (13), and the lowest FoS was 0.94.

4 Discussion

The identification of the most suitable species for quarry restoration projects is crucial to ensure the success of human interventions on fully exploited dump deposits, especially where the overlap of "soil layers" with different characteristics may frustrate restoration efforts due to the inhibition of vegetation establishment (Gilardelli *et al*., 2016b).

Our results highlight that the root reinforcement of perennial herbaceous species, chosen among species that can be naturally found in quarry areas at different phases of spontaneous revegetation processes, *B. erectus*, *S. recta* and *A. vulneraria* in this study, is discriminating for their ability to stabilize the topsoil. In particular, the value of lateral reinforcement provided by roots on superficial "soil" layer stability could give useful indications for restoration purposes. The parameters of the root tensile strength - diameter (Tr - D) relationship were in the same range reported by other studies on different herbaceous species (Table 3). In this study, we choose to present our data in terms of a force (F) - diameter relationship instead of a tensile strength (Tr)- diameter relationship to avoid amplifying the uncertainty involved in the determination of diameters (Vergani *et al*., 2012), which can be relevant especially for fine and very fine roots.

The values of root reinforcement found for the considered species are also in the range reported in the literature for herbaceous species.

Our results showed that the fasciculate root system of *B. erectus* yielded the highest values of root reinforcement at 5 cm from the plant stem, due to the high number of fine roots (diameter mostly between 0.1 and 1.0 mm). The same is true for *S. recta*, which provides root reinforcement values close to *B. erectus* at the 5 cm distance.

Nevertheless, it is also important to consider the spatial distribution of root reinforcement because it was not spatially homogeneous and varied depending on the root system architecture and on the plant distributions (Schwarz *et al*., 2012). At longer distances from the plant axis, the species that provided the highest reinforcement values was *S. recta* because its root system is wider than those root systems of the other considered species. The use of a simple stability model was useful to understand the effect of the analysed species on slope stability.

Considering all the simulations, the effect of the vegetation is remarkable in all the cases. *A. vulneraria* induced stability on the most superficial landslides. Both *B. erectus* and *S. recta* gave the highest stabilization effect by reducing both the number of unstable surfaces and increasing the lowest FoS. At the same time, the effect of stabilization of the selected species is limited to the superficial soil while deeper layers must be stabilized in a proper way (gabion wall, stone or concrete wall, stepped boulders; see Morgan & Rickson 1995).

The data provided here give the first important quantitative information to improve the planning of quarry restoration efforts. Future research should be focused on the performance of development of different species in the field (coverage density by time) and the use of different methods of seeding and superficial soil protection.

It is however important to keep in mind that the capacity of the species to promote soil stability is not the only criteria to be considered in mining restoration. Also the other ecosystem services of the vegetation must be considered, and in particular is important to promote species which allow the starting of a revegetation processes without hindering the succession process towards more mature forms of vegetation complexes / plant communities (Moreno de las Heras *et al*., 2008).

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5 Conclusions

This study contributes to the knowledge of root reinforcement of herbaceous species that can be used in restoration projects of dump deposits of quarry areas to avoid problems of topsoil stability after the phase of soil preparation. The aim is the enhancement of vegetation establishment. Species-specific data are fundamental because the use of species with different types of root systems in restoration projects, inspired by natural revegetation dynamics, could ensure a more effective control of superficial mass movements. The use of species such as *B. erectus* and *S. recta*, with a density of 100 plants/ m^2, has been demonstrated to guarantee the stability of superficial layers in the short and long term.

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Table 1. Characteristics of the selected species

Species	**Family**	**Biological form**	**Height (cm)**	**Preferred substrate***	**Type of root**	**Presence within the Botticino extractive basin****
A. vulneraria	Fabaceae	short basal herb (H scap - scapose hemicryptophyte)	8-40	basic or neutral-basic substrates, even very nutrient-poor substrates, such as arid grasslands	one main tap root and several thinner lateral roots (only secondary), with some mycorrhizae	Presence at late succession stage, usually absent during the initial and intermediate phases of revegetation process; typical of the local grasslands Surrounded the quarry and can be used as a reference for the success of restoration efforts
B. erectus	Poaceae	tussock (H caesp - caespitose hemicryptophyte)	40-60	calcareous substrates that are nutrient-poor, such as arid grassland	fasciculated and composed of thick, dense and fibrous primary roots	
S. recta	Lamiaceae	erect, leafy herb (H scap - scapose hemicryptophyte)	20-40	highly basic substrates, even nutrient-poor ones, such as rocks, heaps of stones and arid grassland	a main tap root and several lateral roots (secondary and tertiary)	present during all the phases of revegetation process, especially on dump deposits abandoned in the previous 1-10 years

Data from: *Pignatti, 1982 and Pignatti *et al*., 2005; **Gilardelli *et al*., 2016a

Table 2. Parameters (a and b values) and R^2 values for the relationships among root tensile strength and root diameter

		A. vulneraria	*B. erectus*	*S. recta*
MORPHOLOGY				
Number of stems	Mean	8	64*	6
	St.dev	6	48*	5
Number of rosettes	Mean	5	0	0
	St.dev	4	0	0
Number of mycorrhizae	Mean	49	0	0
	St.dev	58	0	0
Height of the stems (cm)	Mean	6.00	54.01	50.03
	St.dev	2.55	10.35	11.91
Number of leaves in each stem/rosette	Mean	6	2	59
	St.dev	3	0	34
ROOT SYSTEM				
Maximum depth (cm)	Mean	16.62	26.82	24.48
	St.dev	5.83	10.83	11.21
Maximum lateral extension (cm)	Mean	13.85	20.04	17.62
	St.dev	5.26	3.66	3.30
Number of valid tensile tests		28/35	236/262	107/124
Root length (cm)	Mean	16.59	19.20	17.81
	St.dev	3.66	4.85	3.28
Mean diameter of all roots (mm)	Mean	0.98	0.29	1.24
	St.dev	1.13	0.10	1.30
Mean diameter of tested roots (mm)	Mean	0.86	0.29	1.02
	St.dev	0.98	0.10	1.10
Max. diameter of tested roots (mm)		3.50	0.84	5.30
Min. diameter of tested roots (mm)		0.05	0.07	0.07

*included 41 (± 27) sterile shoots

Table 3. Literature data for root tensile strength, RAR, and root cohesion of herbaceous species; the results of the present study are shown in bold. * RVR was reported for *A. vulneraria*, *B. erectus* and *S. recta*. Legend for authors: A: Schiechtl, 1980; B: Waldron, 1977; C: Wu, 1984; D: Mattia *et al*., 2005; E: de Baets *et al*., 2008.

Species	**D (mm)**	**Tr**			**RAR* (%)**	**Root cohesion (MPa)**	**Author**
		a	**B**	**mean (MPa)**			
Ammophila spp.						0.005-0.010	B
Ammophila spp.	<0.3				0.015-0.15		C
Anthyllis vulneraria	0.05-3.50	11.88	-0.81	55.19	0.0000275	0.00221	-
Atriplex halimus	1.9 (0.8)	73	0.6	57.2 (23.1)			D
Avenula bromoides	0.15–0.32	4.77	−1.52		0.0033		E
Brachypodium retusum	0.10–1.45	45.05	−0.61				E
Bromus erectus	0.07-0.84	33.30	-0.61	81.41	0.000132	0.00043	-
Helictotrichon filifolium	0.34–1.22	14.51	−1.08		0.0046		E
Herbaceous vegetation	<10				0.02-0.08		A
Hordeum vulgare	<0.5				0.002-0.008		B
Hordeum vulgare						0.001-0.0025	B
Juncus acutus	0.18–1.10	23.23	−0.89			0.244-0.304	E
Limonium supinum	0.34–3.90	33.82	−0.85		0.00125		E
Lygeum spartum	0.26–2.72	19.28	−0.68		0.002575		E
Lygeum spartum	1.3-1.7	60.7	1.3	37.8 (12.5)			D
Phragmites australis	0.10–7.91	34.29	−0.78				E
Piptatherum miliaceum	0.10–0.64	11.49	−1.77				E
Plantago albicans	0.21–2.55	16.75	−0.52				E
Stachys recta	0.07-5.30	15.27	-0.71	30.99	0.000104	0.00213	-
Stipa tenacissima	0.43–1.34	24.34	−0.61				E

Table 4. Mean values and standard deviations of lateral reinforcement and RAR at the three considered distances

Species	Distance (cm)	Mean cr lat (kPa)	Standard Deviation	N	Mean RAR	Standard Deviation RAR
A. vulneraria	5	0.43	0.88	10	2.7535E-05	3.91459E-05
	10	0.189555556	0.263845	10	1.51477E-05	2.1245E-05
	15	0.4	1.25	10	9.98229E-06	3.15668E-05
B. erectus	5	2.21	2.32	10	1.32E-04	6.55432E-05
	10	0.08	0.09	10	4.51364E-06	6.11906E-06
	15	0	0	10	0	0
S. recta	5	2.13	2.89	10	1.04E-04	8.70E-05
	10	0.76	1.60	10	4.31E-05	8.57E-05
	15	0.42	1.02	10	1.13E-05	2.62E-05

Fig. 1. The bank on a quarry at the Botticino basin

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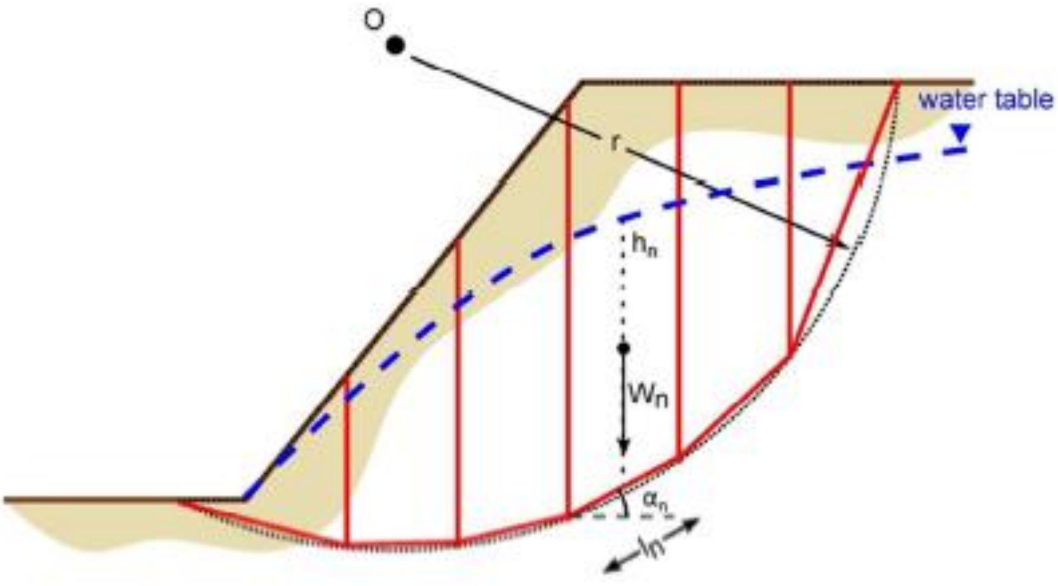

Fig. 2. Illustration of the ordinary method of slices for a finite slope (slope geometry, position of the sliding surface and rotation centre, subdivision in slices).

Fig. 3. Roots of a) *S. recta*, b) *B. erectus* and c) *A. vulneraria*

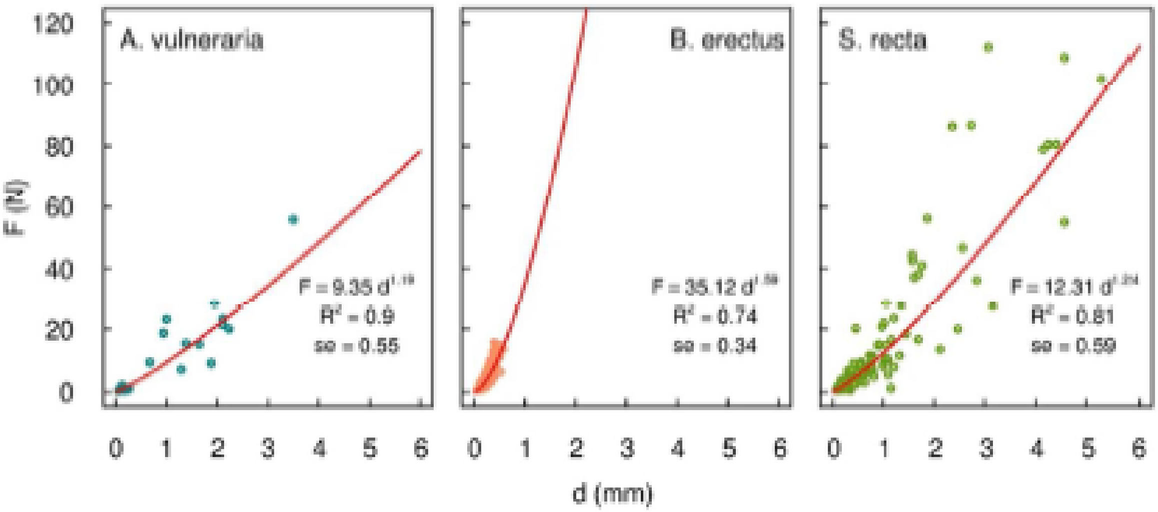

Fig. 4. Tensile force according to root diameter of *A. vulneraria*, *B. erectus* and *S. recta*

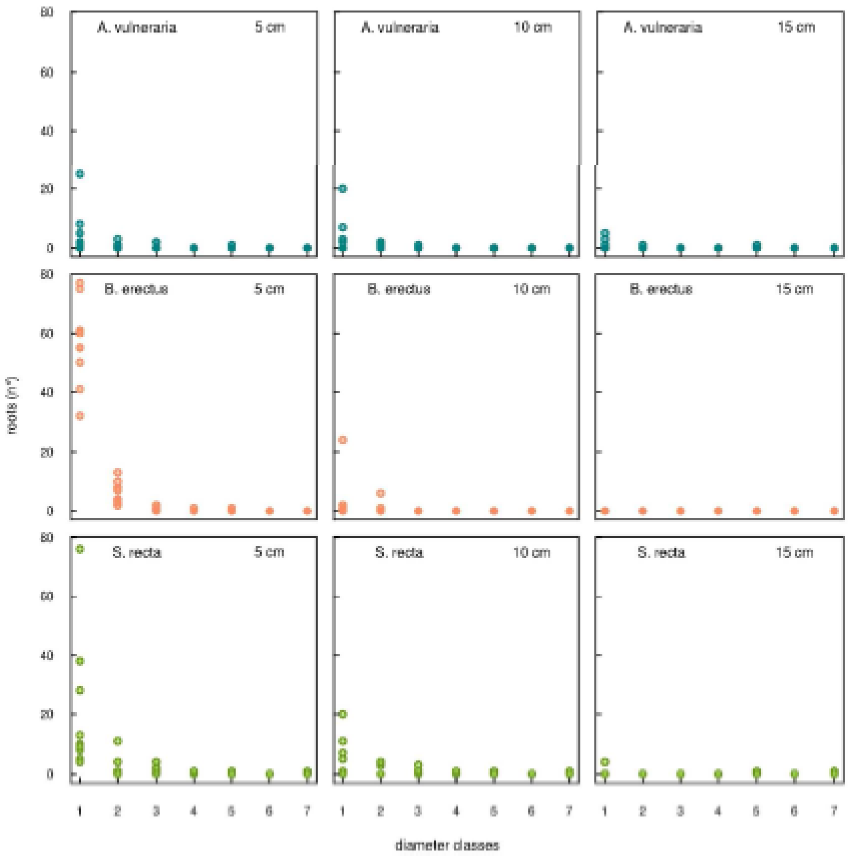

Fig. 5. Number of roots based on diameter classes (in different colors) of a) *A. vulneraria*, b) *B. erectus* and c) *S. recta* at the three distances from the plant *axis*

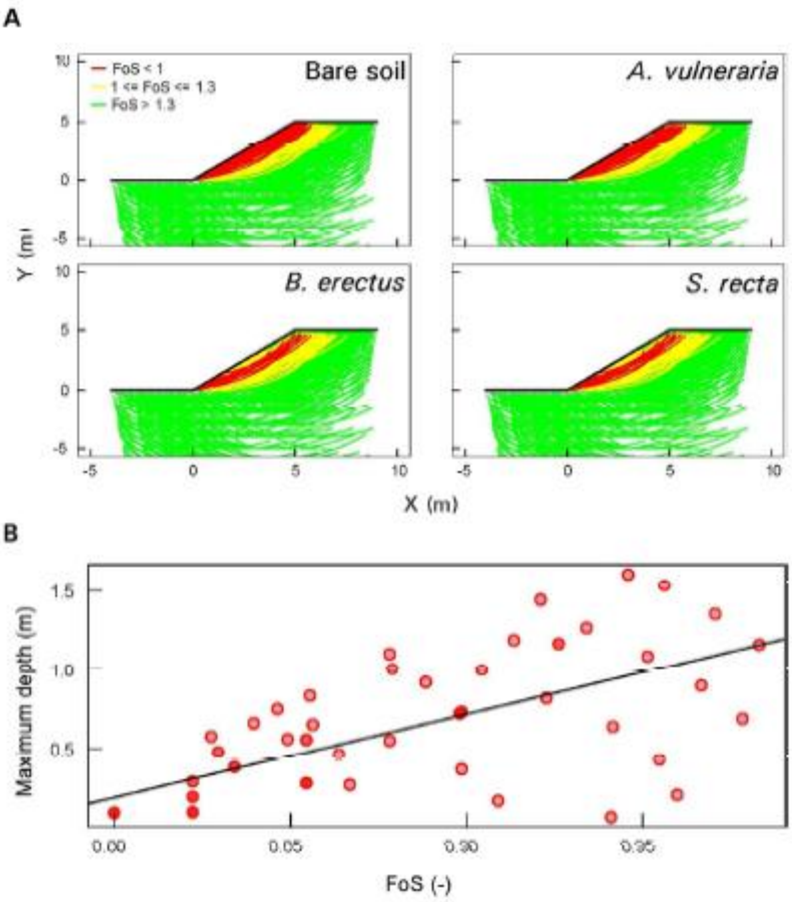

Fig. 6. A) Distribution of the tested sliding surfaces and their representation according to the FoS obtained by equilibrium analysis (green lines mean FoS greater than 1.3, yellow lines mean FoS between 1 and 1.3 included, and red lines mean FoS lower than 1): B) Relationship between the dimension of the sliding volume and the FoS. The most unstable condition is represented by the most superficial sliding surface (approximately 10 cm) in agreement with field evidence.