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Abstract

Hilly slopes cultivated with vineyards are often affected by rainfall-induced shallow landslides, that cause destruction and loss of the cultivations. For this reason, the assessment of mechanical contribution from grapevine roots is fundamental for slope stability analyses and consequently for the slope preservation. In this work, the main results of a research aimed at quantitatively evaluating the soil reinforcement given by grapevine roots are presented. The selected study area (13.4 km^2) is located in the region of Oltrepò Pavese in northern Italy. It has the highest shallow landslides density of the region and is characterized by a land cover mostly constituted of vineyards cultivated in steep slopes, with a lower number of abandoned vineyards and woodlands developed from vineyards abandoned for more than 30 years. The rootstock of the grapevine is a combination of *Vitis Berlandieri* and *Vitis Riparia*. The tested soils are Haplic Calcisols, Petric Calcisols and Calcic Gleysols, with silt loamy or silty clay loamy textures, from with high to very high carbonate content and low organic carbon and nitrogen contents. The grapevine root density (number of roots and Root Area Ratio) is rather variable; the mean rooting depth is of 1.0 m. Root density seems linked with soil permeability and bulk density. The results show that low permeable soils have small number of roots and occur near recent shallow slides. Despite the differences of soil features, type of bedrock, grapevine plants age and vineyards row orientation, a unique relationship between root diameter and root tensile strength can be identified, and in different periods of the year. The total root reinforcement of grapevines, obtained through the Fiber Bundle Model, is then strongly correlated to the root density. It reaches low values in correspondence of sites with low soil permeability, in this case study Calcic Gleysols, where shallow landslides occurred in the past. This indicate that these slopes are the most susceptible slopes to shallow landslides. The results of this study also highlight the role played by different amounts of grapevine root reinforcement on the slope stability during rainfall conditions, which could lead to triggering, on the study area.

1. Introduction

Slope instability is very common in steep terrains cultivated with vineyards, as testified by numerous recent events in many areas traditionally devoted to wine production. In Northern and Central Italy, these phenomena occurred in the Marche region (Gentili et al., 2006), Langhe (Tiranti and Rabuffetti, 2010), Oltrepò Pavese (Zizioli et al., 2013; Bordoni et al., 2015a), Cinque Terre (Cevasco et al., 2014), Valtellina (Camera et al., 2015), and the Prosecco area. Furthermore, widespread landslides affected cultivated vineyards also in other European countries such as Slovenia (Komac and Ribicic, 2006), Spain (Ramos et al., 2007), Germany (Grunert, 2009) and France (Van den Eeckhaut et al., 2010).

Rainfall-induced shallow landslides most frequently occur on landscapes with vineyards. They have additional effects such as damages to adjacent structures and infrastructures (buildings, roads, railways, etc.), or even injuries and loss of human life which are commonly observed. Such events, in fact, generally destroy the cultivations with a great impact on the local economy (loss of plants and soil, reshaping the fields and new plantation or abandonment).

Shallow landslides usually develop in the first 2 meters of soil and are often triggered as a consequence of very intense and concentrated rainfalls. These types of rainfall events cause a sudden increase in soil water content and a decrease in soil suction, which is responsible for the reduction in soil shear strength and for the initiation of the landslide phenomenon (Montrasio and Valentino, 2008).

In spite of the diffusion, the persistence, and consequences of shallow landslides on vineyards slopes, no significant studies have been carried out so far to investigate the role played by grapevine plants on preventing or promoting landslides triggering.

At the same time, the beneficial effect of plants in preventing slope instabilities is well known and vegetation is often used as an effective tool to decrease landslide susceptibility, in particular for shallow landslides (Tosi, 2007; Wu, 2012). In the last few decades, a significant body of literature has been published showing the role exerted by the root systems on soil strength and in helping quantifying it, mainly for forest trees (Abe and Ziemer, 1991; Schmidt et al., 2001; Norris et al., 2008; Stokes et al., 2008; Bischetti et al., 2009; Schwarz et al., 2010; Mao et al., 2012; Preti, 2013) or shrubs and grass (Tosi, 2007).

Generally, the literature up to now has mainly focused on mechanical effects of vegetation in terms of providing additional mechanical root reinforcement to be used in slope stability models. Quantifying the effects played by plants in slopes prone to shallow landslides, then, is considered as an important tool in the assessment of shallow landslides susceptibility and in the development of both hazard and risk mitigation strategies (Schwarz et al., 2010; Vergani et al., 2012).

Since this work has been carried out for forest landscapes, it is clearly it is important to develop analysis in cultivated areas similar to that done in forest landscapes, especially for those of great economical relevance, such as grapevine.

As a contribution to filling the knowledge gap the relationship between vineyards and shallow landsliding, in this work a sample hilly area of Oltrepò Pavese has been considered. This area represents the bigger Controlled Origin Denomination (C.O.D.) wine zone of Lombardy Region, with about 13,000 ha of vineyards and is among the top ten areas for the production of Italian wine. Moreover, the viticulture is the most important branch of the local economy. This sector belongs to the so called "Buttafuoco dell'Oltrepò Pavese" C.O.D. zone and it represents the area with the highest shallow landslides density of all the Oltrepò Pavese region (Zizioli et al., 2013). In particular, our objectives are to quantify the soil strength contribution in terms of additional root reinforcement by: i) providing the grapevine root distribution patterns within the soil profile in different scenarios and by considering different features of the vineyards and the slopes where they are implanted; ii) measuring the grapevine root tensile strength; and, iii) quantifying the grapevine additional root reinforcement to the soil.

2. Methods

2.1 The study area

The study area is located in the north-eastern sector of Oltrepò Pavese which belongs to the north-western Italian Apennines (Fig. 1).

In particular, all the data needed to estimate the grapevine root distribution patterns and the related root reinforcement were collected in some test sites located between the medium traits of Versa River and Scuropasso River basins that belongs to north-eastern Oltrepò Pavese (Fig. 1).

The 13.4 km^2 sector is a hilly area characterized by slopes with medium-high topographic gradient (ranging from 18 to 37°) and elevation ranging between 59 and 323 m above sea level (a.s.l.). The climatic regime is temperate/mesothermal according to Koppen's classification of world climates, with a mean yearly temperature of 12 °C and mean yearly rainfall of 684.4 mm.

The bedrock is composed of arenaceous conglomeratic deposits (Monte Arzolo Sandstones, Rocca Ticozzi Conglomerates) overlying silty-sandy marly deposits and evaporitic chalky marls and gypsum (Sant'Agata Fossili Marls, Gessoso-Solfifera Formation) (Fig. 1; Bordoni et al., 2015b).

Above the bedrock levels, the soils, derived from the bedrock weathering, have a prevalently clayey-silty or silty-sandy texture. The soil thickness ranges between a few centimetres to 2.5-3.0 m and it generally increases from the top to the bottom of the slopes (Zizioli et al., 2013).

The land use was obtained from an automatic interpretation of very high resolution (< 1 m) Pleiades satellite images, acquired on 17 April 2013.

The land use thus constructed can be considered substantially equal to the situation present in 27-28 April 2009, when the most significant shallow landslides occurred in the study area. The vineyards (VN) cover 31.3% of the study area, representing the most widespread land use class (Table 1). The most common type of vineyard is the one with rows oriented parallel to the maximum slope gradient (Par VN), with a slightly lower diffusion of vineyards with row orientation perpendicular to the slope gradient (Perp VN). Approximately 24.9% of the study area is also characterized by the presence of vineyards abandoned in the last 20-30 years (Ab VN; Table 1). The grapevine plants remain in these sectors, but they are progressively substituted with grasses, shrubs and other plants, especially black locust trees (*Robinia Pseudoacacia*). In vineyards abandoned for more than 30 years, natural vegetation has completely colonized the slopes forming grasslands and shrub lands (S) and woodlands (W) made up almost totally of *Robinia Pseudoacacia*. The woodlands cover 12.0% of the study area (Table. 1).

Several rainfall-induced shallow landslides were triggered in the study area in the last 6 years. These phenomena affected the superficial soils with failure surfaces located at depths ranging between 0.7 and 2.0 m from ground level, and occurring at the contact between the soil and the bedrock or at the interface between soil layers with different hydrological and physical properties.

The first and most significant event in terms of number of triggered phenomena occurred on 27-28 April 2009. This event, characterized by an extreme rainfall event of 160 mm of cumulated rain in 62 h (Zizioli et al., 2013), caused the triggering of 384 landslides in the study area, with a density of about 51 landslides per km^2.

Further shallow-landslide events occurred successively, as reported by Bordoni et al. (2015a): a) in the period between March and April 2013, after some rainfall events with a cumulated rainfall amount higher than 40 mm lasting between 30 and 50 h (23-25 March, 4-5 April, 20-22 April); and b) between 28 February and 2 March 2014 as a consequence of an event of 68.9 mm in 42 h. These events caused the triggering of a limited number of shallow landslides (17 and 20 respectively) due to the more limited rainfall amount.

Most shallow landslides occurred in the study area can be classified as complex landslides, which start as shallow rotational-translational failures and then evolve into earth-flows (Cruden and Varnes, 1996). Recent movements affected vineyards (40.7%), abandoned vineyards (22.8%) and woodlands (22.0%) as shown in Table 1.

2.2 Choice of the test sites

A multidisciplinary (geological, pedological, soil physical, geotechnical, agronomical) study was carried out to select vineyard test-sites and to identify relationships between root density and mechanical properties and the main features of the test-sites. Test-site slopes (black star symbols in Fig. 1) were selected according to (Table 2): age of the grapevine plants, row orientation of the vineyard plantations, presence or absence of previously triggered shallow landslides, type of bedrock and soil features.

The studied grapevine plants were between 5 and 30 years old and the vineyards had the row orientation parallel (Par VN) or perpendicular (Perp VN) to the maximum slope gradient.

In the study area, grapevine cultivation has been documented since the Roman Age. Considering aerial ortho-photos acquired since 1954, in CB, COL, CAC1 and CAC2 test sites, grapevine cultivations carry on since those years. SOL1 and SOL2 vineyards were not cultivated only between 1994 and 2007, while CZ vineyards were not cultivated only in the period 1994-2003.

Distance between plants along the same row ranges between 0.8 and 1.9 m, while distance between two adjacent rows is, in every test-site, between 2.1 and 2.4 m. The root stocks used in the test-sites are the 420A and the SO4, both with the same combination of *Vitis berlandieri* and *Vitis riparia*. The grapevine cultivars are Croatina, Uva Rara and Barbera. The soil is usually fertilized, with mineral fertilizers, especially in spring months, and/or with organic and pellet fertilizers in autumn.

In the analyzed slopes previously affected by shallow landslides, the failure surface was located at a depth of 0.85-0.90 m from the ground level.

Table 2 reports the main features of the vineyards test sites.

2.3 Soils characterization

The soils were described and classified in each site according to the WRB system (IUSS Working Group WRB, 2014). The humus forms was classified according to Jabiol et al. (1995).

For this procedure, the following pedological properties of the soil were determined, according to Violante (2000): pH in water, total nitrogen, organic carbon content (SOC), organic matter content (SOM), active lime, cation exchange capacity (CEC), grade of saturation of the exchange complex (BS).

Geotechnical laboratory tests, performed according to American Society for Testing and Materials (ASTM) procedures (1988), allowed for determining the particle size distribution curve, the Atterberg limits and the quantity of calcium carbonate content ($CaCO_3$), on disturbed soil samples. Moreover, on undisturbed soil samples, unit weight (γ) and dry unit weight (γ_d) were determined.

The saturated hydraulic conductivity (K_s) was determined in laboratory for each test site from undisturbed soil samples using a Wind Schindler Method (WSM; Peters & Durner, 2008) technique (Hyprop, UMS GmbH, Munich, Germany). These samples were collected below the most superficial soil horizons, usually in B or C levels, at depths ranging between 0.3 and 0.9 m from ground. In the sites affected by shallow landslides, they were taken at the depth of the sliding surface.

2.4 Root density evaluation

A trench was excavated to collect grapevine root samples for mechanical properties measurement and for evaluating root density and root size distribution with depth at distances from the plant between 0.10 and 1.26 m (Table 2; (Bischetti et al., 2009), given the dimensions of the trench.

Root samplings were performed between spring 2013 and autumn 2014 (Table 2). Furthermore, to investigate possible differences in root mechanical properties along different seasons, in COL and CZ test-sites two samplings were made in different season of 2014, respectively namely in winter and summer for COL and in summer and autumn for CZ (Table 2). In the test sites affected by shallow landslides in the past, the trench was excavated slightly uphill with respect to the shallow landslide source area.

Root density was quantified by measuring the number of roots per root diameter class by means of the root-wall technique (Bischetti et al., 2009). Root diameter and position were measured by the manual digitization of each root located in a frame of known size (0.30 x 0.30 m), that was moved along all the soil profile in correspondence of the considered trench wall. For the digitization of the roots, a Geographical Information System (GIS) software (MapWindow 4.6) was used. The number of roots per diameter class was determined in increments of 0.10 m in depth, considering the following diameter classes: 0.5-1 mm, 1-2 mm, 2-5 mm, 5-10 mm, and > 10 mm, as suggested by literature (Bischetti et al., 2016). Together with the number of roots, root density was evaluated also by the measurement of Root Area Ratio (RAR), which was obtained by dividing the cross sectional area of the roots by the cross sectional area of the soil in the frame of known size (0.30x0.30 m) used for the measurement of root number. The RAR was estimated at depth increments of 0.10 m.

2.5 Root mechanical properties evaluation

Several grapevine roots were collected in each excavated trench for the tests of root mechanical properties. To protect the sampled roots from deterioration they were preserved in plastic containers with a 15% alcohol solution (Bischetti et al., 2005) until the root tensile resistance tests were performed.

Grapevine roots mechanical properties were measured through laboratory tensile strength tests on sampled roots using the MTS Criterion Model 44 (MTS Systems, Eden Prairie, MN, USA) device, according to the experimental method described in Bischetti et al. (2009). Roots were attached to specifically clamping devices that avoid root damage at the clamping points. A tensile force was applied to the root, at a rate of 10 mm/min and strength measured by a load cell (Full Scale F.S. of 500 N, accuracy of 0.1% F.S.). Only specimens that broke near the middle of the roots were included in the data to ensure that the rupture was due to the tension and not structural damage to the root or concentration of stress near the clamps. Tensile force at rupture (N) of each root was calculated from the tensile stress at rupture (Pa) measured by the device and the cross-sectional area of the root (m^2), estimated as the average of three values taken with an electronic caliper at three points near the potential breaking point.

The results of tensile strength tests are then expressed as a power law relationship between the tensile force at rupture (f) and diameter (D) of the tested root (Schmidt et al., 2001; Tosi, 2007; Vergani et al., 2012) (eq. 1):

$$f = aD^b \qquad \text{eq. 1}$$

, where *a* and *b* in eq.1 are fitting parameters of the power-law function. The suitability of these regressions were evaluated using the coefficient of determination (R^2) and the coefficient of significance (p-value) obtained from Fisher's Test, with a significance level of 0.1.

Because the tensile stress of roots is calculated as the ratio between force at rupture and root area, the use of tensile force vs. diameter is probably preferable to the use of stress, which tends to necessarily amplify the uncertainty involved in the determination of diameters (Vergani et al., 2012).

2.6 Root reinforcement evaluation

Force-diameter (f/D) relationship and root density were the input data used to estimate root reinforcement in the soil profile through the application of the Fiber Bundle Model, FBM, described by Pollen and Simon (2005). Based on the pioneering work of Waldron (1977), this model simulates a progressive failure of a bundle of fibers under increasing load. This model takes into account simple rules: (i) an initial load is added and equally distributed between all the parallel fibers (roots) inside the bundle, (ii) the load is continuously increased until a root breaks (when the distributed load is greater than the single root tensile resistance) and then the load is redistributed to the remaining roots (iii) if the redistribution causes a further rupture, the redistribution occurs once again, (iv) the process is repeated until either all of the fibers have been broken. In this study, the

FBM was implemented under the static fiber bundle approach and equal load sharing (Bischetti et al., 2009; Schwarz et al., 2010; Mao et al., 2012;).

The FBM model allowed for assessing total root reinforcement, c_{rtot}, at a certain depth in soil as the sum both of the resistance due to those roots crossing the basal shear surface (basal root reinforcement, c_{rbas}) and the resistance due to those roots intersecting the vertical plane at the detachment scarp (lateral root reinforcement, c_{rlat}). Differently from c_{rbas}, c_{rlat} provides the additional root reinforcement due to the roots located at higher soil levels along the lateral landslide scarp.

Considering both c_{rbas} and c_{rlat} on the computation of total root reinforcement is preferable in slopes affected by shallow landslides. In fact, in the case of shallow landslides, the sliding mass must exceed, besides soil strength, both the resistance due to roots crossing the basal and the vertical shear surface (Schmidt et al. 2001; Bischetti et al., 2009; Schwarz et al., 2010).

For the computation of root reinforcement, we considered only roots with diameter ranging between 1 and 10 mm (Tosi, 2007; Bischetti et al., 2009). Roots with a diameter less than 1 mm are disregarded because their role in reinforcing the soil is questionable in view of the length necessary to keep them from slipping rather than breaking (Waldron, 1977).

2.7 Statistical analyses

A statistical analysis of RAR-depth and force-diameter relationships of each test-site was performed after log transformation of the variables. For evaluating the differences in terms of root distribution and root tensile strength in the different vineyards, analysis of covariance (ANCOVA) was used, taking into account the depth and diameter as covariate factors, for root distribution and root tensile strength, respectively. To verify the assumptions of ANCOVA, Kolmogorov-Smirnov's and Levene's tests were used to check the normality, the independence and the variance homogeneity of the residuals. All statistical analyses were performed with a significance level of 0.05 and using the software R (R Core Team, 2014).

3. Results

3.1 Soils properties

All the studied soils have a deep calcic horizon starting from about 0.6 m from the ground, with typical values of $CaCO_3$ higher than 15% and of active lime around or higher than 6% (Table 3). CZ and CAC1 soils are Calcic Gleysols (Siltic), with gleyic properties due to the presence of saturated conditions along the year which cause the development of reducing conditions. The other tested vineyard soils are Calcisols. Haplic Calcisols (Siltic) are detected in SOL1, CB and COL sites, while SOL2 and CAC2 soils are Petric Calcisols (Siltic) due to the presence of a cemented or hardened calcic horizon at depth greater than 1.0 m from the ground. Also in the Calcisols, the presence of reddish concretions demonstrates a seasonal water logging in the deeper horizons till about 0.4 m above the contact between soil and bedrock. Most of these soils are moderately well drained, except for CB and CAC2, which are well drained (Table 3).

Furthermore, all the soils are characterized by: Eumull humus; alkaline pH (7.8-8.4); low SOM and total N contents (0.3-1.9% and 0.003-0.012%, respectively); low ratio of organic carbon to nitrogen contents (C:N) (between 3.4 and 8.9); CEC with narrow range of values (lower than 18.2 meq/100 g); BS of 100% (Table 3).

All the tested soils have silt loamy or silty clay loamy textures, with high silt content (51-64%) (Table 4). SOL2 and COL test-sites are characterized by a sand content higher than 13.6%, and by a clay content ranging between 21 and 27% (Table 4). In the other study slopes, the soils have a lower sand content (3-12%) and a higher clay content (24-41%) (Table 4). Gravel amount is low in all the tested soils, ranging between 0 and 11% (Table 4). No significant trends can be identified on the distribution of the particle size along depth in the soil profiles. According to USCS classification, all the tested soils can be classified as low-medium plastic soils (CL), with liquid limit (w_L) values ranging between 30.5 and 50.0%, and plasticity index (P_I) values that range between 15 and 29.0% (Table 4).

Total unit weight (γ) and dry unit weight (γ_d) of soils keep also quite steady along depth in all the test-site profiles. SOL2 and CB test-sites are characterized by γ values between 15.2 and 17.2 kN/m^3, which are generally quite lower than in the other test-sites, where γ usually ranges between 17.7 and 19.3 kN/m^3 (Table 4). This feature characterizes also γ_d, which is quite lower in SOL2 and CB (12.5-14.2 kN/m^3) than in the other soil profiles (14.3-16.3 kN/m^3) (Table 4).

K_s values are in the order of 10^{-6}-10^{-7} m/s. It is interesting to note that in sites not affected by shallow landslides (SOL1, SOL2, CB), K_s values are higher of 10^1 m/s than in sites with shallow landslides (Table 4).

3.2 Root density

The number of grapevine roots measured in the analyzed pits shows great variations between the different sites.

The highest amounts of roots were found between 0.2-0.6 m below the ground level, and, as expected, the number of roots decreased with depth in the soil and in some cases they disappeared above the contact between soil and weathered bedrock.

The maximum rooting depth ranged between 0.7 m (CZ test-site) and 1.5 m (SOL2 test-site). Moreover, no roots were observed at the bedrock levels, regardless the depth of the soil limit.

At SOL1 and CB test-sites the roots are more abundant than the other ones are.

Only roots with diameter between 1.0 and 5.0 mm were generally observed at all the soil depths.

At distances from the stem greater than 0.5 m the roots with diameter ranging between 1.0 and 2.0 mm are prevalent with respect to other root size (smaller or greater). At a particular test-site, the number of roots trend is quite similar at different distances from plants.

The grapevine roots number directly influenced the RAR distribution within the soil profile, whose general trends follow the trends of root numbers in the soils (Fig. 2).

ANCOVA analysis was applied to verify the high variation in RAR between the different test-sites. root number. Once verified the parallelism requested for the application of ANCOVA ($F_{1,15}$ = 5.84, p-value = 0.01), this statistical test showed that for the investigated vineyards RAR distribution can be considered statistically different between each test-site ($F_{1,15}$ = 3.41, p-value < 0.001).

The mean RAR values obtained for a soil depth until 2.0 m showed that considering all test sites until 0.9 m from the ground RAR ranges between 0.06 and 0.18% (Fig. 3a). A negligible average value was observe from the depth of 1.1 m (Fig. 3a), even if locally RAR values higher than zero were detected, until a depth of 1.5 m (SOL2 and COL test sites; Fig. 2).

It is worth noting that in the vineyards where shallow landslides occurred, at the same soil level the average RAR values are 0.10-0.15% lower than the average values of the vineyards where no shallow landslides have been triggered (Fig. 3b, c). At a depth of 0.85 and 0.9 m from the ground, where the sliding surfaces were observed, mean RAR value is of 0.08-0.09% (Fig. 3b, c).

Concerning the different measured soil properties, there appears to be a correlation between the mean RAR of the soil profile, which is a proxy of the vertical diffusion of the roots, and the soil hydraulic conductivity K_s measured in correspondence of the B or C horizon of the soil, as indicator of the permeability and the penetrability of the material. We considered as indicator of the root density the mean RAR measured till 0.9 m from ground (depth where RAR is averagely lower than 0.05%) at a distance ranging between 0.20 and 0.65 m from the plant trunk. Although the number of the studied soils is rather limited (7), the mean RAR of the soil profile is strongly correlated to the soil K_s. Increasing the soil K_s the mean RAR of the soil profile also increases, passing from 0.07-0.11% in soil with K_s in the order of 10^{-7} m/s to 0.22-0.27% in soil with K_s in the order of 10^{-6} m/s (Fig. 4a). The lowest mean RAR values are reached in Calcic Gleysols (CZ and CAC1), and in the slopes with Calcisols characterized by a young age of the grapevines (5-6 years old; COL and CAC2).

Moreover, the test-sites with low permeable soils and, thus, lowest values of root density, are also the sites affected in past by shallow landslides (Fig. 4a).

Only a partial relationship seems to link the mean RAR with the mean soil bulk density γ_d (Fig. 4b) in the tested vineyards.

SOL1 has the highest mean RAR value (0.24%) but also a very high γ_d value (15.8 kN/m^3), similar to that one measured in COL and CAC1, where mean RAR values are significantly lower (0.07-0.13%) (Fig. 4b). For the other sites, the decrease in γ_d is coupled with an increase in mean RAR (Fig. 4b).

4.3 Root tensile strength

Diameters of the tested roots ranged from 0.55 to 4.73 mm, with 75% having a diameter lower than 3.00 mm. The force at failure of the tested grapevine roots ranged between 1.45 and 219.55 N.

Table 5 show that the force-diameter power laws for the studied vineyards are similar.

Similar relationships are highlighted in COL and CZ test-sites by considering roots taken in different seasons (Table 5).

After verifying the parallelism of the power laws ($F_{1,6}$ = 0.32, p-value = 0.01), the application of ANCOVA confirmed that the f/d relationships obtained for the different tested vineyards are statistically not different ($F_{6,274}$ = 0.57, p-value = 0.02). Moreover, no differences in terms of mechanical properties can be statistically observed between sites with or without landslides, and according to the year of vineyards plants, the main geomorphological slope features, the bedrock lithology, the properties of the soil and row orientation of the vineyards (p-value = 0.03, ANCOVA). Thus, it is possible to identify a unique force-diameter relationship for tested grapevine roots in the study area.

ANCOVA analysis also confirms that the mechanical properties of grapevine roots do not change in different seasons (Table 5). In fact, for COL and CZ sites, the f/d relationships measured from roots taken in different periods of the year are statistically similar (for COL test site, $F_{1,56} = 4.22$, p-value = 0.04; for CZ test site, $F_{1,60} = 0.45$, p-value = 0.01).

4.4 Additional root reinforcement

According to the statistical homogeneity on root mechanical properties in different vineyard sites and as already observed in previous works concerning forest species (Schmidt et al., 2001; Bischetti et al., 2009), grapevine root reinforcement was estimated using a unique f/d relationship specifically determined for this species.

The difference in additional root reinforcement values at the different test-sites are therefore related only to the peculiar root density of a site. Accordingly, the total root reinforcement c_{rtot} showed great variations on the different analyzed pits (Fig. 5). The differences were more significant in the first 0.9-1.0 m within the soil profile (Fig. 5).

Where a local increase of c_{rtot} along depth is observed, it is related to a local increase of the root density, as observed in CAC1 test-site between 0.8 and 1.0 m from the ground (Fig. 5).

The highest values of c_{rtot} have been observed at a depth between 0.1 and 0.6 m from ground level, where it attained average values of 12.6 and 20.1 kPa (Fig. 5, 6). c_{rtot} also decreased along the soil profile , with an abrupt decrease immediately above or at the contact between soil and weathered bedrock (Fig. 5, 6). Below 1.0 m from ground, grapevine c_{rtot} showed a slower decrease along depth, in the order of 0.3-0.5 kPa every 0.1 m increment in depth (Fig. 6).

Moreover, as for root density, at different depths c_{rtot} was higher in slopes without landslides than the slopes affected by landslides (Fig. 6). Generally, the differences between unstable and stable slopes reached values of 14 kPa till 0.9 m from ground, while, below 0.9-1.0 m from ground, the mean value of c_{rtot} decreased in unstable slopes respect to stable ones to values of 3-9 kPa (Fig. 6).

Furthermore, it is important to highlight that between 0.8 and 1.0 m from ground, where shallow landslides failure surfaces were detected in the analyzed vineyards, c_{rtot} is of 7.3-8.0 kPa.

5. Discussions

Figure 7 provides a schematic flow chart of the main key results reached through this research. The discussion of these results follow.

The grapevine root density, in terms of number of roots and RAR, in soil profile has a great variability with regard to different test-site locations (Fig. 2, 3). This variability generally characterizes all the plant types investigated in the past and it is due to the spatial heterogeneity of root system development, which is dependent upon the interactions of genetic and very local environmental factors (Stokes et al., 2008).

RAR results strictly followed the trend of number of roots and, in spite of great average RAR values variability, general features of grapevine root density with depth can be identified.

The greatest amounts of roots were found between 0.2-0.6 m below the ground level, with a decreasing trend along the depth. This can be associated with the use of mechanical hoes and the trenching of the soil till 0.15 m from ground level during agronomic practices, which cause the partial destruction of the grapevine roots.

Grapevine roots can rarely reach depths greater than about 1 m from the ground (Fig. 2, Table 4). This is in agreement with Swanepoel and Southey (1989) and Shange and Conradie (2012), who suggest that the maximum rooting depth of different types of grapevine rootstocks is between 0.6 and 1.2 m from ground in fine textured soils whereas it can be more than 2.0 m in coarse textured soils where sand is more than 50%.

Considering the lateral development of root system in the same profile, similar values of root density can be observed at distances between 0.10 and 1.26 m from plant trunks (Fig. 2). This feature is consistent with previous works which highlighted, in different soils and environmental contexts, fairly high and constant root density up to 1.5 m from the plant trunk (Saayman and Van Huyssteen; 1980; Morlat and Jacquet, 2003).

As regards the relations between root density and soil properties or agricultural practices, the mean RAR of the soil profile is strongly correlated with soil K_s (Fig. 4a). Where K_s increases, the vertical root density in the soil profile also increases (Fig. 4a). In particular, mean RAR is 0.12-0.20% higher in soils with K_s in the order of 10^{-6} m/s, than in soils with K_s in the order of 10^{-7} m/s (Fig. 4a).

The lowest RAR values correspond to sites with Calcic Gleysols (CZ and CAC1). Low values of mean RAR are also typical of sites characterized by Calcisols and by the young age of the grapevines (5-6 years old; COL and CAC2).

The reasons of the lowest root density in Calcic Gleysols can be due to the development of completely saturated horizons, typical of soils with gleyic features, which cannot be crossed by the roots. Less permeable soils cause water logging, which does not seem promoting the development of a high grapevine roots density (Smart et al., 2006).

The difference of RAR values reflects on the distinction between the slopes affected or not by shallow landslides in the past. The selected vineyards affected in past by shallow landslides have average RAR values 0.10-0.15% lower than the average values of the vineyards where no shallow landslides occurred (Fig. 3).

Low permeable soils had a lower grapevine root density and appear more susceptible to shallow landsliding.

In vineyards affected by past shallow landslides, also γ_d is generally higher than in stable slope (except for SOL1; Fig. 4b). Instead, in respect with other observations of grapevine root density (Van Huyssteen, 1988; Smart et al., 2006), in the selected test-sites, the increase in γ_d is not always coupled with a decrease in mean RAR (Fig. 4b).

Statistical analyses on grapevine root tensile strength showed that in the study area this feature was not affected by location, type of soil and bedrock, grapevine plants age, type of vineyards and seasons of the year (Table 5).

The existence of a unique root mechanical behavior can be linked to the presence of the same combination of *Vitis berlandieri* and *Vitis riparia* rootstocks and for the similar environmental conditions everywhere in the study area, linked to its small size (13.4 km^2). Differences in tensile strength of the same species, in fact, can be partially associated with a difference in cellulose content (Genet et al., 2005) and such an effect can be appreciated only for very different environmental conditions, in terms of slope altitude, wind, air temperature, rainfall amounts.

The f/d relationship determined for grapevine plants of cultivated vineyards in the study area has been compared with the power law functions for forest species (Vergani et al., 2012). This comparison provided by the value of the force at failure for root with a diameter of 2 mm, which is the most common class of diameter we observed, shows that grapevines seems to be strong as most of the considered forest species (Table 6).

Grapevine total root reinforcement (c_{rtot}), calculated through FBM model, follows root density trend of a soil profile. It is highest till 0.6 m from ground, where most of the roots are detected (Fig. 3, 6), and it decreases along depth, passing from average values of 18 kPa till 0.6 m from the ground to 10 kPa between 0.6 and 1.0 m from the ground.

At soil depths higher than 1.0 m, c_{rtot} shows an abrupt decrease, with values that fall down below 6 kPa (Fig. 6). This abrupt decrease is due to the general absence of roots below 1.0 m from the ground. In these soil horizons, c_{rtot} is only due to the lateral root reinforcement, thanks to the roots located in most shallow horizons (Bischetti et al., 2009). Thanks to the presence of this lateral component, c_{rtot} is not completely nullified in each investigated levels (till 2.0 m from ground; Fig. 5, 6).

The tested vineyards affected in past by shallow landslides are characterized by a lower c_{rtot} than the stable ones (Fig. 6). In correspondence of the depths where shallow landslides sliding surfaces formed (between 0.8 and 1.0 m from ground), c_{rtot} of unstable slopes is of 7.3-8.0 kPa, while in stable slopes average values range between 16.9 and 25.0 kPa (Fig. 6).

Unstable tested vineyards have with lower c_{rtot} and low permeable soils, as already observed for root density. This confirms that the cultivated slopes characterized by soil with low permeability are more prone to shallow landslides triggering.

The stability of cultivated slopes can be obviously also linked to the soil shear strength parameters, in particular soil friction angle and effective cohesion. As shown in previous works (Zizioli et al., 2013; Bordoni et al., 2015b), the soils of the study area have average values of shear strength properties distributed in a narrow range, in particular between 24 and 27° for soil friction angle and between 1.5 and 2.0 kPa for effective cohesion, respectively. According to the similar values of soil shear strength, grapevine root reinforcement, and its variation in relation to root density in different soil contexts, controls the predisposition of cultivated vineyards of the study area to shallow landslides.

5. Conclusions

In this work, we presented analyses of grapevine root reinforcement toward slope stability in steep terrains adding new knowledge in this field

Previous studies on vineyards did not deal with root mechanical properties of grapevine roots nor have previous studies on the mechanical properties of plant roots considered grapevine plants.

The results obtained in this work, then, provided important information, which could further be extended to other viticulture areas prone to shallow landsliding, and helping hazard mapping and guiding vineyards management.

Grapevine root density, in terms of number of roots and RAR, shows a great variability in soil profile in the different analyzed test-sites. The highest values are reached between 0.2 and 0.6 m from slope surface, and a significant decrease is evident below 0.9-1.0 m from ground, where grapevine roots can rarely be found.

Soil permeability is the soil property which seems to be strongly associated with grapevine root density, controlling roots amount in soil. The low permeable soils, in this study case mostly Calcic Gleysols, have lower root density and were affected by shallow landslides in the past.

Grapevine root tensile strength appears not to be affected by location, type of soil and bedrock, grapevine plants age, type of vineyards, different seasons of sampling. Analysis of the f/d relationship showed that grapevine roots are strong as most of the forest species analyzed in past.

Grapevine roots can provide a good soil reinforcement, usually in the first 0.6 m from the ground where the roots are more abundant. At depths ranging between 0.8 and 1.0 m from the ground, where shallow sliding surfaces formed in the tested vineyards, c_{rtot} of unstable slopes reached 7.3-8.0 kPa, while in stable slopes average values range between 16.9 and 25.0 kPa for the same horizons. The contribution of the lateral root reinforcement makes the total root reinforcement always greater than 0.0 kPa.

The great variation of root reinforcement between different sites is essentially linked to root density. In slopes with low permeable soils, the root reinforcement is lower, making these slopes the most susceptible ones to shallow landslides.

The obtained results represent fundamental tools for land use planning. For example, it is fundamental to identify the best agricultural practices which could improve root penetration to deeper profiles in slopes with vineyards especially slopes with characterized by lower root density. The increase in root reinforcement within the soil profile will promote resistance to landslides and more sustained slope stability.

Future developments of this research will be the analyses of the effect of different agricultural practices on vineyards (e.g. management of the interrows) on grapevine root density and, then, on grapevine root reinforcement in soil. Grapevine root reinforcement will be also implemented in distributed physically-based stability models for assessing shallow landslides susceptibility at local and regional scales, considering different land use and rainfall scenarios.

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References

Abe, K., Ziemer, R.R., 1991. Effect of tree toots on a shear zone: modeling reinforced shear-stress. Can. J. For. Res. 21, 1012–1019.

American Society for Testing and Materials, 1988. 1988 Annual Book of ASTM Standards. American Society for Testing and Materials, Philadelphia.

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 Soil 278, 1-2, 11-22.

Bischetti, G.B., Chiaradia, E.A., Epis, T., Morlotti, E., 2009. Root cohesion of forest species in the Italian Alps. Plant Soil 324, 71–89.

Bischetti, G.B., Bassanelli, C., Chiaradia, E.A., Minotta, G., Vergani, C., 2016. The effect of gap openings on soil reinforcement in two conifer stands in northern Italy. For. Ecol. Manag. 359, 286–299.

Bordoni, M., Meisina, C., Valentino, R., Lu, N., Bittelli, M., Chersich S., 2015a. Hydrological factors affecting rainfall-induced shallow landslides: From the field monitoring to a simplified slope stability analysis. Eng. Geol. 193, 19–37.

Bordoni, M., Meisina, C., Valentino, R., Bittelli, M., Chersich S., 2015b. Site-specific to local-scale shallow landslides triggering zones assessment using TRIGRS. Nat. Hazards Earth Syst. Sci., 15, 1025–1050.

Camera, C., Apuani, T., Masetti, M., 2015. Modeling the stability of terraced slopes: an approach from Valtellina (Northern Italy). Environ. Earth Sci. doi:10.1007/s12665-015-4089-0.

Cevasco, A., Pepe, G., Brandolini, P., 2014. The influences of geological and land use settings on shallow landslides triggered by an intense rainfall event in a coastal terraced environment. Bull. Eng. Geol. .Environ. 73, 859-875.

Cruden, D.M., Varnes, D.J., 1996. Landslide types and processes, in: Turner, A.K., Schuster, R.L., (Eds.), Landslides: investigation and mitigation. Sp. Rep. 247, Transportation Research Board, National Research Council, National Academy Press, Washington DC, USA, pp. 36–75.

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

Gentili, B., Pambianchi, G., Aringoli, D., Materazzi, M., 2006. Impatto delle viticoltura sulla dinamica dei versanti nelle Marche (Italia Centrale). Boll. Soc. Geol. It. 6, 201-209.

Grunert, J., 2009. Landslides in the Upper Middle Rhine valley and in Rheinhesse as indicators for climate change?, in: Malet, J.P., Remaitre, A., Bogaard, T., (Eds.), Landslides processes: from geomorphologic mapping to landslide modelling, CERG editions, Strasbourg, pp. 51-55.

IUSS Working Group WRB, 2014. World Reference Base for Soil Resources 2014. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106, FAO, Rome.

Jabiol, B., Bretes, A., Ponge, J.F., Toutain, F. Brun, J.J., 1995. L'humus sous toutes ses formes. Ecole Nationale du Genie Rural, des Eaux et des Forets, Nancy.

Komac, M., Ribicic, M., 2006. Landslide susceptibility map of Slovenia at scale 1:250,000. Geologija 49, 2, 295-309.

Mao, Z., Saint-Andréb, L., Genet, M., Mined, F.X., Jourdan, C., Rey, H., Courbaud, B., Stokes, A., 2012. Engineering ecological protection against landslides in diverse mountain forests: choosing cohesion models. Ecol. Eng. 45, 55-69.

Montrasio, L., Valentino, R., 2008. A model for triggering mechanisms of shallow landslides. Nat. Haz. Earth Sys. Sci. 8, 1149-1159.

Morlat, R., Jacquet, A., 2003. Grapevine root system and soil characteristics in a vineyard maintained long-term with or without interrow sward. Am. J. Enol. Vitic. 54, 1-7.

Norris, J.E., Stokes, A., Mickowski, S.B., Cammeraat, E., Van Beek, R., Nicoll, B.C., Achim, A., 2008. Slope stability and erosion control: ecotechnological Solutions. Springer International Publishing, Dordrecht.

Peters, A., Durner, W., 2008. Simplified evaporation method for determining soil hydraulic properties. J. Hydrol. 356, 147–162.

Pollen, N., Simon, A., 2005. Estimating the mechanical effects of riparian vegeta-tion on streambank stability using a fiber bundle model. Water Resour. Res. 41, W07025, doi:10.1029/2004WR003801.

Preti, F., 2013. Forest protection and protection forest: Tree root degradation over hydrological shallow landslides triggering. Ecol. Eng. 61P, 633-645.

R Core Team (2014). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Wien, Austria. URL http://www.R-project.org/.

Ramos, M.C., Cots-Folch, R., Martínez-Casasnovas, J.A., 2007. Sustainability of modern land terracing for vineyard plantation in a Mediterranean mountain environment – The case of the Priorat region (NE Spain). Geomorphol. 86, 1–11.

Saayman, D., Van Huyssteen, L., 1980. Soil preparation studies: I. The effect of depth and method of soil preparation and of organic material on the performance of *Vitis vinifera* (var. Chenin blanc) on a Hutton/Sterspruit soil. S. Afr. J. Enol. Vitic. 1, 107-121.

Schmidt, K.M., Roering, J.J., Stock, J.D., Dietrich, W.E., Montgomery, D.R., Schaub, T., 2001. The variability of additional root reinforcement as an influence on shallow landslides susceptibility in the Oregon Coast Range. Can. Geotech. J. 38, 995–1024.

Schwarz, M., Preti, F., Giadrossich, F., Lehmann, P., Or, D, 2010. Quantifying the role of vegetation in slope stability: a case study in Tuscany (Italy). Ecol. Eng. 36, 285–291.

Shange, L.P., Conradie, W.J., 2012. Effects of soil parent material and climate on the performance of *Vitis vinifera* L. cvs. Sauvignon blanc and cabernet Sauvignon - Part I. Soil analysis, soil water status, root system characteristics, leaf water potential, cane mass and yield. S. Afr. J. Enol. Vitic. 33, 2, 161-173.

Smart, D.R., Schwass, E., Lakso, A., Morano, L., 2006. Grapevine rooting patterns: a comprehensive analysis and a review. Am. J. Enol. Vitic. 57, 1, 89-104.

Stokes, A., Norris, J.E., Beek, L.P.H. Van Bogaard, T.A., Cammeraat, L.H., Mickovski, S.B., Jenner, A., Di Orio, A., Fourcaud, T., 2008. How vegetation reinforces soil on slopes, in: Norris, J.E., Stokes, A., Mickowski, S.B., Cammeraat, E., Van Beek, R., Nicoll, B.C., Achim, A., (Eds.), Slope stability and erosion control: ecotechnological solutions, Springer International Publishing, Dordrecht, pp. 65 -118.

Swanepoel, J., Southey, J.M., 1989. The influence of rootstock on the rooting pattern of the grapevine. S. Afr. J. Enol. Vitic. 10, 23-28.

Tiranti, D., Rabuffetti, D., 2010. Estimation of rainfall thresholds triggering shallow landslides for an 24 operational warning system implementation. Landslides 7, 471-481.

Tosi, M., 2007. Root tensile strength relationships and their slope stability implications of three shrub species in the Northern Apennines (Italy). Geomorph. 87, 268–283.

Van Den Eeckhaut, M., Marre, A., Poesen, J., 2010. Comparison of two landslide susceptibility assessments in the Champagne–Ardenne region (France). Geomorph. 115, 141–155.

Van Huyssteen, L., 1988. Soil preparation and grapevine root distribution: A qualitative and quantitative assessment, in: Van Zyl, J.L., (Ed.), The Grapevine Root and Its Environment, Technical comm. no. 215, Department of Agriculture and Water Supply, Pretoria, pp. 1-15.

Vergani, C., Chiaradia, E.A., Bischetti, G.B., 2012. Variability in the tensile resistance of roots in Alpine forest tree species. Ecol. Eng. 42, 43-56.

Violante P. (2000). Metodi di analisi chimica del suolo. Franco Angeli Edizioni, Milan, Italy (in Italian).

Waldron, L.J., 1977. The shear resistance of root-permeated homogeneous and stratified soil. Soil Sci. Soc. Am. J. 41, 843–849.

Wu, T.H., 2012. Root reinforcement of soil: review of analytical models, test results and application to design. Can. Geotech. J. 50, 259-274.

Zizioli, D., Meisina, C., Valentino, R., Montrasio, L., 2013. Comparison between different approaches to modelling shallow landslide susceptibility: a case history in Oltrepo Pavese, Northern Italy. Nat. Haz. Earth Sys. Sci. 13, 559–573.

Table 1. Percentage of the study area occupied by the different land use classes and frequency of shallow landslides for each class: Ab VN) abandoned vineyards; VN) vineyards; W) woodlands; Sh) shrub lands; B) bare soils; S) sowed areas; U) urban areas.

Land use classes	Area occupied by the class (%)	Frequency of shallow landslides (%)
Ab VN	24.9	22.8
VN	31.3	40.7
W	12.0	22.0
Sh	8.2	4.8
B	6.2	6.5
S	9.8	2.8
U	7.6	0.4

Table 2. Test-site slopes main features. Perp VN: vineyard with row direction perpendicular to the maximum slope gradient; Par VN: vineyard with row direction parallel to the maximum slope gradient.

Site	Age (y)	Land use	Shallow landslides triggering (sliding surface, m)	Altitude (m a.s.l.)	Slope angle (°)	Slope aspect	Type of bedrock	Soil thickness (m)	Season of root samplings	Distance of sampling trenches from plants (m)
SOL1	10	Par VN	-	280.2	17.5	SSW	Rocca Ticozzi Conglomerates: poorly cemented conglomerates	0.9	autumn	0.10, 0.50
SOL2	10-15	Par VN	-	238.0	21.9	SSW	Rocca Ticozzi Conglomerates: poorly cemented conglomerates	1.5	autumn	0.10, 0.50
CB	20-30	Perp VN	-	177.8	21.3	E	Sant'Agata Fossili Marls: sandy marls	2.1	spring	0.50
COL	5-6	Perp VN	1 March 2014	223.0	24.8	W	Monte Arzolo Sandstones:	> 1.2	winter, summer	0.20

			(0.90)				sand			
CZ	13-15	Par VN	27-28 April 2009 (0.90)	185.0	37.0	NW	Sant'Agata Fossili Marls: sandy marls	1.0	summer, autumn	0.65, 0.80, 0.95
CAC1	20-25	Par VN	27-28 April 2009 (0.85)	165.0	22.0	N	Monte Arzolo Sandstones: sand, sandy marls	> 1.0	summer	0.42, 0.81, 1.26
CAC2	5-6	Par VN	1 March 2014 (0.85)	155.0	15.0	E	Monte Arzolo Sandstones: sand, sandy marls	> 1.0	autumn	0.20, 0.71, 0.88

Table 3. Main pedological features of vineyards test-site soils: SOM) organic matter content; total N) total nitrogen content; C:N) ratio between organic carbon content and total nitrogen content; $CaCO_3$) calcium carbonate content; Active lime) active calcium content; CEC) cation exchange capacity; BS) grade of saturation of the exchange complex.

Site	Soil type (WRB, 2014)	Position on the slope	Superficial drainage	pH (H_2O) (-)	SOM. (%)	total N (%)	C:N (-)	$CaCO_3$ (%)	Active lime (%)	CEC (meq/100 g)	BS (%)
SOL1	Haplic Calcisol (Siltic)	top	moderately well drained	7.8-8.4	0.2-1.3	0.004-0.010	3.4-8.0	41.7-82.7	16.3-18.1	3.6-14.4	100
SOL2	Petric Calcisol (Siltic)	medium	moderately well drained	8.0-8.2	0.9-1.2	0.007-0.008	7.6-8.5	21.5-24.0	5.6-7.2	11.9-13.9	100
CB	Haplic Calcisol (Siltic)	top	well drained	7.9-8.3	0.5-1.9	0.007-0.013	4.6-8.4	22.3-35.7	8.8-11.1	12.9-16.6	100
COL	Haplic Calcisol (Siltic)	medium	moderately well drained	7.9-8.3	0.4-1.2	0.003-0.009	7.0-8.9	6.5-26.3	2.5-12.0	13.2-16.6	100
CZ	Calcic Gleysol (Siltic)	top	moderately well drained	8.0-8.2	0.3-1.6	0.003-0.012	5.2-7.8	22.7-35.2	6.8-11.1	11.1-18.1	100
CAC1	Calcic Gleysol (Siltic)	top	moderately well drained	7.8-8.1	0.6-1.4	0.006-0.010	4.0-8.2	21.9-25.9	6.4-10.1	8.1-10.4	100

CAC2	Petric Calcisol (Siltic)	medium	well drained	8.1-8.3	0.5-1.1	0.005-0.008	7.4-7.9	27.9-34.0	12.3-13.3	12.4-15.2	100

Table 4. Main geotechnical features and soil saturated hydraulic conductivity of test-site soils : w_L) liquid limit; P_I) plasticity index); γ) soil unit weight; γ_d) soil bulk density; K_s) saturated hydraulic conductivity.

Site	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	w_L (%)	P_I (%)	γ (kN/m^3)	γ_d (kN/m^3)	K_s (m/s)
SOL1	2	9-10	55-57	32-34	44.4-45.1	23.0-24.5	19.0	15.6	$2.8 \cdot 10^{-6}$
SOL2	4-11	14	54-60	22	40.4-41.4	17.0-17.8	15.2	13.7	$2.9 \cdot 10^{-6}$
CB	0-1	3-7	60-63	33-34	39.6-42.7	17.9-21.6	15.4-17.2	12.5-14.2	$1.8 \cdot 10^{-6}$
COL	1-2	17-23	51-59	21-27	39.7-41.2	17.3-18.2	17.7-18.2	15.2-15.6	$8.0 \cdot 10^{-7}$
CZ	2-5	8-12	58-61	26-31	41.1-50.0	14.7-30.5	17.7-18.7	14.4-15.5	$3.2 \cdot 10^{-7}$
CAC1	1	4-12	61-64	24-33	36.9-45.9	15.1-23.0	16.3-18.6	14.3-16.2	$5.8 \cdot 10^{-7}$
CAC2	0-2	2-4	55-59	39-41	46.5-50.0	24.4-29.0	17.9-19.3	15.7-16.3	$1.4 \cdot 10^{-6}$

Table 5. Coefficients and statistical parameters of f/d relationships for vineyards test-sites: a and b) fitting parameter of force/diameter relationship; R^2) coefficient of determination; se) standard error.

Site	Vineyards age (y)	Number of tested roots (-)	power law relationship				
			a	b	R^2	p-value	se
SOL1	10	35	8.68	2.05	0.77	<0.001	0.38
SOL2	10-15	39	10.97	1.65	0.80	<0.001	0.39
CB	20-30	31	9.31	2.10	0.76	<0.001	0.41
COL-Summer	1-6	30	9.00	1.93	0.85	<0.001	0.35
COL-Winter	1-6	31	7.60	2.12	0.93	<0.001	0.33
CZ-Summer	13-15	34	7.64	1.95	0.77	0.005	0.38
CZ-Autumn	13-15	30	8.85	2.02	0.77	0.005	0.38
CAC1	20-25	30	6.68	1.99	0.81	<0.001	0.34
CAC2	5-6	33	14.00	1.73	0.80	<0.001	0.35
Total		293	9.25	1.93	0.80	<0.001	0.39

Table 6. Comparison between Oltrepò Pavese grapevines and some forest species f/d relationships: a and b) fitting parameters of force/diameter relationship. The f/d relations of the forest species (identified with the asterisk) refer to data collected in Vergani et al. (2012).

Plant species	Parameters of f/d relationship		Root tensile strength (f) linked to a root diameter (d) of 2.0 mm
	a	b	
	(-)	(-)	(N)
Grapevine (combination of *Vitis berlandieri* and *Vitis riparia*)	9.25	1.93	35.2
European beech*	19.66	1.70	63.9
Spruce fir*	8.31	1.85	30.0
Sweet chestnut*	11.57	1.54	33.6
Ash*	10.63	1.74	35.5
Maple tree*	14.71	1.73	48.8
Hornbeam*	14.08	1.63	43.6
European larch*	12.31	1.49	34.6

List of the figures:

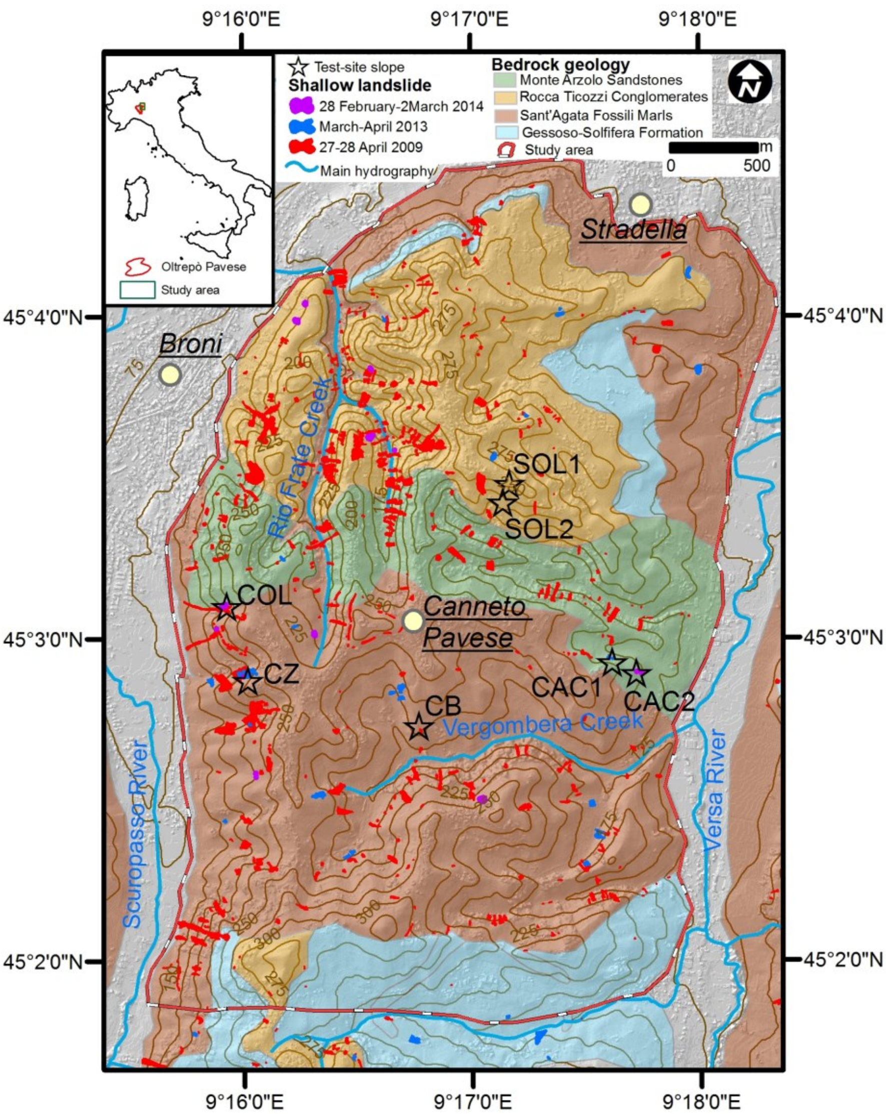


Figure 1. Location and geological sketch map of the study area.

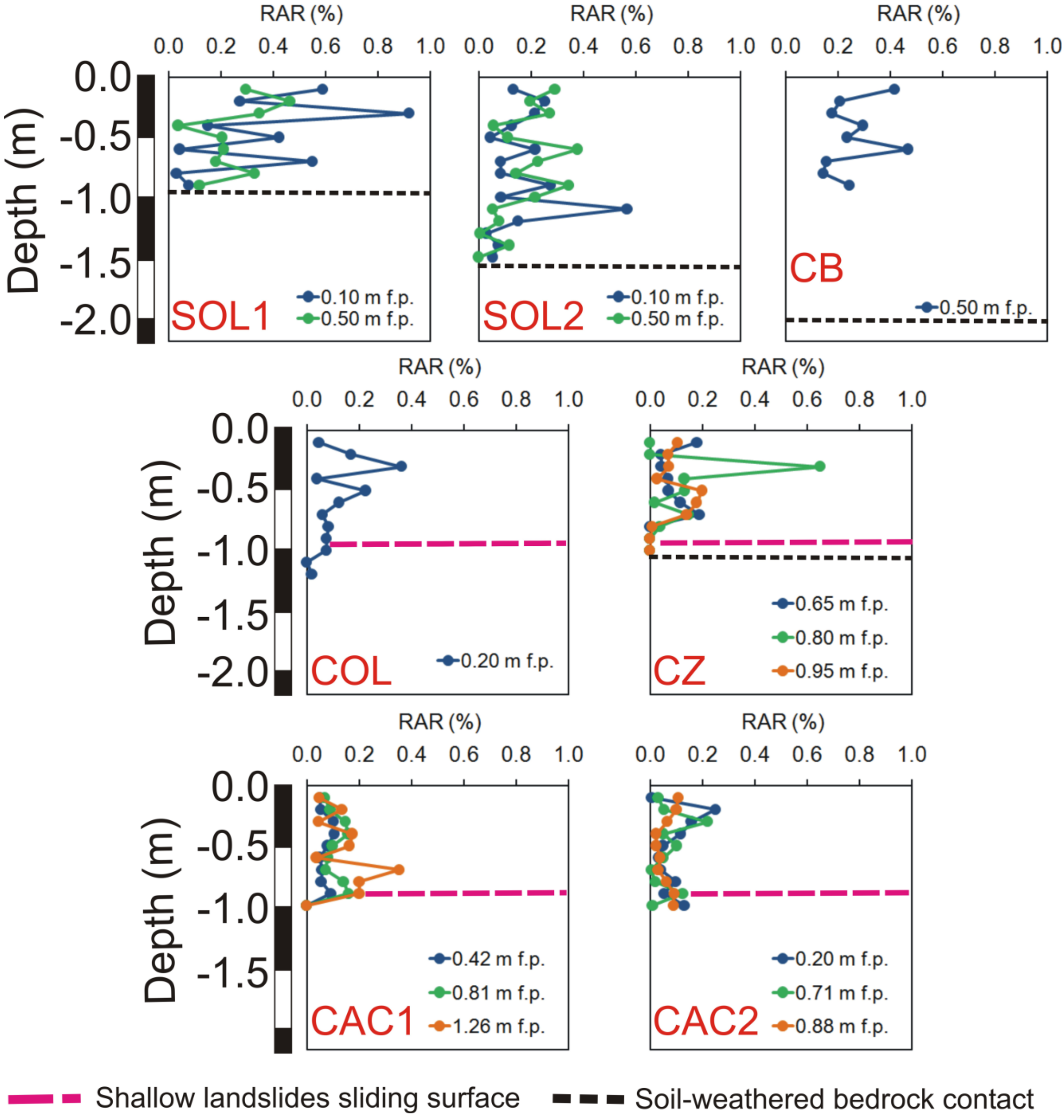


Figure 2. RAR distribution in tested vineyards site at different distance from plant (f. p.).

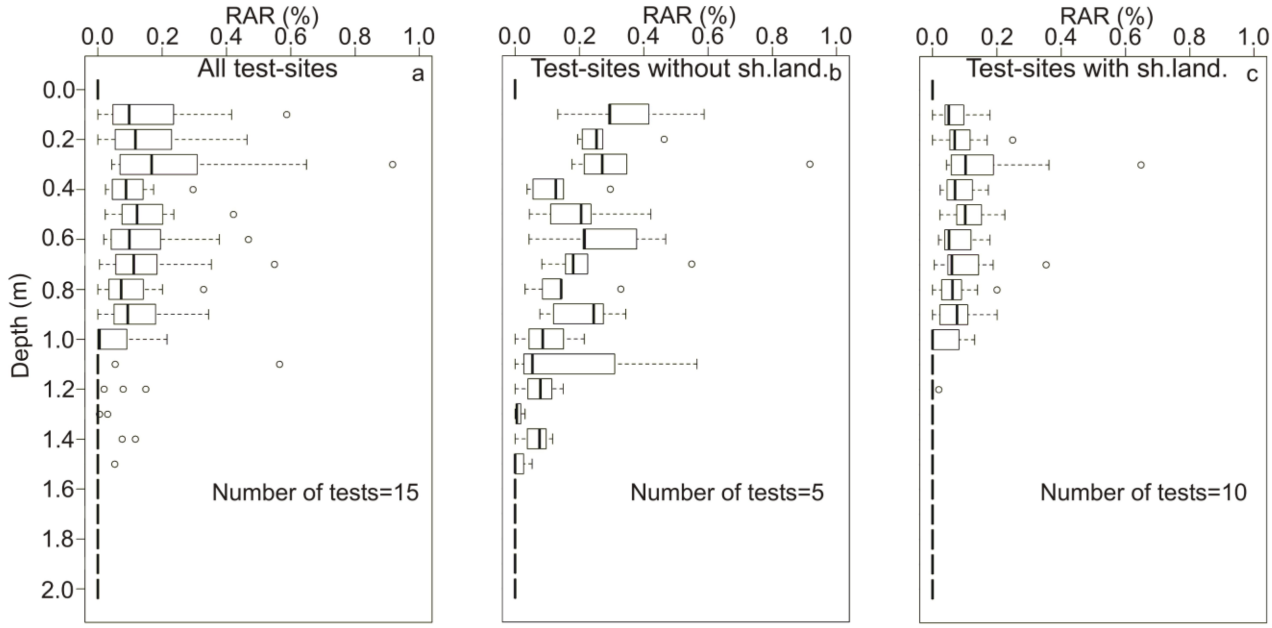


Figure 3. RAR trends with depth in the test-site slopes: a) all test-site slopes; b) slopes without shallow landslides; c) slopes affected by shallow landslides.

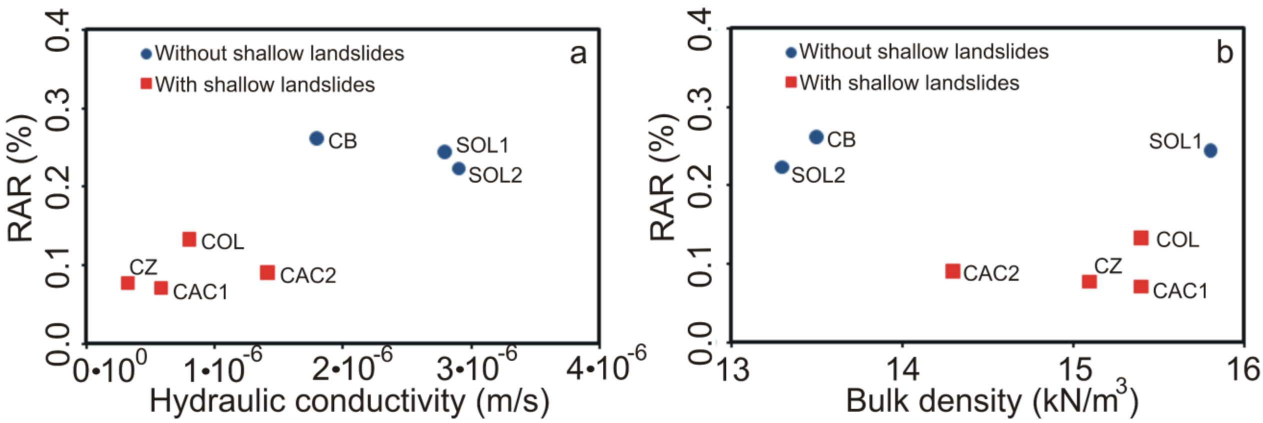


Figure 4. Mean RAR value of the soil profile (distance from plant between 0.20 and 0.65 m from plant) compared with a) saturated hydraulic conductivity (K_s) and b) bulk density (γ_d) for vineyards test-sites.

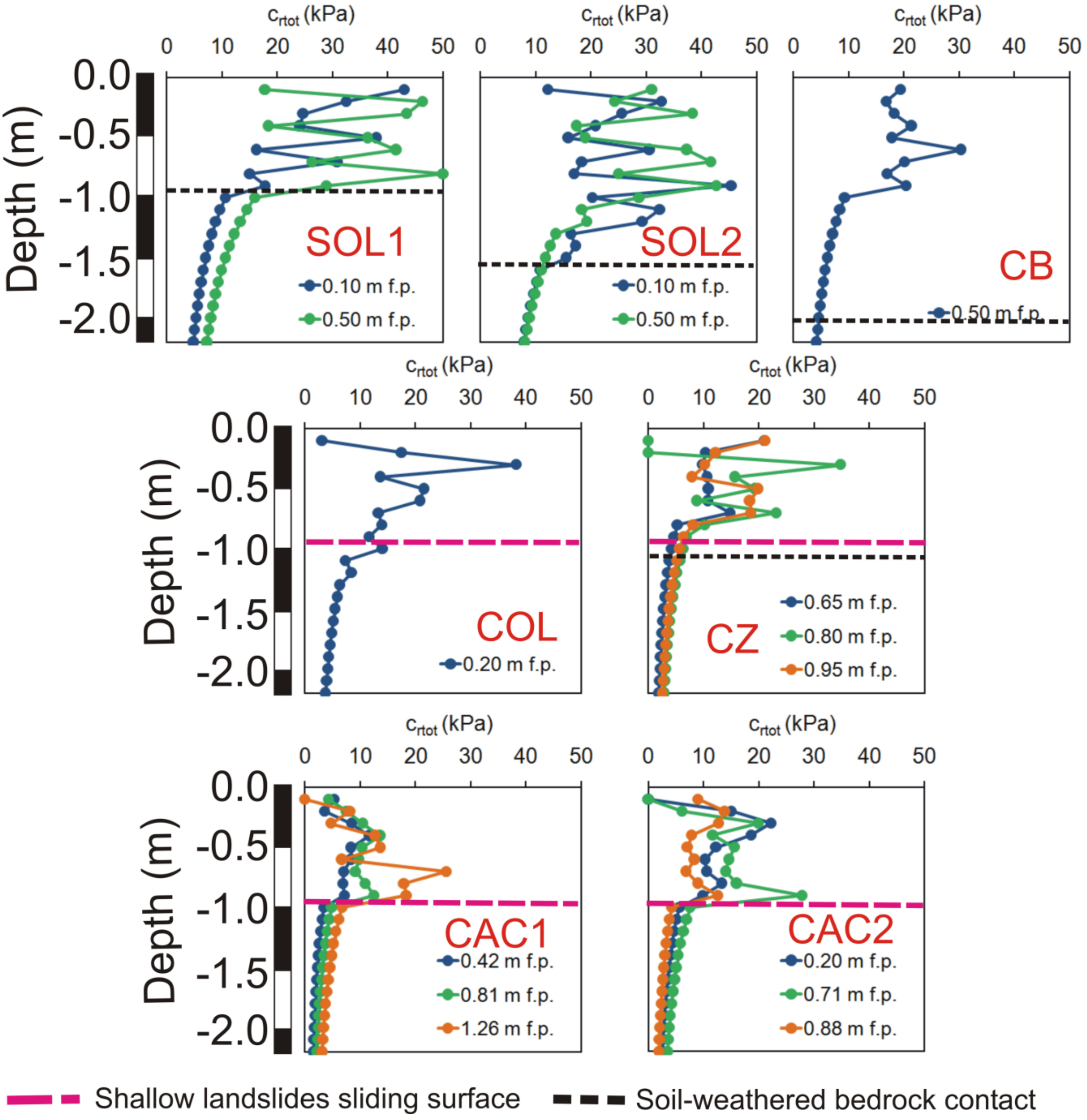


Figure 5. Total root reinforcement c_{rtot} distribution in tested vineyards site at different distance from plant (f. p.).

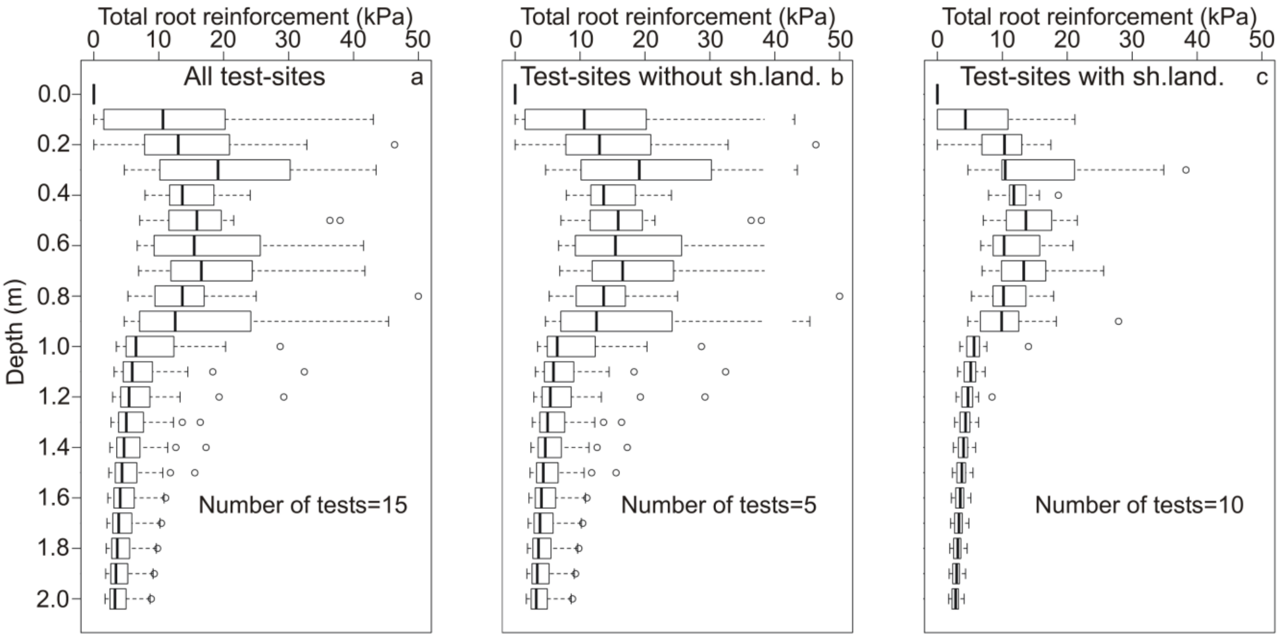
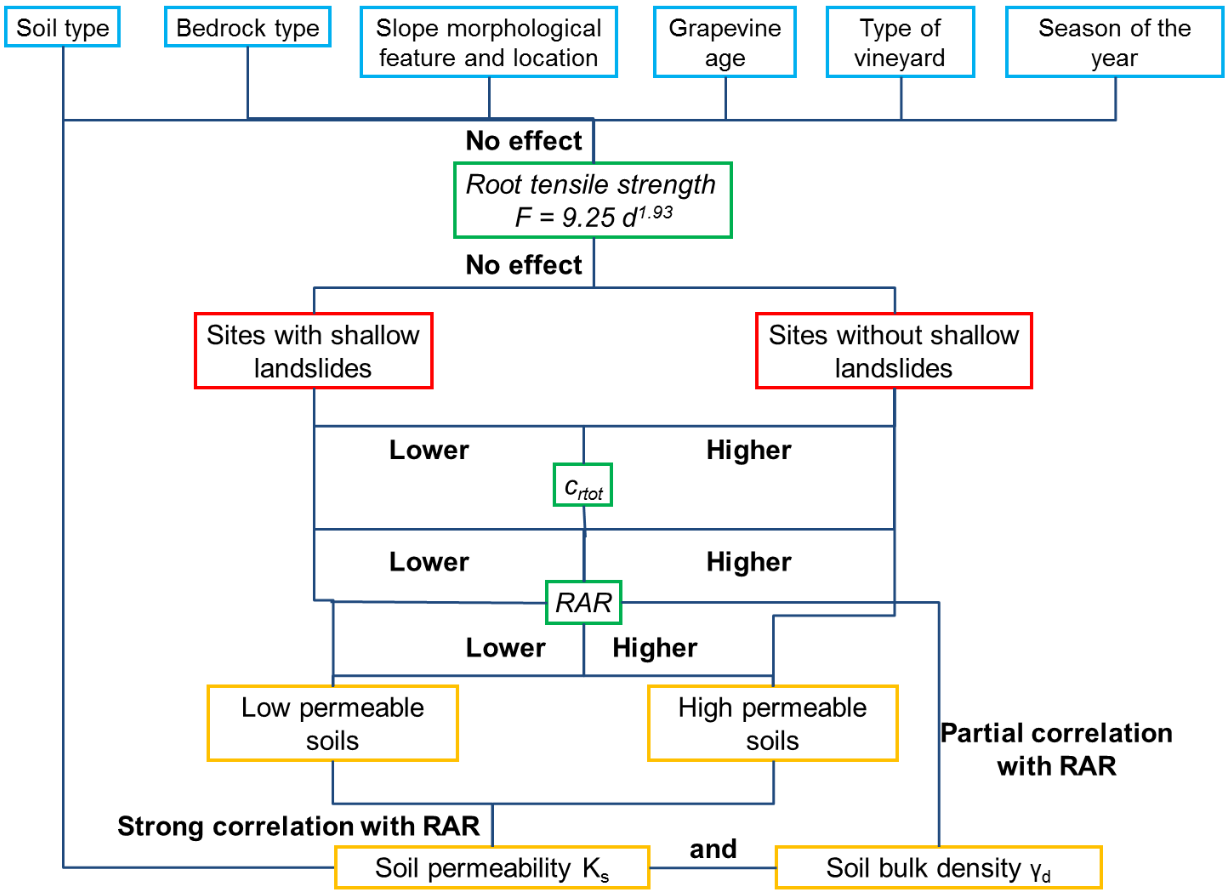


Figure 6. Total root reinforcement c_{rtot} trends with depth in the test-site slopes: a) all test-site slopes; b) slopes without shallow landslides; c) slopes affected by shallow landslides.



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2 Figure 7. Schematic flow chart of the main results of this research.