Root Characteristics of Herbaceous Species for Topsoil Stabilization in Restoration Projects
Federica Gilardelli, Chiara Vergani, Rodolfo Gentili, Anne Bonis, Pierre Chanteloup, Sandra Citterio, Enrico A. Chiaradia

To cite this version:

HAL Id: hal-01631557
https://hal-univ-rennes1.archives-ouvertes.fr/hal-01631557
Submitted on 7 Jun 2018

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
Full title: Root characteristics of herbaceous species for topsoil stabilization in restoration projects

Gilardelli Federica¹†, Vergani Chiara²†, Gentili Rodolfo¹, Bonis Anne², Chanteloup Pierre²,
Citterio Sandra¹, Enrico A. Chiaradia⁴

Short title: ROOTS OF HERBACEOUS SPECIES FOR TOPSOIL STABILIZATION

1. Dipartimento di Scienze dell’Ambiente e del Territorio e di Scienze della Terra, Università degli Studi di Milano - Bicocca, Piazza della Scienza 1, I-20126 Milano, Italy. E-mail addresses: gila.gilardelli@alice.it (Gilardelli F.), rodolfo.gentili@unimib.it (Gentili R.), sandra.citterio@unimib.it (Citterio S.)

2. Bern University of Applied Sciences - Langgasse 85, 3052 Zollikofen (CH). E-mail address: chiara.vergani@hotmail.com (Vergani C.)

3. UMR 6553 “ECOBIO” Université de Rennes 1 - CNRS, Avenue du Général Leclerc, Campus de Beaulieu, 35042 Rennes Cedex, France. E-mail addresses: anne.bonis@univ-rennes1.fr (Bonis A.), chanteloup.pierre@laposte.net (Chanteloup P.)

4. Dipartimento di Scienze Agrarie ed Ambientali, Università degli Studi di Milano – via Celoria 2, I-20133 Milano, Italy. E-mail address: enrico.chiaradia@unimi.it (Chiaradia E.)

† These authors contributed equally to this work

*Author for correspondence (phone +39 64482700; fax +39 64482996; e-mail: rodolfo.gentili@unimib.it)
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/m² guarantees a better stability of the superficial layers.

Key words

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

\[
\text{FoS} = \frac{\tau_f}{\tau_d}
\]

where \( \tau_f \) is the shear strength, and \( \tau_d \) is the shear stress. The shear strength behaviour of a slope is commonly modelled by the Mohr Coulomb failure criterion:

\[
\sigma' = c' \tan \phi'
\]

Eq. 2 means that the effective normal stress, \( \sigma' \), 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, \( \phi' \), 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
The factor of safety (FoS) is then evaluated as follows:

\[
\text{FoS} = \frac{l_n W_n}{\gamma_w l_n} + \frac{h}{\alpha} + \frac{1}{m} \sum_{n=1}^{m} c_r
\]  

Where, \( l_n \) is the width of the slice, \( W_n \) is the weight of the slice, \( \gamma_w \) is the volumetric weight of the water, \( h \) is the local elevation of the water table with respect to the sliding surface, \( \alpha \) 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:
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.
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, $\phi'$, 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).
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/ m², has been demonstrated to guarantee the stability of superficial layers in the short and long term.

Acknowledgments

The present work was funded by the Province of Brescia (Lombardy, Italy). Authors are grateful to Dr Pierangelo Barossi (Province of Brescia), Prof. Gian Battista Bischetti (University of Milano), Dr. Lorenzo Fongaro (DiSTAM - University of Milano), Prof. Mara Lucisano (DiSTAM - University of Milano) and Prof. Sergio Sgorbati (University of Milano-Bicocca) for their technical support to this research.

References


Quaderni della Scuola d’Ingegneria Naturalistica 2. Scuola Regionale di Ingegneria Naturalistica, Centro Regionale per la Flora Autoctona. 177 pages


Valori di indicazione secondo Ellenberg (Zeigerwerte) per le specie della Flora d’Italia.

Braun-Blanquetia 39: 1-97


DOI: 10.2136/sssaj2013.12.0511


DOI: 10.1029/2004WR003801


Table 1. Characteristics of the selected species

<table>
<thead>
<tr>
<th>Species</th>
<th>Family</th>
<th>Biological form</th>
<th>Height (cm)</th>
<th>Preferred substrate*</th>
<th>Type of root</th>
<th>Presence within the Botticino extractive basin**</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>A. vulneraria</em></td>
<td>Fabaceae</td>
<td>short basal herb</td>
<td>8-40</td>
<td>basic or neutral-basic substrates, even very nutrient-poor substrates, such as arid grasslands</td>
<td>one main tap root and several thinner lateral roots (only secondary), with some mycorrhizae</td>
<td>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</td>
</tr>
<tr>
<td><em>B. erectus</em></td>
<td>Poaceae</td>
<td>tussock (H caesp - caespitose hemicryptophyte)</td>
<td>40-60</td>
<td>calcareous substrates that are nutrient-poor, such as arid grassland</td>
<td>fasciculated and composed of thick, dense and fibrous primary roots</td>
<td></td>
</tr>
<tr>
<td><em>S. recta</em></td>
<td>Lamiaceae</td>
<td>erect, leafy herb</td>
<td>20-40</td>
<td>highly basic substrates, even nutrient-poor ones, such as rocks, heaps of stones and arid grassland</td>
<td>a main tap root and several lateral roots (secondary and tertiary)</td>
<td>present during all the phases of revegetation process, especially on dump deposits abandoned in the previous 1-10 years</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>MORPHOLOGY</th>
<th>A. vulneraria</th>
<th>B. erectus</th>
<th>S. recta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of stems</td>
<td>Mean 8</td>
<td>64*</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>St.dev 6</td>
<td>48*</td>
<td>5</td>
</tr>
<tr>
<td>Number of rosettes</td>
<td>Mean 5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>St.dev 4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Number of mycorrhizae</td>
<td>Mean 49</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>St.dev 58</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Height of the stems (cm)</td>
<td>Mean 6.00</td>
<td>54.01</td>
<td>50.03</td>
</tr>
<tr>
<td></td>
<td>St.dev 2.55</td>
<td>10.35</td>
<td>11.91</td>
</tr>
<tr>
<td>Number of leaves in each stem/rosette</td>
<td>Mean 6</td>
<td>2</td>
<td>59</td>
</tr>
<tr>
<td></td>
<td>St.dev 3</td>
<td>0</td>
<td>34</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ROOT SYSTEM</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum depth (cm)</td>
<td>Mean 16.62</td>
<td>26.82</td>
<td>24.48</td>
</tr>
<tr>
<td></td>
<td>St.dev 5.83</td>
<td>10.83</td>
<td>11.21</td>
</tr>
<tr>
<td>Maximum lateral extension (cm)</td>
<td>Mean 13.85</td>
<td>20.04</td>
<td>17.62</td>
</tr>
<tr>
<td></td>
<td>St.dev 5.26</td>
<td>3.66</td>
<td>3.30</td>
</tr>
<tr>
<td>Number of valid tensile tests</td>
<td>Mean 28/35</td>
<td>236/262</td>
<td>107/124</td>
</tr>
<tr>
<td>Root length (cm)</td>
<td>Mean 16.59</td>
<td>19.20</td>
<td>17.81</td>
</tr>
<tr>
<td></td>
<td>St.dev 3.66</td>
<td>4.85</td>
<td>3.28</td>
</tr>
<tr>
<td>Mean diameter of all roots (mm)</td>
<td>Mean 0.98</td>
<td>0.29</td>
<td>1.24</td>
</tr>
<tr>
<td></td>
<td>St.dev 1.13</td>
<td>0.10</td>
<td>1.30</td>
</tr>
<tr>
<td>Mean diameter of tested roots (mm)</td>
<td>Mean 0.86</td>
<td>0.29</td>
<td>1.02</td>
</tr>
<tr>
<td></td>
<td>St.dev 0.98</td>
<td>0.10</td>
<td>1.10</td>
</tr>
<tr>
<td>Max. diameter of tested roots (mm)</td>
<td>3.50</td>
<td>0.84</td>
<td>5.30</td>
</tr>
<tr>
<td>Min. diameter of tested roots (mm)</td>
<td>0.05</td>
<td>0.07</td>
<td>0.07</td>
</tr>
</tbody>
</table>

*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.

<table>
<thead>
<tr>
<th>Species</th>
<th>D (mm)</th>
<th>Tr</th>
<th>RAR* (%)</th>
<th>Root cohesion (MPa)</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Ammophila spp.</em></td>
<td>&lt;0.3</td>
<td>0</td>
<td>0.015-0.15</td>
<td>0.005-0.010</td>
<td>B</td>
</tr>
<tr>
<td><em>Anthyllis vulneraria</em></td>
<td>0.05-3.50</td>
<td>11.88</td>
<td>-0.81</td>
<td>55.19</td>
<td>0.0000275</td>
</tr>
<tr>
<td><em>Atriplex halimus</em></td>
<td>1.9 (0.8)</td>
<td>73</td>
<td>0.6</td>
<td>57.2 (23.1)</td>
<td>D</td>
</tr>
<tr>
<td><em>Avenula bromoides</em></td>
<td>0.15-0.32</td>
<td>4.77</td>
<td>1.52</td>
<td>-</td>
<td>0.0033</td>
</tr>
<tr>
<td><em>Brachypodium retusum</em></td>
<td>0.10-1.45</td>
<td>45.05</td>
<td>0.61</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><em>Bromus erectus</em></td>
<td>0.07-0.84</td>
<td>33.30</td>
<td>0.61</td>
<td>81.41</td>
<td>0.000132</td>
</tr>
<tr>
<td><em>Brachypodium filifolium</em></td>
<td>0.34-1.22</td>
<td>14.51</td>
<td>1.08</td>
<td>-</td>
<td>0.0046</td>
</tr>
<tr>
<td><em>Herbaceous vegetation</em></td>
<td>&lt;10</td>
<td>0</td>
<td>0.02-0.08</td>
<td>0.002-0.008</td>
<td>A</td>
</tr>
<tr>
<td><em>Hordeum vulgare</em></td>
<td>&lt;0.5</td>
<td>0</td>
<td>0.008</td>
<td>-</td>
<td>B</td>
</tr>
<tr>
<td><em>Juncus acutus</em></td>
<td>0.18-1.10</td>
<td>23.23</td>
<td>-0.89</td>
<td>0.001-0.0025</td>
<td>0.0025</td>
</tr>
<tr>
<td><em>Limonium supinum</em></td>
<td>0.34-3.90</td>
<td>33.82</td>
<td>-0.85</td>
<td>0.00125</td>
<td>E</td>
</tr>
<tr>
<td><em>Lygeum spartum</em></td>
<td>0.26-2.72</td>
<td>19.28</td>
<td>-0.68</td>
<td>0.002575</td>
<td>E</td>
</tr>
<tr>
<td><em>Phragmites australis</em></td>
<td>1.3-1.7</td>
<td>60.7</td>
<td>1.3</td>
<td>37.8 (12.5)</td>
<td>D</td>
</tr>
<tr>
<td><em>Piptatherum miliaceum</em></td>
<td>0.10-7.91</td>
<td>34.29</td>
<td>-0.78</td>
<td>-</td>
<td>E</td>
</tr>
<tr>
<td><em>Plantago albicans</em></td>
<td>0.10-0.64</td>
<td>11.49</td>
<td>1.77</td>
<td>-</td>
<td>E</td>
</tr>
<tr>
<td><em>Stachys recta</em></td>
<td>0.07-5.30</td>
<td>15.27</td>
<td>-0.71</td>
<td>30.99</td>
<td>0.000104</td>
</tr>
<tr>
<td><em>Stipa tenacissima</em></td>
<td>0.43-1.34</td>
<td>24.34</td>
<td>-0.61</td>
<td>-</td>
<td>E</td>
</tr>
</tbody>
</table>
Table 4. Mean values and standard deviations of lateral reinforcement and RAR at the three considered distances

<table>
<thead>
<tr>
<th>Species</th>
<th>Distance (cm)</th>
<th>Mean cr lat (kPa)</th>
<th>Standard Deviation</th>
<th>N</th>
<th>Mean RAR</th>
<th>Standard Deviation RAR</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>A. vulneraria</em></td>
<td>5</td>
<td>0.43</td>
<td>0.88</td>
<td>10</td>
<td>2.7535E-05</td>
<td>3.91459E-05</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.189555556</td>
<td>0.263845</td>
<td>10</td>
<td>1.51477E-05</td>
<td>2.1245E-05</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>0.4</td>
<td>1.25</td>
<td>10</td>
<td>9.98229E-06</td>
<td>3.15668E-05</td>
</tr>
<tr>
<td><em>B. erectus</em></td>
<td>5</td>
<td>2.21</td>
<td>2.32</td>
<td>10</td>
<td>1.32E-04</td>
<td>6.55432E-05</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.08</td>
<td>0.09</td>
<td>10</td>
<td>4.51364E-06</td>
<td>6.11906E-06</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><em>S. recta</em></td>
<td>5</td>
<td>2.13</td>
<td>2.89</td>
<td>10</td>
<td>1.04E-04</td>
<td>8.70E-05</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.76</td>
<td>1.60</td>
<td>10</td>
<td>4.31E-05</td>
<td>8.57E-05</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>0.42</td>
<td>1.02</td>
<td>10</td>
<td>1.13E-05</td>
<td>2.62E-05</td>
</tr>
</tbody>
</table>
Fig. 1. The bank on a quarry at the Botticino basin
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.