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PhD Thesis

SPATIAL AND TEMPORAL DYNAMICS OF ROOT REINFORCEMENT IN ALPINE FORESTS

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Abstract

Protection forests represent an effective tool to prevent and mitigate hydrogeological instabilities and are object of renewed interest in the European Alps, where there is a long history of cohabitation between people and natural hazards. The quantification of the effects of forests against the different types of natural hazards is however still a challenge, and represents a key step for the implementation of an integrated protection strategy able to combine engineering structures with forests. Forests provide different protection mechanisms depending on the type of natural hazards we consider. The aim of this work is to give a contribution to the quantification of the effects of forest vegetation against shallow landslides.

Mechanical reinforcement of soil given by root systems is considered the most important contribution of alpine forests against shallow landslides. Many studies proved that it plays a key role in slope stability, but its quantification is still a challenge due to the huge variability that characterizes root reinforcement values. Understanding and modeling this variability is a key step in the development of stability models able to account for the role of vegetation, and to provide practical guidelines to foresters involved in the management of protection forests.

Root mechanical reinforcement depends primarily on the density and distribution of roots of different diameter class (i.e. number and size of roots) and on their mechanical properties. Both these factors are subject to a huge variability in natural slopes. We can distinguish a spatial variability, due to the different environmental and stand characteristics that influence root systems development, and a temporal variability, due to the anthropic or natural disturbances that modify the forest stand and as consequence the root systems.

The first section of this work presents a review on the role of forests against shallow landslides and the state of the art of the studies on root reinforcement, the models used for its quantification and its implementation in the stability models.

The second section deals with the spatial variability of root reinforcement at both the regional and stand scale. The variability of root mechanical properties in several alpine species is analyzed basing on a wide data base obtained by laboratory tensile tests on roots coming from different forest sites in northern Italy, and a possible criterion for the interpretation and synthesis of this variability is proposed. The influence of both root mechanical properties and root distribution variability on the estimation of root reinforcement is then assessed in the case of a common alpine species, *Picea abies*, by means of the Root Bundle Model. Results show the importance of micro variability of root distribution at the stand scale that heavily affects root reinforcement estimation; the variability of root mechanical properties on the other hand cannot be ignored because it can lead to important errors in root reinforcement estimation.

In the third section of the work the temporal dynamics of root reinforcement as consequence of logging activities are studied with intensive field work carried out in two different case of study, two mixed Silver fir – Norway spruce stands in the Italian Alps and four Norway spruce stands in the Swiss Alps. New experimental data for the quantification of root reinforcement decay after cutting for the selected species are provided, paying attention to both root mechanical properties and root distribution. A model for the estimation of root reinforcement decay that takes into account both the processes is proposed. Results show the importance of modeling horizontal root distribution in the study on root reinforcement decay and underline the need of further research on the role of natural regeneration in stabilizing gaps after cutting.

Riassunto

Le foreste di protezione sono uno strumento fondamentale per la prevenzione dei fenomeni di dissesto idrogeologico, a maggior ragione nelle Alpi, dove c'è una lunga tradizione di coabitazione tra gli abitanti e i pericoli naturali. La quantificazione degli effetti della vegetazione contro i diversi tipi di pericoli naturali è tuttavia ancora difficile, sebbene rappresenti un passaggio necessario per l'adozione di una strategia integrata nella lotta al dissesto idrogeologico, in cui le foreste possano giocare un ruolo accanto alle tradizionali opere ingegneristiche. Le foreste di protezione agiscono in modo diverso a seconda del pericolo naturale considerato. L'obbiettivo di questo lavoro è di dare un contributo alla quantificazione degli effetti della vegetazione forestale contro le frane superficiali.

Il contributo più significativo fornito dal bosco contro questo tipo di pericolo naturale è il rinforzo meccanico del suolo esercitato dagli apparati radicali. Diversi studi hanno dimostrato che il rinforzo radicale può fare la differenza tra versanti stabili e instabili, ma la sua quantificazione è ostacolata dalla estrema variabilità che lo caratterizza. Comprendere e riuscire a modellizzare tale variabilità è un passaggio fondamentale per procedere a un'affidabile implementazione del rinforzo radicale nei modelli di stabilità dei versanti che tengano conto del ruolo della vegetazione, e per dare indicazioni tecniche agli operatori e ai decisori coinvolti nella gestione delle foreste di protezione.

Il rinforzo radicale dipende in primo luogo dalla densità e dalla distribuzione delle radici nelle diverse classi di diametro, e dalle proprietà meccaniche delle radici stesse. Entrambi questi fattori sono soggetti a un'estrema variabilità negli ecosistemi forestali. Si può distinguere una variabilità spaziale, dovuta alle caratteristiche ambientali e del popolamento forestale, e una variabilità temporale, dovuta a disturbi naturali e antropici che condizionano l'evolversi dell'ecosistema forestale e quindi anche dell'apparato radicale.

In questo lavoro viene dapprima presentata una revisione sul ruolo delle foreste contro le frane superficiali e sullo stato dell'arte degli studi sul rinforzo radicale. Successivamente, nella seconda sezione è stato affrontato il tema della variabilità spaziale del rinforzo sia a scala locale (cioè di popolamento forestale) che regionale. Ci si è concentrati innanzitutto sulla variabilità delle caratteristiche meccaniche delle radici di un consistente numero di specie diffuse nell'arco alpino, basandosi su un consistente database ottenuto grazie a prove di trazione di laboratorio su radici provenienti da diverse stazioni forestali alpine. Sulla base dell'analisi di questi dati viene proposto un possibile criterio per l'interpretazione della variabilità delle caratteristiche meccaniche delle radici di una data specie. Successivamente è stata valutata l'influenza sulla stima del rinforzo da parte della variabilità sia delle caratteristiche meccaniche sia della distribuzione radicale sulla stima del rinforzo. Per perseguire tale scopo sono state eseguite una serie di simulazioni con il Fiber Bundle Model su un consistente database di dati relativi a un'importante specie alpina, l'abete rosso. I risultati ottenuti

evidenziano l'importanza della micro variabilità della distribuzione delle radici come fattore determinante nella stima del rinforzo radicale; al tempo stesso anche la variabilità delle caratteristiche meccaniche non può essere ignorata perché può condurre a importanti errori nelle stime del rinforzo.

Nella terza parte del lavoro è stata affrontata la dinamica temporale del rinforzo radicale dopo i trattamenti selvicolturali. Sono stati analizzati due diversi casi di studio, due abieteti nelle Alpi lombarde e quattro peccete nelle Alpi svizzere. Nuovi dati sperimentali per la quantificazione del decadimento del rinforzo radicale dopo i tagli vengono forniti, sia in riferimento alla densità e distribuzione delle radici che alle loro proprietà meccaniche. Viene inoltre proposto un modello per la stima del decadimento del rinforzo radicale che tiene conto di entrambi i processi. I risultati evidenziano l'importanza della modellizzazione della distribuzione delle radici negli studi sul decadimento del rinforzo radicale e la necessità di studi sulla rinnovazione naturale post taglio che può dare un contributo significativo alla stabilizzazione dei versanti sottoposti a trattamenti selvicolturali.

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Introduction and aims of the work

Floods and landslides are natural phenomena which have an important role in shaping mountain areas and in redefining geomorphic structures (Sidle and Ochiai, 2006), but they often turn into catastrophic events when they impact human settlements and activities. Actually, about 14 million people lives in the European Alpine mountain region, and the Alps affect the lives of 56 million of people living in the neighboring metropolis (CIPRA Annual Report, 2012). The expansion of human activities in areas prone to natural hazards leads to an increase of the risk, which is defined as the combination of the presence of a hazard and human activities or interests (vulnerability). A research carried out by CNR-GDCI documented in Italy 28804 floods and 32059 landslides between 1918 and 2005, with a trend drastically increasing (Bischetti and Ricci, 2013). A densely populated territory covered for the 70% by hills and mountains makes Italy the country with the highest number of landslides casualties in Europe (an average of 18 casualties per year, Sidle and Ochiai, 2006) and with the 70% of the municipalities subjected to the risk of floods and landslides (Legambiente, 2006).

The problem of hydrogeological instability is often faced in Italy with the well known “logic of the emergency” with the sporadic construction of huge single infrastructures, without a long term planning at the catchment scale (Bischetti and D’Agostino 2010). The costs of such a policy are huge, with 16 billions of euro spent in the last 50 years to remediate the damages due exclusively to floods (ISPRA, 2008). In a social and economic context where the resources are tailing off, it is mandatory to change the strategy in the mountain risk management, moving from the logic of the emergency to the logic of the prevention and mitigation with an integrated approach. In such a view forests can play a key role, integrating the effect of the engineering structures in the protection against natural hazards as landslides, floods, rock falls. The protection role of forests, known from centuries in the Alpine communities, have been rediscovered in the last decades as an effective, less impacting and cheaper instrument to face the hydrogeomorphological risk. This opportunity today is practically used in most alpine regions as Austria, Switzerland and Slovenia, and starts to be considered in some Italian regions.

Forestry and natural hazards policies need to base on scientific background, which can support the decision’s makers and the forest managers. A simple and reliable quantification of the effect of forests against the different types of natural hazards is a key step in order to define a comprehensive and feasible risk mitigation strategy. Such an issue still remains largely unresolved.

The aim of this work is to contribute to fill the gap focusing on the role of forests in the protection against shallow landslides by means of the mechanical effect of the root systems, known as root reinforcement. In particular, the quantification of spatial and temporal dynamics of root reinforcement in alpine forests is addressed. It has been shown by many studies that root reinforcement can provide the difference between stable and unstable slopes (Rienstenberg and Sovonick-Dunford, 1983; Abe and Iwamoto, 1986; Schmidt et al., 2001). However, the lack of comprehensive data on root reinforcement values in soils and the high variability in the reported values have complicated the integration of root reinforcement into landslide analyses (Swanston, 1970; Terwilliger and Waldron, 1990, Schmidt et al., 2001). Root reinforcement has been proved to vary spatially not only in function of the species considered, but also in function of the stand characteristics and the environmental conditions. There is a variability at the local scale (stand level) and at the regional scale (catchment level). A better comprehension of this variability is needed to upscale of root reinforcement distribution from the tree to the catchment scale; moreover, it can provide some useful indications about the use of the data already available from the literature and about the priority in the collection of new data, which is demanding and time consuming when dealing with root systems. A second important point is the temporal variability of root reinforcement, due to natural disturbances or to forest management. The second part of this work focuses on the effect of forest management on root reinforcement, with the aim to provide data of interest for the management of protection forests.

In chapter 1, the effect of forests against shallow landslides is discussed, with a focus on root reinforcement. A review on the state of the art on root reinforcement, on the models used for its quantification and its implementation in the hillslope stability models is presented.

In chapter 2, the spatial variability of root reinforcement is addressed, as consequence of both root force variability and root distribution variability. In chapter 2.1 the variability of root force for different species in the alpine context is discussed basing on a wide database realized in the SISIFO project (Bischetti et al., 2010), and a key for the interpretation of this variability is proposed. In chapter 2.2 the effect of root distribution and root force spatial variability on root reinforcement is quantified, focusing on Norway spruce, one of the most interesting species for alpine protection forests due to its wide diffusion in the alpine environment. To assess the sensitivity of root reinforcement to the variability of both force and root distribution, root force data presented in chapter 2.1 for Norway spruce are combined with a large dataset of root distribution data of the same species obtained from literature, covering both the north (Switzerland) and south (Italy) side of the Alps.

Chapter 3 focuses on the temporal variability of root reinforcement as consequence of the disturbances affecting forest stands after forest management. Two cases of study in European Alps are presented, focusing on two common alpine species, *Abies alba* M. (chapter 3.1) and *Picea abies* L. (chapter 3.2). New experimental data are provided and results are discussed in the perspective of the implications for future research.

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1 Quantifying protection forests contribution against shallow landslides

1.1 Protection forests: history and modernity

The awareness of the importance of mountain forests to protect people and human's activities against natural hazards has deep roots in the history of the mountain communities all over the world. There are allusions to this forest role in Greek, Hebrew and Roman literature (Hamilton et al., 1992). A Chinese print of the 16th century shows a tree restoration project to pursue "river conservancy" (Hamilton et al., 1992). Japanese land managers have been using protection forests for the purpose of protecting railroads for more than 100 years (Sakals et al., 2006), as well as in Taiwan protection forests have been designated for more than a century (Cheng et al., 2002). In the European alpine region, where there is a very long history of cohabitation between people and natural hazards, rules for protection forests are known since the Middle Age. In the Valle d'Aosta Region there are documents dating back to 13th century recognizing the function of forest in preventing damage from extreme events and that limited the exploitation of woods (Motta and Haudemand, 2000). Rules limiting forest-clearing activities can be found similarly in documents and regulations of the Republic of Venice from as early as the 13th and 14th centuries (Bischetti et al., 2009). These rules were finally codified into laws in the 19th century in some alpine countries: France in 1850 experienced extensive floods with 100 year time of return, which lead to the promulgation of a law in 1860 concerning mountain restoration and reforestation; in Switzerland a law on protection forest was codified in 1872 (Zwerman and Richard, 1959). In Austria, the massive flood disaster that occurred in the territory of Austria-Hungary in 1882 led to the initiative for sediment control and forest conservation as a national undertaking that started in 1884 (Yamakoshi, 2008).

If no forests existed in the Alps, human populations would not inhabit most valleys (Motta and Haudemand, 2000). Actually, about 14 million people lives in the European Alpine mountain region, and the Alps affect the lives of 56 million of people living in the neighboring metropolis (CIPRA Annual Report, 2012). With the extension of human settlement and activities in mountainous area, the risk due to natural hazards (defined as the combined presence of a natural hazards and human activities or interests) is increasing. This is a critical issue especially for the Italian territory, where from the second postwar period there was been an increasing of the hydrogeological instability (Fig. 1.1.1) with 70.000 people involved and 30.000 billion of euro spent in the last 20 years (ISPRA, 2008). Some events turn into big disasters as Val di Pola landslide (1987), Piemonte floods (1994), Versilia (1996), Sarno (1998), Friuli (2003) and

Giampilieri (2009). Actually, the 70% of the Italian municipality are considered at risk of floods and landslides (Legambiente, 2006).

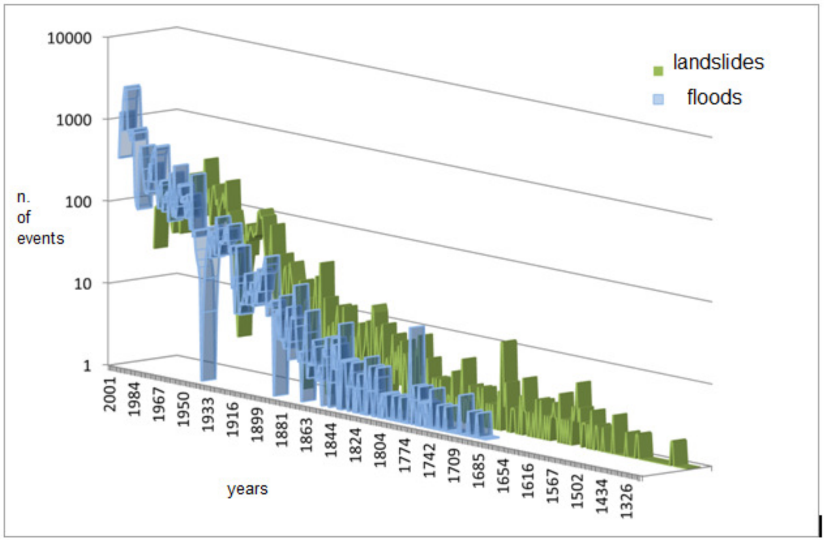

Fig. 1.1.1 Landslides and floods events surveyed by the project AVI (CNR-GDCI) in Italy. Bischetti and Ricci, 2013.

Given the gravity of the issue and the present social and economic context, where the resources are continuously getting lower, it is mandatory to reconsider the strategy in contrasting the hydrogeological risk in mountainous and hilly areas, moving from the logic of an enduring emergency to a prevention strategy based on an integrated approach.

Such an approach entails that vegetation, and in particular the forests, can be considered as a tool able to prevent and mitigate natural hazards next to the traditional engineering structures. The advantages of such an approach are a lower environmental impact and a significant reduction in the costs, because the maintenance of forests to make them suitable for the protection function partially substitutes the investments for more expensive engineering works. For instance, a Swiss study estimates that a protection forest costs in 100 years about 100.000 Swiss francs per hectare, whereas the traditional engineering structure would require about one billion of francs, that is 10 times more expensive (Zimmermann et al., 2008). The appropriate identification and management of protection forests can therefore make mountain regions safer for people and protect resources (Sakals et al., 2006).

The MCPFE Report on Sustainable Forest Management in Europe (MCPFE 2007) defines forests with protective functions as forests where "[…] *management is clearly directed to protect soil and its properties or water quality and quantity or other forest ecosystems, or to protect infrastructure and managed natural resources against natural hazards. Forests and other wooded land are* *explicitly designated to fulfill protective functions in management plans or other legally authorized equivalents. Any operation negatively affecting soil or water or the ability to protect other ecosystem functions, or the ability to protect infrastructure and managed natural resources against natural hazards, is prevented.*"(Bauerhansl et al., 2010).

This definition implies that there are two different types of protection provided by a forest (Meloni et al., 2006, Brang et al., 2006): indirect and direct protection. Forests with indirect protective function provide a first level of protection, which is typical of all the forest ecosystems: they generally improve hillslope stability, reduce soil erosion and improve watershed conditions regulating the yield and transport of sediments. This kind of forest in the steep areas also guarantees a mitigation of natural hazards, not primarily at a local scale, but at a regional scale (catchment area). The forest impact mainly depends on the proportion of forests at a landscape level, and the exact location of the forest is not important. This makes impossible to establish a relationship between the protective effects of the forest and the potential damage. As stated by Brang et al., (2006), a direct protection forest is instead a forest that has its primary function in the protection of people or settlements or infrastructures against the impacts of natural hazards (Fig. 1.1.2 and Fig. 1.1.3). This definition implies the simultaneous presence of: i) a natural hazards or a potentially adverse climate that may cause the damage, ii) people or assets that may be damaged, iii) a forest that has the potential to mitigate this potential damage (Schònenberger, 1998). Protection forests may not prevent hydrogeomorphic events from occurring, but may decrease and mitigate their effects even for large events (Sakals et al., 2006). The natural hazards that protection forests defend against include snow avalanches, rockfalls, shallow landslides (which are the focus of this work), debris flows, surface erosion and floods.

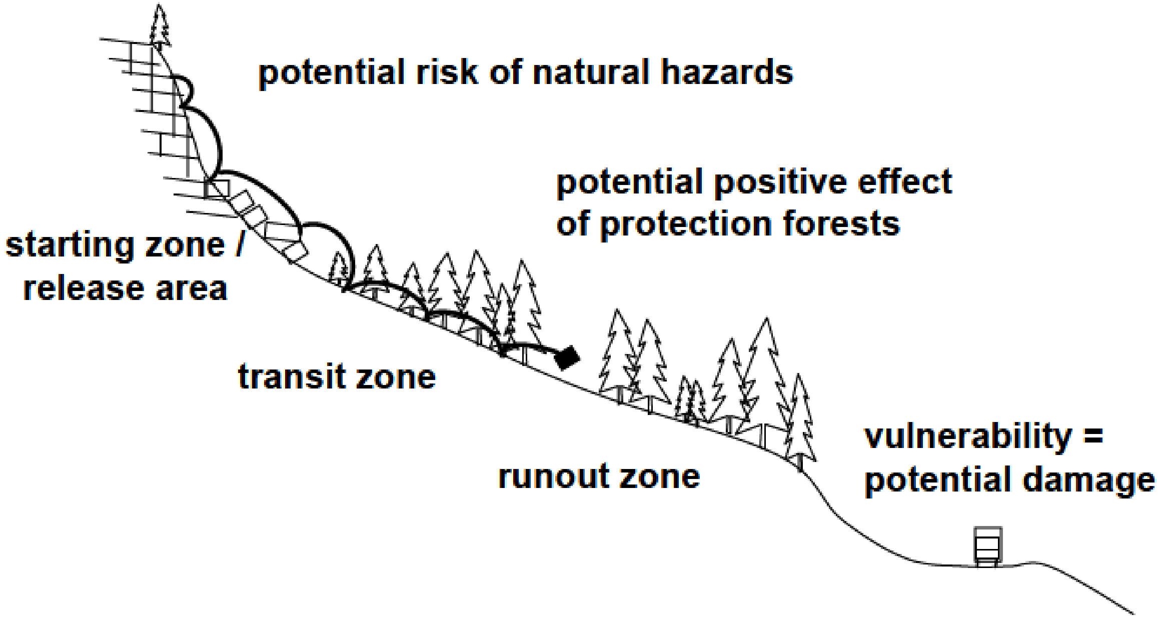

Fig. 1.1.2 Direct protection forest scheme. Bauerhansl et al., 2010.

Fig. 1.1.3 The "Bawald" of Ritzingen, Canton Vallese (CH): direct protection forest against snow avalanches. Frehner et al., 2005.

The role of forests in the protection against natural hazards is nowadays widely rediscovered not only by the scientific community but also by governments of the different countries, especially where natural disasters are frequent. In some Asian countries, for instance, the awareness of the importance of protection forest is increasing: in China, Republic of Korea, Myanmar, Thailand and Viet Nam the area of protection forest has expanded significantly in the past 20 years, often as a results of programs aimed directly at watershed protection (Forbes and Broadhead, 2011). It is important to underline that not always the forestry policies adopted in response to natural disasters are effective. For instance, the logging moratoria pronounced in the Philippines in 2011 and the reforestation project adopted afterwards was not appropriated in relation to the deep seated landslides that occurred in the affected area. In the same way a logging ban was pronounced in Thailand after the landslides occurred in 1988 following heavy rains, but some reports suggested that the landslide density was independent of vegetation cover. For this reason is essential a sound scientific and technical understanding about the benefits of forest and the conditions under which they can and cannot stabilize hillslopes, in order to guide future policies and to plan a sustainable management of existing forests.

Focusing on European Alpine regions, in Austria, Switzerland, France, Germany and Slovenia protection forests are mapped distinguishing between forests with direct and indirect protection function. Forest with direct protection function protect people, settlements, infrastructures, cultivated land (Austria and Slovenia) from natural hazards; forests with indirect protection function protect the forest site and improve the capacity of hydrological retention.(Bauerhansl et al., 2010). The considered natural hazards are gravitational natural hazards (avalanches, rockfall, landslides) and natural processes with indirect impacts like flood, water and wind erosion. Logging of forest with protective function is forbidden; the forest owners are restricted in their forest management, and subsides can be given for adequate management in forests with protective effect, with priority to the forest with direct protection effect (Switzerland). In Italy, due to a recent administrative decentralization process, there are different rules adopted by the different Regional Authorities for the definition and delimitation of the protection forests. A specific map of the forests with direct protective function has been developed by the region Valle d'Aosta (Meloni et al., 2006). In Piemonte are classified as protection forests those that directly protect settlement and infrastructure and the forests relevant for the protection of the streams from erosion. In Lombardia the forests with protection function are individuated in the plans for the forest management and include slope protection, floods protection, erosion protection and quality of water protection. Finally, in Liguria protection forests are identified distinguishing between protection against shallow landslides and protection against water erosion.

The effectiveness and reliability of the protection function provided by a forest depends on the natural hazards considered, the frequency and intensity of damaging events, and the condition of the protection forest itself (Brang et al., 2006). The management of the protection forests influences forest dynamics in order to obtain a forest suitable for the protection function and is a key issue for an effective mitigation strategy against natural hazards. For centuries, the only action regarding alpine forests was to ban timber harvesting (Motta and Haudemand, 2000). This can be explained if we consider the social and economic context of the time: especially after the industrial revolution, the primary need was to protect the forests and the landscape from an indiscriminate exploitation. Today we face the opposite problem, a progressive abandon of forests due to the lack of adequate profit, because costs exceed benefits. Nowadays leaving a protection forest unmanaged can be an option, but it is accepted just if the potential damage is small and it depends on the forest conditions (Brang et al., 2006). A not managed forest cannot always ensure the protective function with continuity: when a forest becomes over mature due to a lack of disturbances, disease and windthrow become more common, creating gaps characterized by reduced structure (Schonenberg et al., 2005) and reduced root reinforcement (Sakals and Sidle, 2004). This situation may increase snow avalanches, rock fall and landslide hazards (Sakals et al., 2006). The resistance to disturbance and the recovery rate following the disturbance form the long term capacity of protection forests. Resistant forests are less susceptible to losing their protective function as a result of hydrogeomorphic events or other disturbances; resilient forests will recover protective functions more rapidly after a disturbing event (Sakals et al., 2006). Healthy and mature forests are supposed to have higher levels of resilience and resistance, but not always. For this reason, maintaining an high level of protection may therefore require active management direct to increase this attributes; in particular forestry based on the natural cycles of forests guarantees the stability of mountain protection forest (Berger and Rey, 2004). Due to the probabilistic nature of natural hazard risk, maximum protection could be an inappropriate target. Returns on investment diminish as the residual risk (the risk associated to the hazard beyond the design level), is reduced to relatively small values (Sakals et al., 2006, Fig. 1.1.4). The optimum level of management should therefore be assessed considering the actual condition and the potential future condition of the protection forest, the desired levels of protection and the socio-economic issues. Motta and Haudemand, (2000), suggest that an acceptable degree of stability should be aimed to ensure the functions required for the protective forests over the following 20-50 years. Operations aimed to achieve this level of stability are called “minimal tending of protective forest” (Wasser et al., 1996).

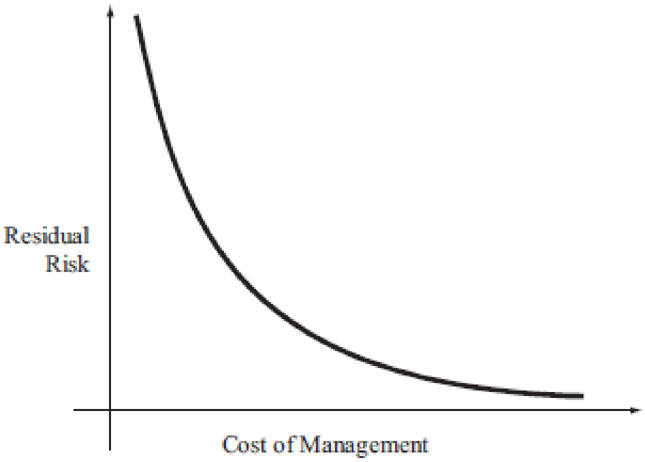

Fig. 1.1.4 Diagram relating residual risk to cost of management of protection forest. Sakals et al., 2006.

Foresters of the European alpine countries agree that guidelines are necessary, giving recommendations for field observation and intervention planning. In Switzerland this issue has been addressed with practical guidelines for the forestry activities in the protection forests (Frehner et al., 2005), developed collaboratively by forest managers and scientists, with the aim of guarantee a protection effective and continuous. The approach is based on a comparison between the current condition of the forest and the target forest condition, which is specific for both natural hazards and site conditions (Brang et al., 2006). The target condition consists in an ‘ideal’ forest condition and on a ‘minimum’ forest condition. The first one describes long-term forestry objectives, the second one is the lower threshold for forest management. Also in Italy some regions (Valle d’Aosta, Piemonte, Liguria) carried out projects in order to face the problem of the management of the protection forests, with practical forestry indications based on the type of natural hazards and the typology of the forest stand.

During the last decades, research made a consistent improvement in the understanding of the effect of protection forests to allow science-based decision making. Nevertheless many questions are still a challenge. As stated previously, the development of adequate strategies in the management of protection forests depends on the natural hazards considered, on the environmental conditions and on the ecological needs of each species. Furthermore, it is crucial to quantify the effect of the vegetation against natural hazards, as it can be done for the engineering structure. The effects of forest against shallow landslides are briefly described in the following chapter.

1.2 The role of forests against shallow landslides

Today landslides represent a growing risk primarily because of the expansion of settlement and human activities on unstable areas; moreover, it is likely that climate change will contribute to exacerbate these problems (Forbes and Broadhead, 2011). Landslides can be defined as a variety of processes that result in a down slope movement of slope-forming materials as rock ,soil, artificial fill or a combination of these materials; gravity is always the main triggering factor and it may be supplemented by water (Sidle and Ochiai, 2006).

Landslides can be classified in different types based on the type of movement (falling, toppling, sliding, spreading, flowing and their combinations) and material (soil or rock) (Highland and Bobrowsky, 2008). Different and complex classifications have been proposed providing detailed descriptions of the initiation and failure mechanism, materials and velocity (Varnes, 1978; Cruden and Varnes, 1978; Sassa 1989). From a land management point of view, a broad functional classification of landslides can be more useful (Sidle and Ochiai 2006). Based on this classification, five functional categories of mass movements can be identified: 1) shallow, rapid landslides; 2) rapid, deep slides and flows; 3) slower, deep-seated landslides; 4) slow flows and deformations; 5) surface mass wasting (dry ravel). This type of classification takes into account the depth of the failure plane, which is an important element to consider when dealing with the effect of the forest vegetation (Frehner et al., 2005). Deep seated landslides have a failure depth superior than 2 meters, with a slope movement in the order of the centimeters or decimeters per year, and usually involve great surfaces. Shallow landslides (Fig. 1.2.1) have a failure depth comprised between 0 and 2 meters, the landslide activity lasts from minutes to months , the scar area is limited (between 50 to 1000 m^2) and volumes range from a few to several hundred cubic meters (Frehener et al., 2005, Rickli and Graf, 2009). Climatic triggering factors of shallow landslides are typically heavy rainfall of short duration and high intensity, or long duration with low intensity (Rickli and Graf, 2009) and rapid snowmelt (Sidle and Ochiai, 2006). Shallow landsliding is one of the most common geomorphic process in the mountain areas of the world (Begueria, 2006). The danger due to these slope instabilities is considerable since they often evolve in debris flow that more frequently affect human activities; they also constitute a major process of land degradation and are responsible for a substantial fraction of the total sediment delivery that may increase the danger due to sediment transport during rainstorms (Rickli and Graf, 2009, Begueria, 2006).

Fig. 1.2.1 Shallow landslide in Val del Riso, northern Italy.

Forests can have both positive and negative effects on slope stability, depending on their structure and state; however empirical evidence shows that the effects are mostly positive and that natural forests provide the greatest level of slope protection compared to other forms of land use (Forbes and Brodhead, 2011).

The importance of the role of the vegetation becomes evident observing the consequences of the unlimited exploitation of the forests. Many studies in North America, New Zealand, Japan have shown an increase in landslide frequency after forest logging for up to two decades (Sidle et al., 2006, Montgomery et al. 2000, O'Loughlin and Ziemer, 1982, Bishop and Stevens, 1964, Fig. 1.2.2). Jacob (2000) observed a frequency of landslides events nine times higher in the areas subjected to clear cutting than in forest areas in British Columbia. Analyzing landsliding phenomena in three watershed in the same region (Vancouver Island, British Columbia), Guthrie (2002) found a substantial increase in the number of landslides following logging, and an increase also in the number of landslides reaching streams. The impact on shallow landslides is higher in the first 10-17 years after cutting, but lasts until 25 years after (Imaizumi et al., 2008, Dhakal and Sidle, 2003). Moreover, once forests are cleared, less extreme events, which are also more frequent, are likely to be sufficient to trigger landslides on a great number of slopes due to lowered resistance thresholds.

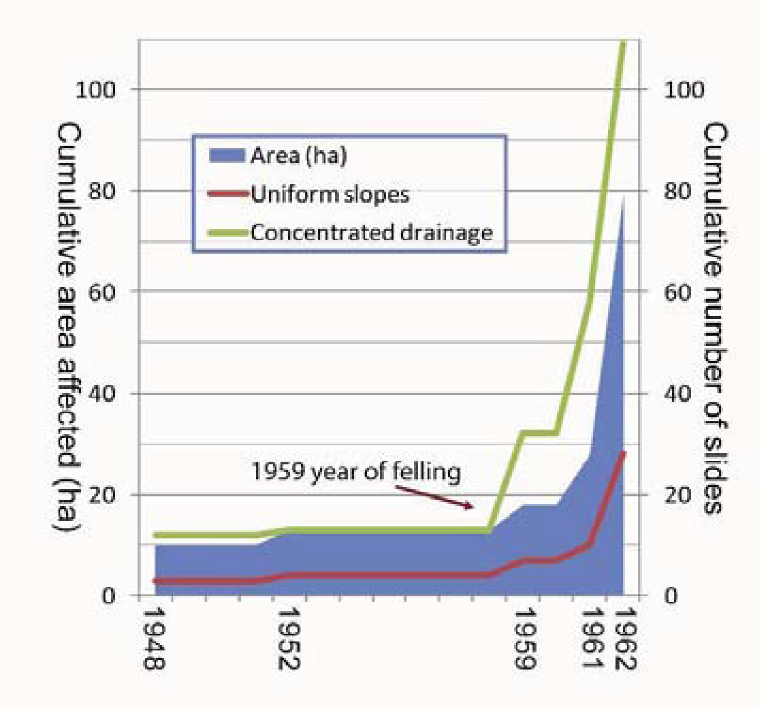

Fig. 1.2.2 A study from Bishop and Stevens (1964) shows a substantial increase in landslides frequency and size of affected areas after clear cutting in Hollis, Alaska. Forbes and Broadhead, 2011.

The positive effects of forest on slope stability can be distinguished in two big classes of processes: mechanical processes and hydrological processes. If we consider deep seated landslides, the role of forest is considerably less although they can have an indirect beneficial effect due to hydrological mechanisms. Shallow landslides instead involved the area interested by root systems: in this case besides the indirect hydrological mechanisms there is a direct action due to root mechanical effects. Several landslides inventories found that shallow landslides are less frequent in forests than in open land and it has been shown that landslides within the forested areas occurred on steeper slopes than those in open land (Rickli and Graf, 2009). Slopes in forested areas can be therefore assessed as stable at inclinations several degrees higher than those of slopes covered by herbaceous vegetation only.

Hydrological effects reduce the moisture content of the soil and thereby delay the onset of soil saturation levels at which landslides are triggered (Forbes et Broadhead, 2011). The main processes are the following:

- ✓ Interception and evaporation: through these processes the volume of effective rainfall reaching the ground is reduced. In a light rain most of the rainfall may be intercepted and even in high intensity storms trees intercept about 15-25 percent of rainfall (Coppin and Richards, 1990). A study in a coast Douglas fir stand in the Pacific Northwest region, USA, showed that maximum intensity precipitation were reduced under forest canopy, and the modeling of water pore-pressure response resulted in a greater stability of the same slope under the forest canopy than without forest canopy (Keim and Skaugset, 2003, Fig. 1.2.3). Different species have different interception capacity: the maximum value for beech and spruce have been measured at 2.6 mm and 4.7 mm respectively (Ulrich and Benecke, 1981). Temperate deciduous forests intercept 15-25 percent of the annual precipitation while temperate coniferous forest 25-35 percent (Styczen and Morgan, 1995). Forests if harvested loose most rainfall interception. One example from northwest California estimates that clearcut logging of redwood (*Sequoia sempervirens*) and Douglas fir *(Pseudotsuga menziesii)* would increase effective annual rainfall by 20-30 percent, and most of the increase would occur during large storms, potentially influencing slope stability (Reid and Lewis, 2009).

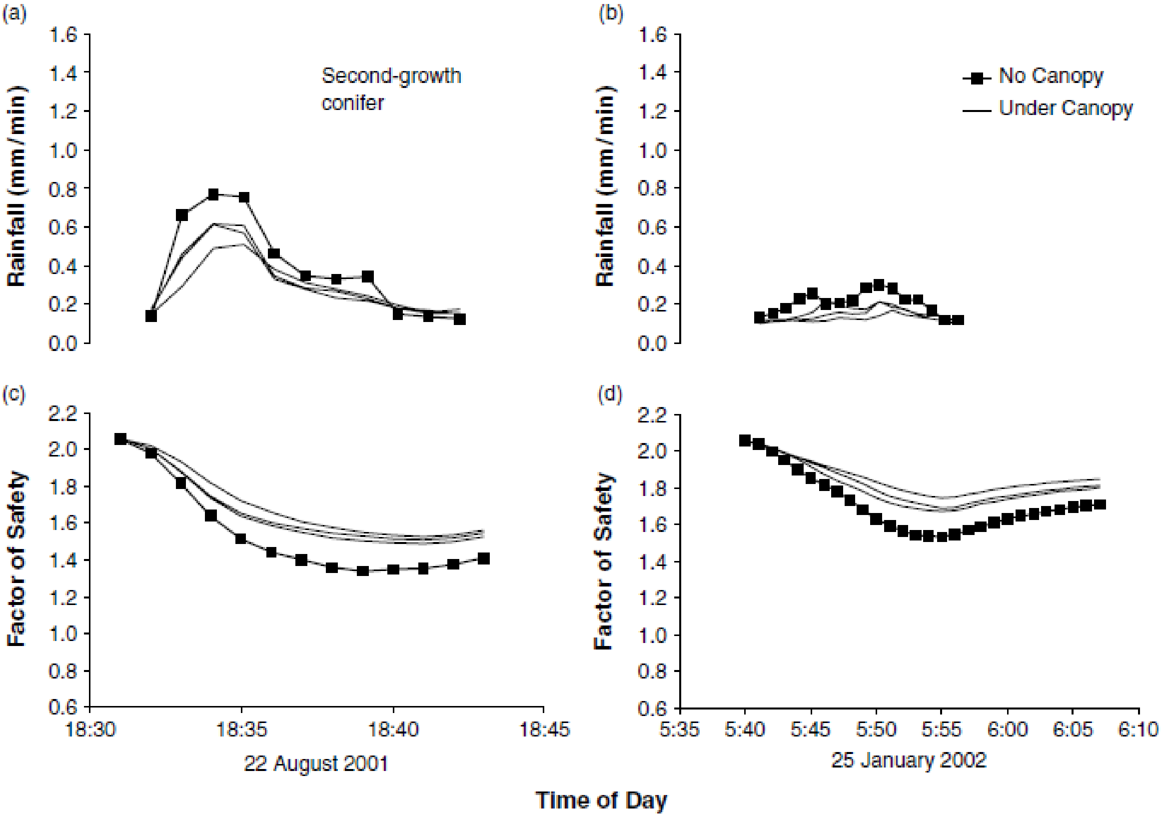

Fig. 1.2.3 Observed rainfall under and adjacent a 60 years old stand of Douglas fir in western Oregon, and corresponding values of the factor of safety of a hypothetical 45° slope. Keim and Skaugset, 2003.

✓ Suction and transpiration. Trees are able to extract moisture from the soil at a considerable depth and reduce moisture levels at a distance of up to three times the radius of the crown (Gray and Sotir, 1996). Where precipitation considerably exceeds potential evapotranspiration, such as in cool temperate and sub alpine regions, the reduction in soil moisture through transpiration and evaporation is small and the effect of vegetation is minimal. A study in British Columbia showed that reduced evapotranspiration after logging may increase pore water pressure during moderate winter storms, but for large storms differences in pore water pressure due to logging were difficult to detect (Dhakal and Sidle, 2003).

- ✓ Infiltration and subsurface flow. Forest lands usually have high infiltration rates, but they may reduce soil moisture through subsurface flow facilitated by pipes and channels formed by root decay and burrowing animals. Tree roots contribute to soil pore formation and form networks that can help slopes to drain faster than if the channels were absent. Root channels also raise infiltration rates and soil moisture content, which can increase landslide hazards.

Negative hydrological effects on slope stability are the increase in surface roughness and the resulting high levels of infiltration, but the net effect is positive.

The mechanical effects of forest vegetation against shallow landslides can be summarize as follows (Sidle and Ochiai, 2006, Forbes and Broadhead, 2011):

- ✓ Soil reinforcement and anchoring: individual strong woody roots anchor the soil mantle into the more stable substrate; strong roots tie across planes of weakness and potential slip surfaces, thereby anchoring the soil; small roots provide a membrane of reinforcement to the soil mantle, increasing soil shear strength. The loss of root reinforcement is one of the major cause for the increase in landsliding after logging: the window of susceptibility begins when roots start to decay. Loss of protective function persists until woody vegetation is reestablished and sufficient root density is achieved (Fig. 1.2.4).

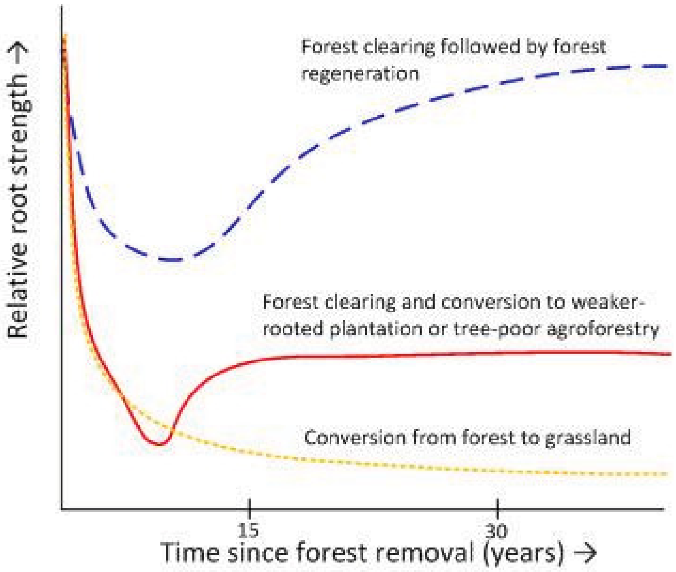

Fig. 1.2.4 Effects of timber harvesting on root reinforcement. Forbes and Broadhead, 2011.

- ✓ Buttressing and arching: roots of woody vegetation at the bottom of the slope anchor into firm strata, thus supporting the upslope soil behind them
- ✓ Weight of trees (surcharge) increases the normal force components
- ✓ Forest can play a role in attenuating and blocking smaller debris flows and rock falls by forming a physical barrier.

The negative effects related to mechanical processes are wind loading, surcharge, uprooting and bedrock fracturing by roots.

In mountain catchments, root reinforcement is one of the most important contributors of vegetation to slope stability (Phillips and Watson, 1994; Sidle, 1992; Rickli and Graf, 2009; Forbes and Broadhead, 2011). However the beneficial effects of forest on slope stability are strictly connected to forest conditions: there is a positive correlation between a forest's condition and the landslide density (Rickli, 2001, Schmidt et al., 2001, Markart et al, 2007). Species mix, tree height and weight, stand density, rooting depth, root architecture all have an impact on slope stability (Forbes and Broadhead, 2011). The most a forest stand has well adapted tree species, few gaps and a diverse stand structure, the most this forest is effective against shallow landslides. To allow an effective consideration of forest protection potential against shallow landslides an effort to quantify the effect of vegetation is needed. In the next section the state of the art in the estimation of root mechanical effects, focusing on root reinforcement, is presented.

1.3 Models for the quantification of root reinforcement

Roots reinforce soil mantle increasing its shear strength by virtue of their tensile strength and extensive subsurface reach (Gray and Lieser, 1982). The quantitative estimation of root reinforcement is challenging due to the complexity of soil root interactions, to the heterogeneity of root distribution and mechanical properties and to the difficult of measuring them in the field (Cohen et al., 2011). In order to quantify root reinforcement two methods have commonly been used (Pollen and Simon, 2005).

In the first method, the values collected from in situ shear tests of root permeated soil have been used to replace the value of the soil strength alone (Wu et al., 1988a). This kind of tests present a number of problems: they provide a direct assessment of the amount of reinforcement provided to the soil by the roots, but isolating a block of root permeated soil is not an easy task, and the soil and the anchoring of the roots may be disturbed before shearing is undertaken. In addition to this problem Wu et al., 1988b, commented that when carrying out these in situ tests the force developed in the roots are dependent on the dimensions of the shear box.

The second method for the quantification of root reinforcement involves the development of physically based models to describe the relationships between the root and the soil properties that cause the roots to increase the shear strength of the soil. During the last three decades, attempts were made to develop analytical models of soil reinforcement for implementing eco and bio engineering technologies. The prevailing approach in root reinforcement estimation is accounting for the condition where a slope fails through shear and the deformed roots provides an additional cohesion due to the mechanical resistance of roots in tension and roots friction with soil particles, which has been named root cohesion *Cr*.

The apparent cohesion term is added to soil shear strength in the Mohr-Coulomb failure criteria (Endo and Tsuruta, 1969; Waldron, 1977; Wu et al., 1979):

$$s = (c' + Cr) + (\sigma - \upsilon) \tan\varphi \qquad (1.3.1)$$

Where s is soil shear strength (kPa), c' is the effective soil cohesion, *Cr* is the apparent cohesion term due to roots crossing the failure surface, σ is the normal stress acting on the failure surface, υ is the pore water pressure and φ' is the effective angle of soil internal friction.

The quantification of *Cr* is a key step to estimate the stability of a slope, usually quantified by the factor of safety (FS). Root cohesion is commonly estimated by referring to two classes of models:

the Wu & Waldron model - W&W model (Wu et al.,1976; Waldron and Dakessian,1977) and the Fibre Bundle Model -*FBM* (Pollen and Simon, 2005; Schwarz et al., 2010a).

Two pioneering mechanistic models for the estimation of Cr were developed simultaneously by Wu (1976) and Waldron (1977), with the same theoretical basis. They assumed that roots are elastic fibers that are extending perpendicular to the shear surface. When the rooted soil is shared, the roots across the interface bend and mobilize their tensile strength by means of root soil friction (Fig. 1.3.1). The tensile strength of roots is resolved in two components, one normal and one parallel to the shear surface. The tangential component opposes to shear resistance while the normal component increases the shear resistance *s*.

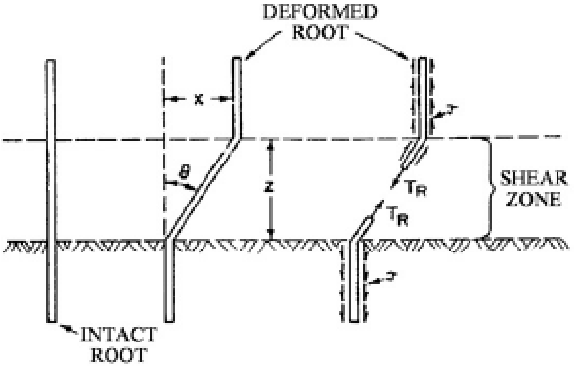

Fig. 1.3.1 Perpendicular root reinforcement model. Gray and Lieser, 1982.

Cr (kPa) can therefore be expressed as:

$$\mathrm{Cr} = \mathrm{tr}\ (\cos\theta\ \tan\varphi + \sin\theta) \qquad (1.3.2)$$

Where θ is the root bending angle respect to the vertical, φ is the soil friction angle and *tr* is the mean root tensile strength mobilized per unit area of soil. *tr* can be estimated as

$$tr = Tr\frac{Ar}{A} \qquad (1.3.3)$$

Where *Tr* is the mean tensile strength of the roots and A_r/A is the *root area ratio (RAR)* which is the ratio between the cross sectional area of the roots crossing a plane of soil and the plane area.

It has been shown that for $40° < \theta < 90°$ and for $25° < \varphi < 40°$, which are generally considered reliable values in most cases (Wu et al., 1979), the term $(\cos\theta\ \tan\varphi + \sin\theta)$ assumes values comprised between 1 and 1.3, and therefore an average value can be used. Eq. 1.3.2 can be rewritten as:

$$Cr = k'tr \tag{1.3.4}$$

The parameter k' is the factor accounting for the decomposition of root tensile strength according to the bending angle of roots respect to the shear plane. k' is usually set equal to 1.15 (Waldron, 1977) or 1.2 (Wu et al., 1979), but other studies (Docker and Hubble, 2008) report a value of k' inferior, obtaining for riparian vegetation in New Zealand a value inferior than 1.

Root tensile strength Tr is function of root diameter, following a power law form (Burroughs and Thomas, 1977; Abe and Iwamoto, 1986; Gray and Sotir, 1996; Nilaweera and Nutalaya, 1999; Genet et al., 2005; Bischetti et al., 2009):

$$Tr = ad^{-b} \tag{1.3.5}$$

Where d is the root diameter and a and b are parameters depending on the species and growing conditions.

To account for the variability in root diameter, eq. 1.3.4 can be rewritten as:

$$Cr = k' \sum_{i=1}^{N} (Tr\ ar)_i \tag{1.3.6}$$

Where *i* is the root diameter class, *ar* is the RAR and *N* is the number of the root diameter classes.

The Wu and Waldron model has been widely adopted thanks to its simplicity. The perpendicularity of roots to the slip plane is a strong assumption; extended models allowing for inclined roots have been developed, but Gray and Ohashi (1983) have shown from laboratory tests that perpendicular orientations of reinforcing fibers provide comparable reinforcement to randomly oriented fibers. The main problem in the use of this model is that it assumes that all the roots crossing the shear surface break at the same time. This does not correspond to real cases, where roots with different diameters break at different times, in function of their different tensile strength, with an associated redistribution of stress at each root breaks. This phenomenon has been demonstrated by means of pullout experiments on branched roots (Riestenberg 1994; Norris, 2005; Docker and Hubble, 2008) and direct shear test (Docker and Hubble, 2008). As consequence, the W&W model overestimates significantly root cohesion, as observed by several authors (Waldron and Dakessian, 1981; Operstein and Frydman, 2000; Pollen and Simon, 2005; Docker and Hubble, 2008). To account for non simultaneous breaking of roots, some authors proposed a correction factor k'' which reduces the root cohesion estimated with the W&W model:

$$Cr = k'k'' \sum_{i=1}^{N} (Tr\ ar)_i \tag{1.3.7}$$

Different values of k'' have been proposed: for forest vegetation, 0.4 (Preti, 2006) and 0.56 (Hammond et al., 1992), whereas for herbaceous plant lower values have been proposed (Waldron and Dakessian, 1981; Operstein and Frydman, 2000; Docker and Hubble, 2008); e.g. Greenwood et al., 2004 suggest a conservative value of 0.12.

Other authors (Pollen and Simon, 2005) faced the problem of the non-simultaneous breaking of roots adopting a different model, the Fiber Bundle Model (FBM). FBM was firstly introduced by Daniels (1945) to study the properties of composite materials, and has been adapted to the root behavior to simulate the successive breakage of root elements according to their individual tensile resistance. In FBM a bundle of parallel fibers (roots) is considered and loaded parallel to the fibers direction. Roots are assumed to be parallel to each other and to have the same elastic properties (Pollen and Simon, 2005). Roots fail when the applied load exceeds a threshold value, given by the maximum tensile strength of the single root. After the failure, the applied load is redistributed among the remaining intact roots. This load redistribution consists of transferring stress from the broken to the unbroken roots, inducing secondary failures that, in turn, induce tertiary ruptures, and so on. The failure avalanche is terminated when the unbroken roots are able to withstand the entire load or when the material collapses. When the system comes back to a new equilibrium and if some intact roots are still remaining, another increment of load is applied and the process is repeated until the whole root bundle is broken. The load redistribution can be applied following two different criteria. The simplest one is the equal load sharing or global load sharing (ELS or GLS) which redistribute the load between all the remaining intact fibers (Hidalgo et al., 2002). The alternative to GLS is the local load sharing (LLS) which redistributes the load according to the proximity of intact fibers to the broken fibers (Hidalgo et al., 2002). Whatever group of fibers is consider, the load can be redistributed between roots regardless of root diameter, and therefore each root is subjected to a force equal to the total force divided by the number of roots considered (Daniels, 1945). In alternative, the load can be redistributed as function of root diameter: each root is subjected to a force proportional to the ratio of its diameter to the sum of root diameters (Pollen and Simon, 2005). Finally, a third way is that each root is subjected to the same tensile stress, applying a force equal to the total force multiplied to the ratio of the current cross section area to the cross section area of the whole bundle. In the simplest version of FBM fibers are considered static, with their strength independent of time, while there are further extensions of FBM where the fibers are considered dynamic, with strength dependent on time and particular type of stress are taken into account (Gomez et al., 1998). FBM was proved to give more accurate estimates of soil shear strength reinforced by roots than W&W model (Fig. 1.3.2), (Pollen and Simon, 2005; Bischetti et al., 2009; Loades et al., 2010; Mao et al., 2011), and can be used to estimate the correction factor *k''* to reduce W&W model estimates. Pollen and Simon (2005) found for riparian species in America a reduction factor comprised between 0.6 and 0.82. Bischetti et al. 2009 (Fig. 1.3.3) found values comprised between 0.32 and 1, and observed that k'' is always greater than 0.5 for a density smaller than 400 roots/m^2, similar to the values suggested by Hammond et al., 1992 for forest species. The estimation of the correction factor is therefore strongly associated with the number of roots (Bischetti et al., 2009; Pollen and Simon, 2005).

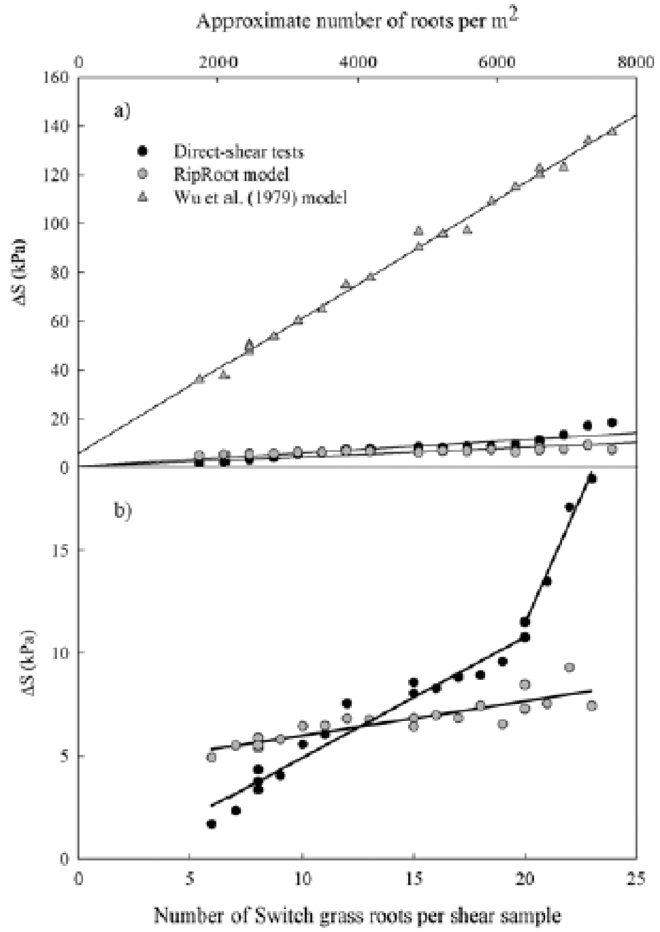

Fig. 1.3.2 Comparison between values of root reinforcement of switchgrass roots obtained with direct share test, Wu model and FBM. Pollen and Simon, 2005.

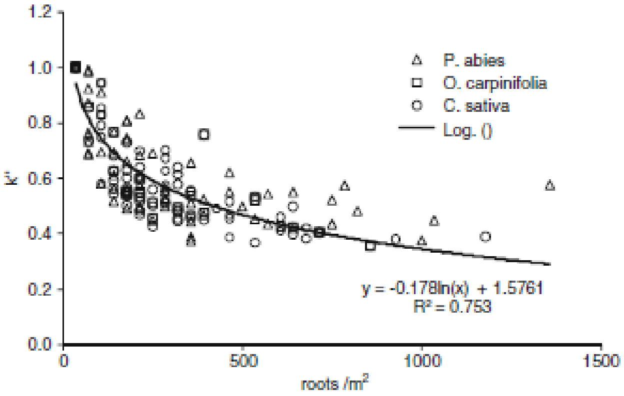

Fig. 1.3.3 Values of the correction factor k'' in function of the number of roots. Bischetti et al., 2009.

For shallow bedrock or shallow slip surfaces, the primary function of roots is enhancement of basal shear strength. For deeper soil bedrock interface, basal root reinforcement has a minor importance because just few roots can reach the depth of the failure plane (Schwarz et al., 2010b, Schmidt et al., 2001). Lateral reinforcement has been proved to be important because it can affect the onset and size of shallow landslides (Reneau and Dietrich, 1987; Schmidt et al., 2001; Roering et al., 2003). In the presence of a significant lateral root reinforcement, the area that must be destabilized in order to trigger a shallow landslides increases (Reneau and Dietrich, 1987). The effect of lateral root reinforcement can be calculated as lateral root cohesion (cr_{lat}) as proposed by Bischetti et al., 2009 and implemented in the Mohr Coulomb failure criteria, depending on the specific situation and on the sliding model adopted (Bischetti et al., 2009):

$$cr_{lat} = \sum_{j=1}^{M} \left[k'k''\left(\sum_{i=1}^{N} (Tr\ ar)_i\right) \frac{\Delta z_j}{z} \right] \qquad (1.3.8)$$

Where *N* is the number of roots at a given depth *z*, *M* is the number of depth classes of thickness Δz_j and *Z* is the whole depth considered.

Schwarz et al., (2010) and Cohen et al., (2011) proposed a new modeling framework to estimate and to overcome some problems linked with the estimation of root cohesion with the W&W model and the FBM. Since its introduction, the *FBM* has been used extensively to estimate root reinforcement (Bischetti et al., 2009, Hales et al., 2009, Mickovski et al., 2009, Mao et al., 2012, Ji et al., 2012), adopting different hypothesis on the load sharing criteria during the progressive rupture of roots (Mao et al., 2012, Ji et al., 2012). The *FBM* is implemented with a stress step loading approach, it does not take into account the combined effects of root geometry and mechanics and it drives root bundle deformation only by load instead of by displacement (Cohen et al., 2009).

As also Pollen and Simon 2005 observed in discussing the W&W model, an important assumption at the basis of eq. 1.3.1 is that the full tensile strength of roots is mobilized when soil shears. However, laboratory and field testing of strength of steam bank materials and riparian roots showed that root strength is typically mobilized at much larger displacement than soil strength (Pollen et al., 2002; 2004). In a soil, in fact, peak strength is generally mobilized in the first few millimeters of strain; whereas, in the case of some roots, straightening of the root to remove its tortuosity may occur before strain is taken up. Roots which have been straightened before breaking will generally break at greater displacements than the displacement of soil at its peak strength (Pollen et al., 2002, 2004). This suggests that peak root strength may not be fully mobilized at the time of maximum soil instability, and that the banks may fail before the full theoretical contribution from roots is achieved (Pollen et al., 2004). In situ shear tests by Fannin et al. (2005) showed that the shear stress peaks twice, once due to soil mobilize at its peak shear strength and once due to the tensile strength mobilization of roots. Over prediction of the increased soil shear strength may therefore occur, and therefore analysis on the stress displacement characteristics of root are necessary to evaluate how significant is this overestimation (Pollen et al., 2005); both *W&W* and *FBM* do not permit calculation of root elongation for realistic root bundles (Schwarz et al., 2013).

Another critical point is that both *FBM* and *W&W* consider that all roots breaks, but laboratory and field tests have shown that roots failure occurs by two mechanisms (Waldron and Dakessian, 1981; Coppin and Richards, 1990; Pollen and Simon, 2005): pullout (slipping due to bond failure) or rupture (tension failure). The friction between soil and root determines the type of mechanical failure: in cohesive soils, small roots tend to break under dry conditions and slip out under wetter conditions (Pollen, 2007). For each soil type and each moisture content a threshold root surface area exists above which the frictional bond between the root and the soil is stronger than the tensile strength of the root; the full tensile strength of the root can thus be realized and the root breaks. Below the threshold, the roots will be pulled out from the soil as their frictional bonds with the soil are weaker than their tensile strength; in this case the frictional bonds are not strong enough to allow the uptake of tension in the roots and they are simply pulled out of the soil. When roots break, the observed root strength drops abruptly to zero, whereas when a root slips out, the apparent root strength may drop to lower values that decrease exponentially with root length (Mickovski et al., 2009; Docker and Hubble, 2008), Fig. 1.3.4.

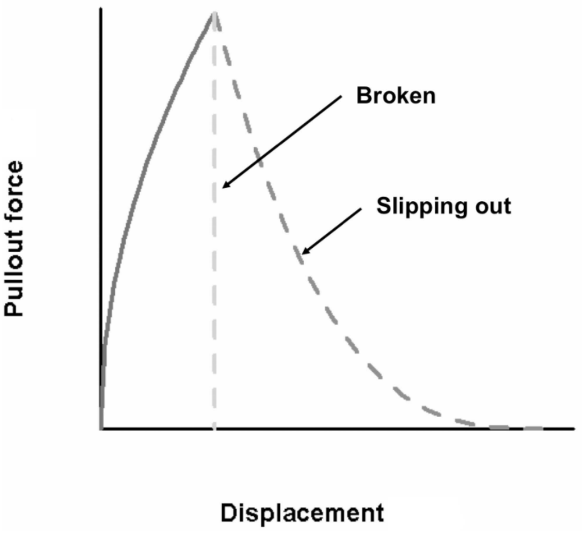

Fig. 1.3.4 Pullout curves of a root on a force-strain diagram. The initial elastic stretch of a root (solid line) may be followed by gradual slip out (black dashed line), or abrupt failure and breakage (vertical gray dashed line). Modified from Waldron and Dakessian, 1977, in Schwarz, 2010.

Schwarz et al. (2010a) proposed the implementation of a strain step loading approach in an extended version of *FBM* called the *RBM* (Root Bundle Model), with the aim to model primary the lateral root reinforcement. *RBM* can be defined as a displacement controlled *FBM*, while the original *FBM* is stress controlled. The model consists of imposing successive displacements to the bundle of roots, by which the calculation of pullout forces takes into account single root strength, elastic modulus and length as functions of diameter. With the *RBM* it is possible to calculate the complete force-displacement curve of a bundle of roots and derive the total pullout work; furthermore, the model allows the evaluation of the progressive mobilization of root strength along the activation length during the pullout process due to root soil friction for each root in the bundle (Fig. 1.3.5). The characterization of full force-displacement behavior of root bundles under shear, as well as under tensile and compressive loading was demonstrated to be important for the understanding of the triggering mechanisms of shallow landslides and for a realistic implementation of root mechanical effect in numerical model for slope stability calculations, e.g. SOSlope3 (Schwarz and Cohen, 2011).

The original version of *RBM* (Schwarz et al., 2010c) models also the slip out of roots; here it is presented just the simplified version (Cohen et al., 2011) that considers only root breakage.

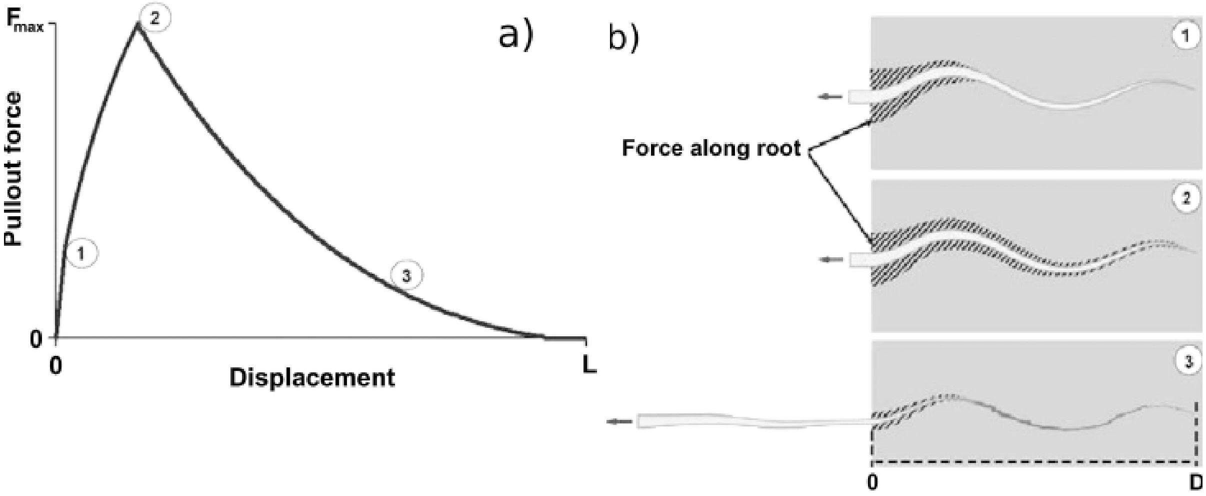

Fig. 1.3.5 Force-displacement behavior of a 2 mm diameter root (a) calculated using the RBM. The three numbered points indicate the position at which correspond the three illustrations of the slipping root, showing the cumulative force distribution along the root length. Schwarz et al., 2010c

RBM is based on three geometric and mechanical root charachteristics which can all be estimated through power law equations as a function of root diameter: root maximum force at failure (N) (eq. 1.3.9), root length (eq. 1.3.10) and root Young modulus (Pa) (eq. 1.3.11).

$$F_{max} = F_0 d^{\xi} \quad (1.3.9)$$

$$L = L_0 d^{\gamma} \quad (1.3.10)$$

$$E = E_0 d^{\beta} \quad (1.3.11)$$

The effect of root tortuosity can be included in Young modulus calculation through a tortuosity coefficient *r* (Schwarz, 2010b) that reduces Young modulus, or included in the calibration of the Hooke's constant if eq. 1.3.11 is implemented following the Hooke's law.

Considering the elasticity law and substituting its parameters with eqs. 1.3.9, 1.3.10, and 1.3.11, the tensile force (N) of a root as a function of displacement Δx (m) can be expressed as:

$$F(d, \Delta x) = \frac{E_0 \pi r}{4 L_0} d^{2+\beta-\gamma} \Delta x \text{ with } F(d, \Delta x) < F_{max}(d).. \quad (1.3.12)$$

Considering a bundle of roots, the force F_b (N) mobilized by the bundle is:

$$F_b(\Delta x) = \sum_{i=1}^{N} F(d, \Delta x) \quad (1.3.13)$$

Where N is the number of roots.

The application of *RBM* confirms the overestimation of root reinforcement obtained through the *W&W* model (Fig. 1.3.6) and shows that this overestimation is strongly dependent on root size distribution.

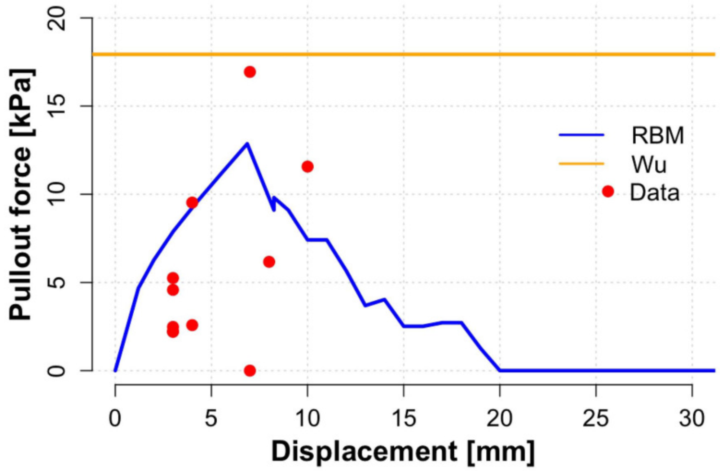

Fig. 1.3.6 Modeled behavior of root reinforcement for the data of Zhou et al. [1998] for one square meter soil profile: maximum root reinforcement calculated with W&W model and maximal pull out forces calculated with RBM. Schwarz et al., 2010c.

A study of Ji et al. 2012, compared the root reinforcement profile obtained by the different models (*W&W*, modified *W&W*, *FBM* with different load sharing criteria, *RBM*). They found that *W&W* always gave the highest values of root reinforcement, while modified *W&W* (with a correction factor *k''* of 0.4) gave the smallest values of root reinforcement, except for deeper soil layers, Fig. 1.3.7. RBM gave the highest value of root reinforcement between the *FBMs*. However, root diameter distribution was found to be the main variable influencing root reinforcement estimated with the different models, in function of the basic hypothesis of the models.

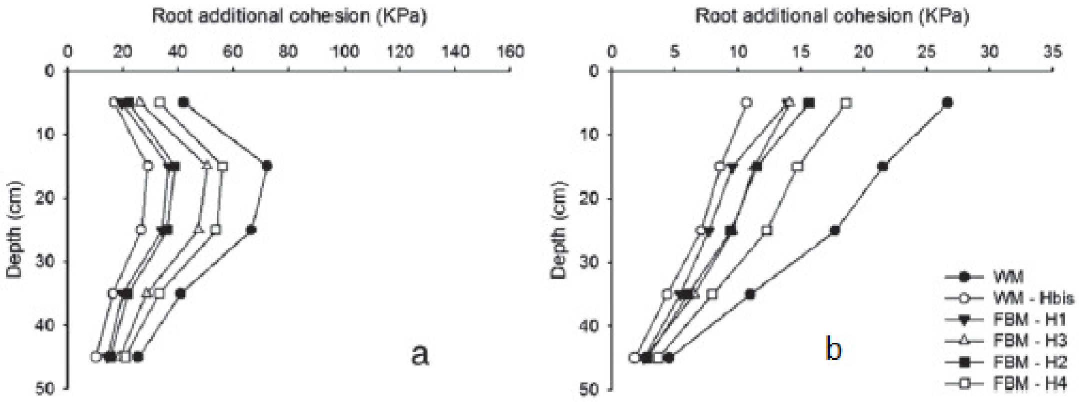

Fig. 1.3.7 Values of root reinforcement provided by Robinia pseudacacia (a) and Platycladus orientalis (b) determined using different models: WM = W&W; WM-hbis= modified Wu, FBM H1,2,3 = FBM with different load sharing criteria, FBM-H4 = RBM. Ji et al., 2012.

W&W model, *FBM* and *RBM* take into account the variability of root mechanical properties only as a function of diameter and assume that roots of a certain diameter class are mechanically homogeneous between them, and mobilize the same maximal tensile force. Different studies

(Schwarz et al., 2011, Loades et al., 2011) and empirical observations both on field and in laboratory tests show high variability in root mechanical properties also inside the same diameter class. For given diameter or small diameter range there is a variability due to the anatomy and geometry of roots, resulting in different force and displacement at rupture. Many factors can influence root biomechanics, such as root age, root constituents, environmental conditions in which root grow (Loades et al., 2007, Hales, 2009). To take into account this variability and analyze how it affects the mechanics of root bundles, Schwarz (2013) proposed a modified version of *RBM*, *RBMw*. Respect to the "simple" *RBM*, the extended root bundle modl, *RBMw*, implement the Weibull function in order to consider the probability distribution of breakage of roots of the same diameter class. Considering eq. 3.1.12 the displacement at which root fail is:

$$\Delta_{max} = F_0 \frac{4L_0}{E_0 \pi r} d^{\gamma+\xi-2-\beta} \tag{1.3.14}$$

For each root two displacement values at rupture can therefore be calculated, following equation (1.3.14): Δx considering the measured value of tensile force at root breakage and Δx_{fitmax} considering the fitted value of tensile force following the fitted root-diameter power law. The ratio between these two values of displacement $\Delta x / \Delta x_{fitmax}$ is the normalized displacement Δx_{norm}. The probability of a root to fail as a function of displacement can be described, as proposed by Schwarz et al. (2013), by a Weibull probability distribution function:

$$W(\Delta x) = 1 - exp\left[-\left(\frac{\Delta x}{\lambda}\right)^{\omega}\right] \tag{1.3.15}$$

Where λ is a scaling factor and ω the Weibull form coefficient.

Assuming $\lambda = \Delta x_{fitmax}$ we have:

$$W(\Delta x) = 1 - exp\left[-\left(\frac{\Delta x}{\Delta x_{fitmax}}\right)^{\omega}\right] \tag{1.3.16}$$

And the function depends only from ω:

$$W(\Delta x_{norm}) = 1 - exp[-(\Delta x_{norm})^{\omega}] \tag{1.3.17}$$

If we consider the probability of roots to survive instead of to fail in function of displacement, we obtained a so-called Weibull Survival function *S* which is:

$$S(\Delta x_{norm}) = exp[-(\Delta x_{norm})^{\omega}] \tag{1.3.18}$$

The reinforcement of a bundle of roots can be obtained by summing the force contribution of each root multiplied by the Survival function *S*:

$$F_{tot}(\Delta x) = \sum_{i=1}^{N} F(d, \Delta x) S(\Delta x_{norm}), \; F(d, \Delta x) < F_{max}(d) \tag{1.3.19}$$

In Fig. 1.3.8 are shown the effects of root strength variability using the survival function. High values of the Weibull exponent indicate little variability in root mechanical behavior within a diameter class and reproduce the average value of force of that diameter class. Adopting high values of the Weibull exponent leads to a smoother curve and to a maximum force much lower than the average with spread of the reinforcement force over a much larger range of displacement. As a consequence, the variability of root mechanical properties inside the same diameter class strongly influence the progressive failure of bundle under tension (Schwarz et al., 2013). Schwarz et al., 2013, found for both tensile and pull out tests values of the Weibull exponent approximately equal to 2.

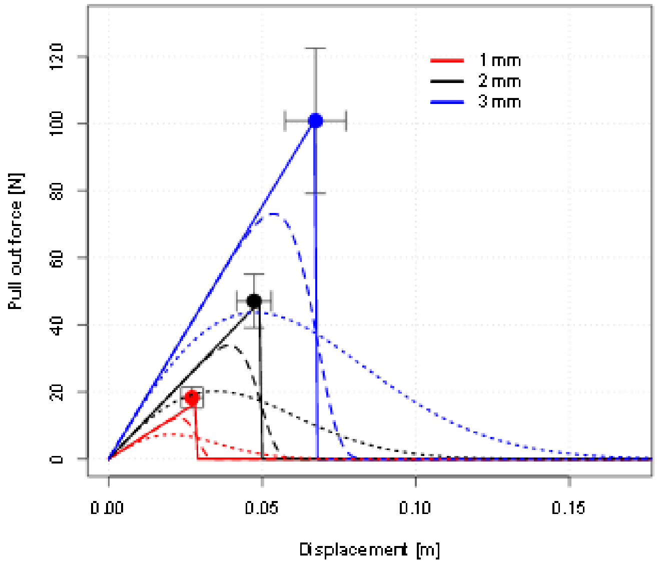

Fig. 1.3.8 Force-displacement behavior of 1 (red), 2 (black) and 3(blue) mm diameter root classes. Points and error bars indicatemean and standard deviation measured in field pullout experi-ments (Schwarz et al.,2011). Curves show the modeled force-displacement for three values of the Weibull exponent: 2 (dot-ted line), 10 (dashed line), and 100 (solid line). Schwarz et al., 2013.

1.4 Implementation of root reinforcement in slope stability analysis

It has been shown clearly that in some cases root strength provides the difference between stable and unstable slopes (Riestenberg and Sovonick Dunford, 1983; Abe and Iwamoto, 1990; Schmidt et al., 2001; Roering et al; 2003). Incorporating root reinforcement values into landslide analyses however is not an easy task, due to the lack of comprehensive data on rooting strength in soils and to the high variability in the reported values (Swanston, 1970; Abe and Iwamoto, 1986; Terwilliger and Waldron, 1990; Schmidt et al., 2001). Root reinforcement is usually considered as an increase of cohesion (chapter 1.3) even if some authors underlined the inaccuracy of such definition (Pollen and Simon, 2005; Cohen et al, 2011). Such additional cohesion is usually implemented, together with the effect of the weight of trees, in the infinite slope model, which has been widely used to analyze the stability of natural and artificial slopes (Sidle and Ochiai, 2006). The infinite slope model is based on the principles of limit equilibrium analysis. It analyzes the equilibrium of the forces acting on a slice of soil on a slope and identifies an index, the safety factor of the slope, which is defined as the ratio of the resistance force S acting on the sliding surface to the driving force T acting on the potential slide mass:

$FS = S/T$

Slope failure occurs when the resistant force becomes smaller than the driving force, i.e. when $FS < 1$. The condition $FS= 1$ is not an absolute indicator of slope failure, but rather an index of likely failure because of the model assumptions and possible errors in the parameters.

The infinite slope model relies on several simplifying assumptions (Hammond et al., 1992):

- ✓ The failure plane and the groundwater surface are assumed to be parallel to the ground surface;
- ✓ the failure plane is assumed to be of infinite extent: the length of the sliding surface is sufficiently greater than the depth of the moving soil mass so that the difference between the forces on the uphill and downhill sides of the sliding blocks are negligible (usually length is more than an order of magnitude larger than depth);
- ✓ only a single layer is considered.

With reference to Fig. 1.4.1 let’s consider a slip surface parallel to the slope and with an inclination of β. To easily evaluate the forces acting on slice, the length l along the sliding surface of a portion of the sliding mass is assigned a unit length.

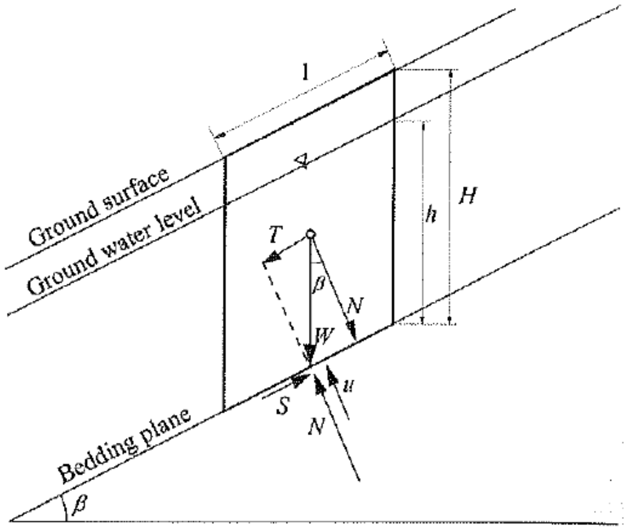

Fig. 1.4.1: Infinite slope scheme. Sidle and Ochiai, 2006

The force between slices acting on the sides of the slice is balanced both horizontally and vertically. The water pressure acting on the sides of the slice is also balanced, and the water pressure acting on the bottom of the slice is u when the vertical water depth is *h.* the combination of loads acting on the soil mass give raise to the tangential *T* and normal *N* forces along the sliding surface. The resistance force *S* along the sliding surface is given by the shear strength of soil. *S* can therefore be calculated by Coulomb's law, which for a soil column of unit length is expressed in terms of force as:

$$S = c + (Wcos\beta - u)\tan\varphi \qquad (1.4.1)$$

Where c is the cohesion of the soil at the sliding surface, φ is the internal friction angle, for seepage parallel to sliding surface, and *W*, the weight acting on the slice, is defined as

$$W = \ [\gamma_t(H-h) + \gamma_{sat}h]cos\beta \qquad (1.4.2)$$

Where γ_t is the unit moist weight of the soil above the water table and γ_{sat} is the saturated weight of soil. The driving force that may cause slope failure is:

$$T = Wsin\beta \qquad (1.4.3)$$

The safety factor is therefore calculated as:

$$FS = \frac{c}{Wsin\beta} + \frac{tan\varphi}{tan\beta} - \frac{utan\varphi}{Wsin\beta} \qquad (1.4.4)$$

To account for the effects of vegetation on slope stability, including both root reinforcement and the weight of the trees, the infinite slope model can be modified adding a new root cohesion term Cr to soil cohesion c and the surcharge S of trees to the term W:

$$FS = \frac{c+Cr}{(W+S)sin\beta} + \frac{tan\varphi}{tan\beta} - \frac{utan\varphi}{(W+S)sin\beta} \qquad (1.4.5)$$

For shallow soil mantles on steep slopes of coastal Alaska, the stabilizing effect of the removal of tree weight due to harvesting was determined to be negligible in comparison with the destabilizing effect from the reduction in rooting strength (Sidle and Ochiai, 2006). The calculation of the factor of safety is at the basis of physically based landslide models.

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2 Spatial variability of root reinforcement

The quantification of root reinforcement is an important issue in slope stability problems, and it has been demonstrated to be challenging due to the variability of spatial root distribution and mechanical root properties. A better comprehension of this variability can permit the upscale of root reinforcement distribution from the tree to the catchment level; it can moreover give some indications about the use of the data already available in literature and about the priority in the collection of new data. This is important in order to optimize the planning of field campaigns, especially if we consider how demanding and time consuming the field works for the analysis of root systems are.

As explained in chapter 1.3, root reinforcement is a function of two main factors: root tensile resistance and root density and distribution in diameter classes. Both these components are subjected to huge variability on natural slopes, and this variability has been described in previous works (Bischetti et al., 2005; Hales et al., 2009; Schwarz et al., 2012).

Root tensile resistance is diameter-dependent and normally expressed as a power law in function of diameter (Ziemer and Swanston, 1977; Nilaweera and Nutalaya, 1999; Kondo et al., 2004; Genet et al., 2010, Vergani et al., 2012). Moreover, it has been found to vary in function of species (Schiechtl, 1980; De Baets et al., 2008; Genet et al., 2005, Vergani et al., 2012, Ji et al., 2012) as roots of different species have specific mechanical properties. A big variability has been found also inside the same species, as function of environmental and stand parameters such as: tree age, season, soil environment, water logging, altitude and orientation along the slope (Hathaway and Penny,1975; Schiechtl, 1980; Goodman and Ennos, 1999; Genet et al.,2008; Abdi et al., 2010; Sun et al., 2008; Hales et al., 2009; Loades et a., 2013).

Root distribution varies in function of species composition, soil depth, tree spatial density, distance from the stem, position on the slope, local growth conditions as soil temperature, nutrient and moisture content or soil biochemical properties (Mattia e al., 2005, Stokes et al., 2008,Mao et al., 2012; Schwarz, 2010, Ji et al., 2012, Yaangisawa and Fujita, 1999; Neukirchen et al., 1999; Schwarz et al., 2012).

In the following chapters the variability of root tensile force of different species in the Italian Alps is analyzed and a possible key of interpretation of such variability id proposed (section 2.1). The data of root force of one of the most common alpine species, *Picea abies*, are then extracted and combined with a large dataset of root distribution to assess the sensitivity of root reinforcement to the variability of both root force and root distribution (section 2.2).

2.1 Variability in the tensile resistance of roots at regional scale: a case study in Lombardy Alps.

2.1.1 Introduction

Root tensile resistance values are needed to estimate the magnitude of the soil reinforcement and consequently are key factors when dealing with the stability of forested slopes. The issue has been studied in detail by several researchers in recent years (Hathaway and Penny, 1975; Abe and Iwamoto, 1986; Genet et al., 2005, 2008, 2010; Tosi, 2007; Hales et al., 2009; Burylo et al., 2011). One of the major findings of these studies is that tensile resistance is significantly affected by root diameter and plant species (Abernethy and Rutherfurf, 2001; Bischetti et al., 2005; De Baets et al. 2008; Norris et al., 2008; Bischetti et al., 2009). This relationship has recently been attributed to variations in tissue density and cellulose content (Genet et al., 2005; Hales et al., 2009; Genet et al., 2011; following the pioneering work of Hathaway and Penny, 1975). Although a connection between cellulose content and tensile resistance has been established, the observed variability in root resistance is high and has still not been fully explained in terms of species and environmental variables. Most researchers have found that variations in root tensile resistance with respect to diameter are dependent on the species (Schiechtl, 1980; De Baets et al., 2008; Bischetti et al., 2009). Some other researchers did not find significant differences in roots belonging to different species (Abernethy and Rutherfurd, 2001; Hales et al., 2009). Still other researchers found intra-specific differences to be due to environmental and population parameters such as tree age, season, soil environment, altitude, and orientation along the slope (Hathaway and Penny, 1975; Schiechtl, 1980; Goodman and Ennos, 1999; Genet et al., 2008, 2011; Abdi et al., 2010; Sun et al., 2008; Hales et al., 2009). An increasing number of recent studies have focused on root resistance for one or a few species (Tosi, 2007; Genet et al., 2008; Abdi et al., 2009, 2010; Preti and Giadrossich, 2009; Comino and Druetta, 2009; Hudek et al., 2010). The comparison of several species have been performed in few works, but not at multiple sites (Pollen and Simon, 2005; Hales et al., 2009; Genet et al., 2010; Burylo et al., 2011): there is very little information concerning the variability of root resistance for a given species growing in significantly different areas. The present study focuses on the root resistance of seven species typical of the Italian Alps, sampled under various growing conditions in 2–6 different sites, to increase the available data concerning root tensile resistance and to improve understanding of the relationships between resistance, diameter, species and environmental factors. Root resistance values are compared, taking into consideration the diameter effect, both among different species and within a given species sampled at different sites, to quantify the related variability. Using statistical tools, differences among the species and sites are established and discussed to identify the environmental conditions that drive such variability. We investigate, in particular, the possibility of extending the data obtained for a given species in specific sites to the same species in larger areas that can be identified as similar based on certain criteria. In this way will be possible to give some indications about the use of existing root strength data and about the priority in the acquisition of new experimental data.

2.1.2 Materials and methods

Root tensile resistance: stress or force?

Root tensile resistance can be expressed in terms of force or stress (as the ratio between force and the area of the root section). Most of the authors cited in the paragraph 1.3 presented data on tensile resistance in terms of stress by means of an inverse power law with diameter (Abernethy and Rutherfurf, 2001; Bischetti et al., 2005; Mattia et al., 2005; De Baets et al. 2008; Norris et al., 2008; Bischetti et al., 2009). Other authors preferred to express the resistance–diameter relationship in terms of force (Hathaway and Penny, 1975; Ziemer and Swanston, 1977; Nilaweera and Nutalaya, 1999; Schmidt et al., 2001; Kondo et al., 2004; Norris, 2005; Tosi, 2007; Hales et al., 2009; Genet et al., 2011). Although a unique equation was not proposed, the commonly adopted form is again a power law relationship:

$$F = ad^b \tag{2.1.1}$$

where F is the breaking force (N) and d is the related root diameter (mm). Because the tensile stress of roots is calculated as the ratio between breaking force 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. Besides the potential error in measuring diameters, which can be considerable for fine and very fine roots, the exact point of rupture (and the associated diameter) cannot be known before the test. The point of rupture is known after the test, but the root diameter at this point is reduced because of the strain. Furthermore, the rupture process is related to the characteristics of a (small) portion of the root rather than to a single infinitesimal section. Therefore, the accepted method of diameter estimation (Genet et al., 2010, 2011; Abdi et al., 2010; Comino et al., 2010; Burylo et al., 2011) is to measure the diameters at various positions along the root and then take the average of the measurements (usually three) at the points closest to the breaking point. In the present study, root resistance is presented as the force F required to break a root of diameter d. Values expressed in terms of stress are also reported for comparison with previous studies.

Species and study sites

Seven tree species, two conifers and five broadleaves, common in the Alpine environment and with different ecological requirements (e.g., soil type and depth, water and light availability, range of temperature, aspect) were studied: spruce fir (*Picea abies L.*), European larch (*Larix decidua Mill.*), European beech (*Fagus sylvatica L.*), sweet chestnut (*Castanea sativa Mill.*), maple (*Acer pseudoplatanus L.*), ash (*Fraxinus excelsior L.*), and hornbeam (*Ostrya carpinifolia Scop.*). For each species, various growing sites in Lombardy (northern Italy) were studied, for a total of 24 sample sites (Fig. 2.1.1 and Tab. 2.1.1): Morterone (LCMort), Alpe Gigiai (COAlGi), Monte Pora (BGMnPo), Fino del Monte (BGFino), Casargo (LCCasa), Crandola (LCCran), Pasturo(LCPast), Oneta (BGOnet), Artogne (BSArto), Boario (BSBoar), Gianico (BSGian), Incudine (BSIncu), Malegno (BSMale), Prestine (BSPres), Moggio (LCMogg), Piuro (SOPiur), and Villa di Chiavenna (SOViCh). These species and sites were selected based on the distribution of shallow landslides in Lombardy, where this phenomenon is frequent (Carelli et al., 2006).

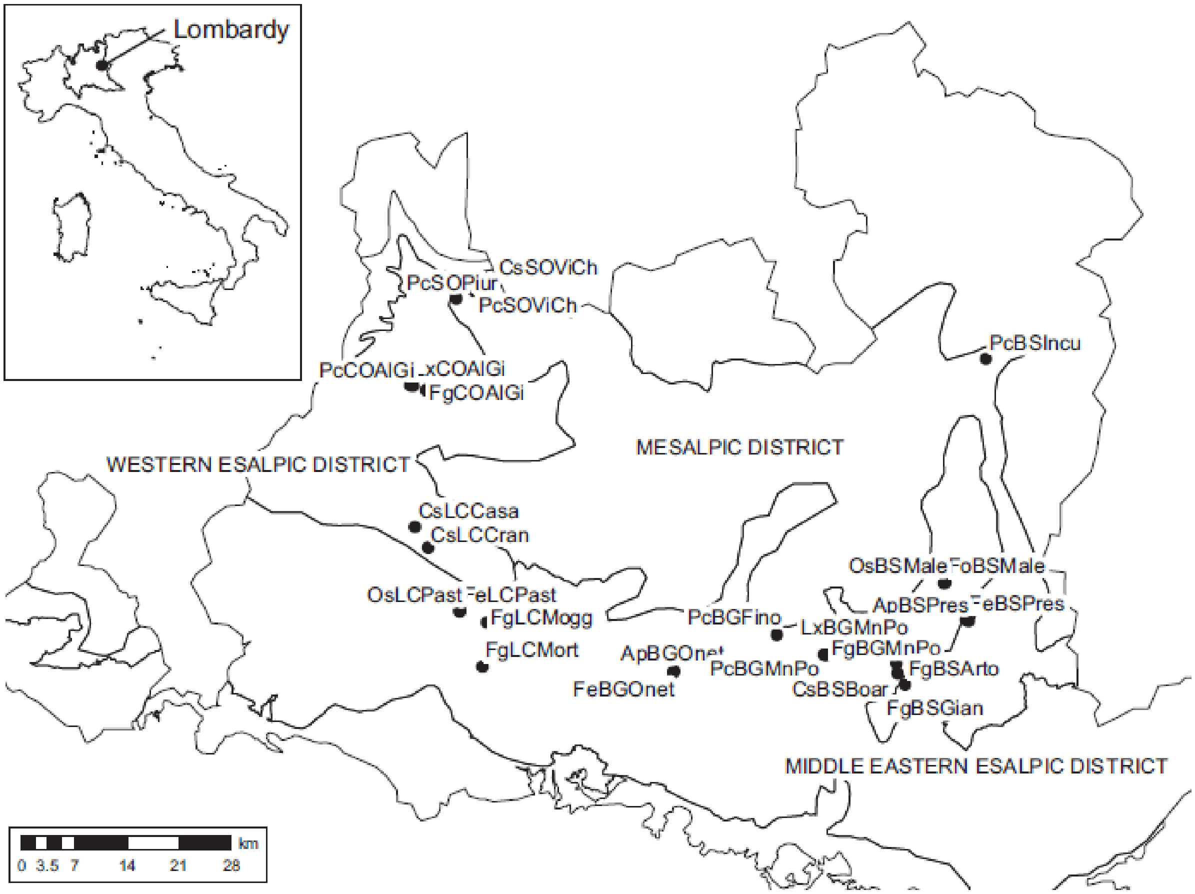

Fig. 2.1.1 Sampling sites location and forest districts partition.

At each site, up to 10 trenches were dug to expose the roots, and the following characteristics and properties were evaluated: stand characteristics, altitude, mean slope, drained area, wetness index (Beven and Kirkby, 1979) and soil characteristics (Tab. 2.1.1). Each site was associated with a particular forest district that groups together areas with similar growing conditions from a holistic perspective, as defined for the Lombardia Region by Del Favero (2002). These forest districts, in fact, summarize phytogeographic, geolithological, and climatic factors and can be used to interpret the distribution of vegetation in a given area. The study sites cover three forest districts of the Italian Alps: the Mesalpic district, the Middle-Eastern Esalpic district and the Western Esalpic district (Fig. 2.1.1). The Mesalpic district is characterized by high precipitation and cold temperatures; consequently, broadleaves are less competitive in this area than conifers (particularly the dominant *Picea abies* and *Abies alba*). In the Esalpic district, broadleaves are dominant and often form the tree-line; firs have been artificially introduced and are characterized by a high growth rate and early ageing. The Esalpic district has been divided into two sub-districts: the Middle-Eastern district (where carbonate bedrock dominates) and the Western district (where silicate bedrock dominates).

Tab. 2.1.1 Species and sampling sites

species	sample site	short form	n. of trenches	elevation (m asl)	mean annual rainfall (mm)	mean steepness (-)	drained area (m^2/m)	WI	mean tree diameter (cm)	mean distance tree-trench (m)	silvicultural system	forest district
spruce fir	Fino del Monte	PcBGFino	5	961	1500	0.52	295	6.33	33.60	2.13	high forest	Middle-Eastern Esalpic
	Monte Pora	PcBGMnPo	10	1484	1500	0.51	729	6.23	36.70	4.90	high forest	Middle-Eastern Esalpic [1]
	Piuro	PcSOPiur	5	1097	1350	0.70	883	6.12	46.25	2.50	high forest	Mesalpic
	Villadichiavenna	PcSOViCh	5	1082	1350	0.35	10634	9.29	22.15	2.20	high forest	Mesalpic
	Alpe Gigiai	PcCOAlGi	3	1542	1750	0.68	697	6.32	23.80	3.50	high forest	Western Esalpic
	Incudine	PcBSIncu	5	1227	1040	0.69	90	4.87	26.68	2.70	high forest	Mesalpic
European beech	Morterone	FgLCMort	5	1237	1800	0.57	109	5.18	22.35	2.02	coppice	Middle-Eastern Esalpic
	Moggio	FgLCMogg	5	953	1680	0.88	119	4.90	33.73	3.85	coppice	Middle-Eastern Esalpic
	Artogne	FgBSArto	5	1207	1350	0.83	1594	6.85	23.42	2.18	coppice	Mesalpic[2]
	Gianico	FgBSGian	5	964	1350	0.52	284	5.91	23.80	2.31	coppice	Middle-Eastern Esalpic
	Alpe Gigiai	FgCOAlGi	3	1344	1750	0.44	297	6.39	13.88	4.20	coppice	Western Esalpic
sweet chestnut	Boario	CsBSBoar	5	593	1350	0.60	344	6.33	13.25	1.63	coppice	Middle-Eastern Esalpic
	Casargo	CsLCCasa	5	968	1550	0.78	280	5.88	20.16	2.04	coppice	Western Esalpic
	Crandola	CsLCCran	5	1017	1550	0.74	79	4.66	18.20	1.81	coppice	Western Esalpic
	Villadichiavenna	CsCOViCh	5	777	1350	0.43	812	7.54	31.01	2.10	coppice	Mesalpic[3]
ash	Oneta	FeBGOnet	4	655	1800	0.14	71476	8.55	23.00	1.33	coppice	Middle-Eastern Esalpic
	Pasturo	FeLCPast	1	733	1600	0.71	161	5.42	6.00	1.06	coppice	Middle-Eastern Esalpic
	Prestine	FeBSPres	3	873	1390	0.68	363	6.22	19.46	2.19	high forest	Middle-Eastern Esalpic [4]
maple tree	Oneta	ApBGOnet	2	655	1800	0.16	43457	3.20	21.75	1.15	nd	Middle-Eastern Esalpic
	Prestine	ApBSPres	2	955	1390	0.54	566	6.89	30.00	1.85	high forest	Middle-Eastern Esalpic [4]
hornbeam	Pasturo	OsLCPast	4	755	1600	0.76	184	5.46	10.00	1.10	coppice	Middle-Eastern Esalpic
	Malegno	OsBSMale	4	775	1300	0.82	301	5.91	13.50	1.26	coppice	Middle-Eastern Esalpic
European larch	Monte pora	LxBGMnPo	2	1463	1500	0.43	214	7.84	55.00	2.27	high forest	Middle-Eastern Esalpic
	Alpe Gigiai	LxCOAlGi	4	1582	1750	0.54	2638	7.44	23.00	3.90	high forest	Western Esalpic

[1] Close to Mesalpic boundary
[2] Close to Middle-Eastern Esalpic boundary
[3] Close to Western Esalpic boundary
[4] Close to the Mesalpic boundary

Root sampling and tensile tests

For each species in each station, samples of live roots of various diameters were collected by carefully digging pits without damaging the plants. Because of the differing accessibility of the sites (their altitudes ranged from approximately 600–1600 m a.s.l.), sampling was performed at different times but always in the summer season. To protect the sampled roots from deterioration (it was impossible to test all of them within a short time), they were preserved in plastic containers with a 15% alcohol solution (Meyer and Göttsche, 1971; Böhm, 1979; Bischetti et al., 2003; Abdi et al., 2010; Burylo et al., 2011) until the tensile tests were performed.

A device consisting of a strain apparatus controlled by an electrical motor was used for the tensile tests. The roots were attached to specially developed clamping devices (with a distance between the jaws of 50 mm) that avoided root damage at the clamping points, and tensile force was exerted by a system of gears at a rate of 10 mm/min. The tensile force was measured as a function of the strain by a load cell (F.S. = 500 N, accuracy = 0.1% F.S.) connected to an acquisition system. Only specimens that ruptured near the middle of the root between the clamps were considered, thus ensuring that the rupture was due to the tensile force applied and not to root structural damage or stress concentration near the clamps.

The tensile force, F (N), at the point of rupture was taken as the peak load, and the related stress, Tr (Pa), was calculated by dividing the breaking force by the cross-sectional area of each tested root (m2),which was estimated from the average root diameter (obtained from the measurements taken at three points near the section of potential breaking).

The diameters of the tested roots ranged from 0.04 to 6.59 mm. Roots with a diameter greater than 8 mm were difficult to test with the device because of clamping constraints (De Baets et al., 2008). Roots with a diameter less than 0.05 mm were generally too short for testing and very difficult to manipulate.

There is not complete agreement in literature regarding the size of roots that must be considered in root reinforcement estimation. Some authors consider only roots with diameters in the range of 1–10 mm, because fine and thin roots (diameter less than 10 mm), which act as tensile fibers during slope failures, provide the major contribution (expressed as cr) to slope stability (Tosi, 2007; Genet et al., 2010; Abdi et al., 2010). Other authors indicated that roots of size from 1 up to 20 mm in diameter contribute most slope reinforcement (Styczen and Morgan 1995), although in some cases, roots up to 40 mm are said to be important for slope stability (O’Loughlin and Watson 1979). Roots with a diameter less than 1 mm are generally not considered because of different reasons. First of all there is great uncertainty regarding their identification; they undergo rapid turnover (Stokes et al., 2009; Gan et al., 2010; Mainiero et al., 2010; Finér et al., 2011; Garkoti, 2011; Wu et al., 2011), and finally their role in reinforcing the soil is questionable in view of the length necessary to keep them from slipping rather than breaking (Waldron, 1977).

In this work only roots with diameters in the range of 1–10 mm were considered. The root force–diameter relationship was represented through a power law in two ways: species-averaged F–d relationships obtained by grouping the data from a given species sampled at different sites, and site-specific F–d relationships obtained from the data for each species sampled at each site.

Statistical analyses

The relationship of root tensile force F (N) as a function of root diameter d (mm) was interpreted through power regressions. The suitability of the regressions was evaluated using the coefficient of determination (R2) and the coefficient of significance (p-value) obtained from Fisher's Test, with a significance level of 0.01. Fisher's Test was applied to the linear regressions obtained from log-transformed values of F and d.

To compare root force values between species and within the same species and to take diameter into consideration as a covariate, ANCOVA was applied to the linear regressions log F–log d, with a significance level of 0.01.

The normality and homogeneity of variance required for ANCOVA was verified using, respectively, Kolmogorov–Smirnov's test and Levene's test, both of which are suitable for small samples, with a significance level of 0.05. The normality test was applied to log-transformed values and residuals; Levene's test was applied to log-transformed values.

Various regression models were considered to explain within species differences based on the following environmental and stand characteristics: elevation, mean slope, drained area, wetness index, mean distance of trenches from trees, and mean diameter of trees around the trench. The suitability of multiple regressions was evaluated using R2 and the p-value; the regression coefficient of each variable and its significance in the whole model were evaluated using Student's t-test and Fisher's Test, respectively. For each species, we considered all the log-transformed values of root force and root diameter obtained from the tensile tests.

All statistical analyses were performed using the software program R (http://www.r-project.org/).

2.1.3 Results

Force–diameter relationships

The main statistical parameters (average, minimum, maximum and standard deviation) for each species and site are shown in Tab. 2.1.2. The force values range from approximately 2.5 N to over 900 N. As expected, the variability within a given species is high because of the variability of diameter. The values are also given in terms of stress in tab. for the purpose of comparison with other studies.

The relationships between force values and diameter have been interpreted through a power regression as described previously by several authors (Ziemer and Swanston, 1977; Nilaweera and Nutalaya, 1999; Kondo et al., 2004; Genet et al., 2010; Abdi et al., 2010). The coefficients and statistical parameters of regression (p-value, coefficient of determination, and standard error) are shown in Tab. 2.1.3. The power regressions are consistent with the force–diameter relationship; the R2 values are always higher than 65%, with the exception of Monte Pora larch (R2 = 53%), and they are highly significant in all cases ($p < 0.001$).

Tab. 2.1.2 Statistical parameters of tensile tests.

ID	**n.**	**diameter (mm)**				**Breaking force (N)**				**Tensile strength (MPa)**			
		mean	**max**	**min**	**SD**	**mean**	**max**	**min**	**SD**	**mean**	**max**	**min**	**SD**
PcBGFino	31	2.94	6.02	1.04	1.43	71.59	249.12	5.02	65.68	9.43	30.37	4.28	5.30
PcBGMnPo	29	2.25	5.92	1.00	1.26	66.01	360.60	5.15	76.94	13.04	19.17	6.35	3.32
PcBSIncu	46	2.90	6.36	1.10	1.36	64.81	347.73	3.36	69.28	7.76	15.78	1.36	3.10
PcCOAlGi	26	2.22	4.34	1.01	0.98	97.00	325.40	11.10	88.68	21.40	56.00	10.15	9.06
PcSOPiur	29	2.84	6.55	1.00	1.27	62.57	236.15	2.52	59.03	8.27	24.04	2.84	4.60
PcSOViCh	26	2.92	6.55	1.00	1.28	63.04	236.15	6.54	57.70	8.04	18.54	2.84	3.43
FgBSArto	28	2.78	5.37	1.03	1.36	116.47	387.54	6.23	109.48	16.51	42.70	3.38	7.98
FgBSGian	30	2.58	6.13	1.03	1.36	101.92	554.14	16.07	105.07	18.15	28.47	7.01	5.69
FgCOAlGi	21	2.30	4.59	1.03	1.20	164.54	469.53	20.30	131.17	40.33	75.22	13.04	18.45
FgLCMogg	15	2.68	5.04	1.00	1.25	114.90	332.16	20.07	92.07	19.31	27.67	7.01	6.54
FgLCMort	27	2.47	4.86	1.01	1.13	113.83	297.56	14.64	87.24	22.10	46.69	12.24	7.02
CsBSBoar	27	2.78	6.55	1.07	1.37	41.81	124.61	10.43	27.51	7.98	15.45	2.01	3.60
CsLCCasa	18	1.87	3.82	1.00	0.83	40.33	118.70	9.18	30.43	15.15	35.77	4.82	7.30
CsLCCran	26	2.26	5.92	1.02	1.29	70.07	397.30	8.45	88.60	5.26	27.54	0.81	6.42
CsSOViCh	27	2.73	4.53	1.13	1.06	74.57	235.43	9.54	66.90	11.55	25.03	2.83	5.50
FeBGOnet	22	2.46	5.46	1.10	1.16	45.70	124.22	7.47	34.91	9.41	21.25	3.89	4.20
FeBSPres	29	2.95	6.32	1.02	1.35	95.76	380.63	5.60	93.03	11.62	17.73	4.85	3.35
FeLCPast	22	2.78	6.59	1.13	1.72	13.93	290.39	10.87	77.74	13.93	24.91	4.66	5.50

ApBGOnet	27	2.49	5.30	1.05	1.28	67.83	200.80	5.60	58.44	12.65	21.87	3.68	4.92
ApBSPres	33	2.85	6.58	1.02	1.50	131.05	671.25	16.60	131.25	19.51	31.48	7.13	6.89
OsBSMale	28	3.05	6.29	1.08	1.55	94.88	256.86	8.35	81.45	12.21	26.15	1.80	5.62
OsLCPast	26	2.83	6.11	1.19	1.36	102.75	325.53	10.89	78.33	16.36	30.17	6.73	6.83
LxBGMnPo	23	2.12	5.85	1.05	1.25	22.94	74.77	6.99	16.65	8.30	28.90	1.03	5.72
LxCOAlGi	25	2.55	5.47	1.02	1.40	149.83	916.22	13.84	200.42	24.05	61.73	6.95	12.20

Comparisons among species

All of the studied species were compared to assess the possible significant differences among species.The force–diameter data for all of the species were assembled regardless of the sampling site to obtain species-averaged F–d curves (Tab. 2.1.3 and Fig. 2.1.2). These F–d curves are parallel for all of the species (ANCOVA, $F_{6,612} = 1.33$, $p = 0.24$) and are significantly different (ANCOVA, $F_{6,618} = 8.27$, $p < 0.001$). The force corrected mean values indicate the resistance ranking of the species; in decreasing order, they are as follows: beech 84 N, maple 65 N, hornbeam 56 N, ash 47 N, larch 46 N, sweet chestnut 44 N, and spruce 40 N. By grouping species according to the conifer/broadleaf criterion, a significant difference was observed (ANCOVA, $F_{1,623} = 57.4$, $p < 0.001$), with a force corrected mean value that was higher for broadleaves (58 N) than for conifers (41 N). These mean values, however, are affected by the high values for beech and maple; the values for ash and sweet chestnut are similar to those for larch and spruce.

Tab. 2.1.3 Coefficients and statistical parameters of species averaged F-d relationships.

		breaking force					**tensile strength**				
species	**n**	**a**	**b**	**R^2**	**p**	**es**	**a**	**b**	**R^2**	**p**	**es**
European beech	118	19.66	1.70	0.73	< 0.001	0.49	26.39	-0.35	0.10	< 0.001	0.49
Spruce fir	183	8.31	1.85	0.73	< 0.001	0.55	10.54	-0.14	0.01	0.08	0.55
Sweet chestnut	98	11.57	1.54	0.72	< 0.001	0.47	14.83	-0.46	0.18	< 0.001	0.47
Ash	73	10.63	1.74	0.83	< 0.001	0.39	13.54	-0.26	0.10	0.006	0.39
Maple tree	40	14.71	1.73	0.81	< 0.001	0.45	18.74	-0.27	0.09	0.02	0.45
Hornbeam	54	14.08	1.63	0.73	< 0.001	0.50	17.93	-0.36	0.12	0.01	0.50
European larch	40	12.31	1.49	0.51	< 0.001	0.79	15.77	-0.35	0.05	0.12	0.82

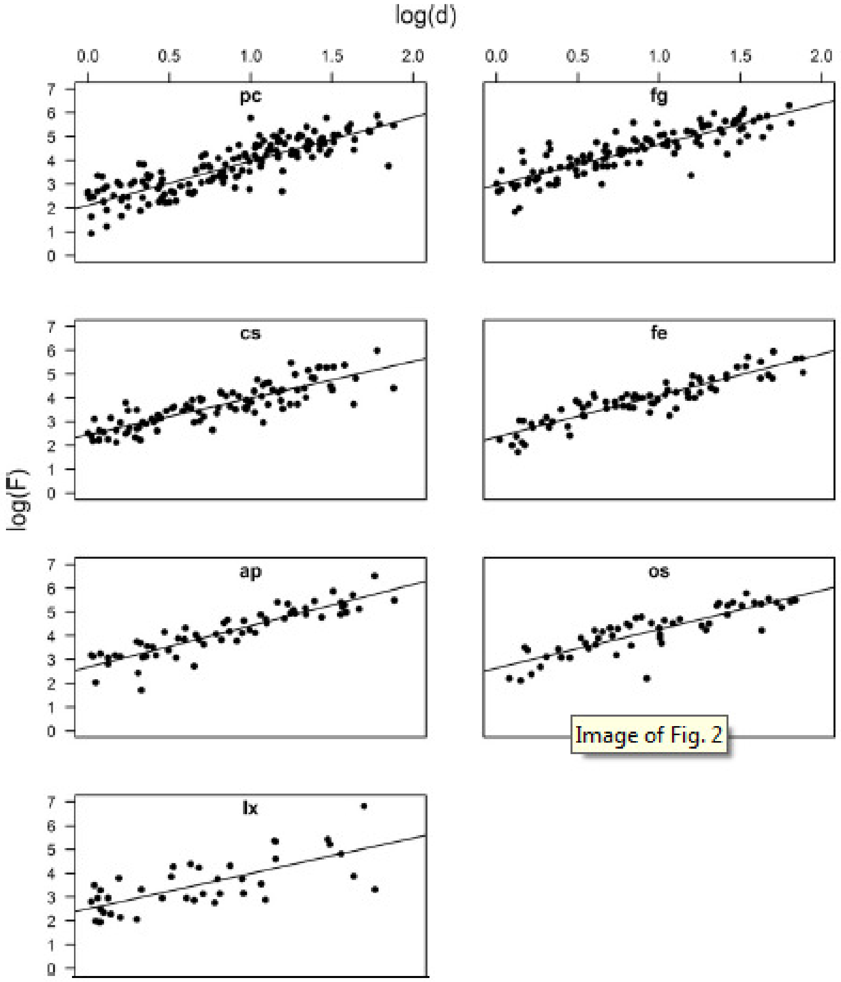

Fig. 2.1.2 Log force–log diameter species-averaged regression lines Spruce fir (Pc), Beech (Fg), Sweet chestnut (Cs), Ash (Fe), Maple tree (Ap), Hornbeam (Os), Larch (Lx).

Within-species variability

To investigate the influence of the environment on force–diameter relationships within a given species, regression lines from that species sampled at different sites were developed and compared by ANCOVA. The results (corrected means and significance) are shown in Tab. 2.1.4, Fig. 2.1.3 and Fig. 2.1.4. The requirements for normality and homogeneity of variance were always satisfied, except for one case of sweet chestnut for which the variances are not homogeneous (Tab. 2.1.4; CsLCCran–CsBSBoar). For *Picea abies*, the five series are parallel (ANCOVA, $F_{5,171} = 0.34$, $p = 0.88$) and significantly different (ANCOVA, $F_{5,176} = 26.4$, $p < 0.01$).

When the series are compared in pairs, Monte Pora and Alpe Gigiai are different from all of the other series (ANCOVA, $p < 0,01$) and between each other (ANCOVA, $F_{1,51} = 27.8$, $p < 0.01$), whereas the remaining four series are not statistically different between each other (ANCOVA, $F_{3,121} = 0.46$, $p = 0.7$).

Three groups for which the root force behaviour is considered to be the same are thus identified: (i) Alpe Gigiai; (ii) Monte Pora; and (iii) Fino, Incudine, Villa di Chiavenna and Piuro. The force ranking (in terms of the corrected means of force) is as follows: Alpe Gigiai 94 N, Monte Pora 59 N, Fino 38 N, Piuro 34 N, Villa di Chiavenna 34 N, Incudine 33 N. For F. sylvatica, the five series are parallel (ANCOVA, $F_{4,108} = 0.99$, $p = 0.41$) and significantly different (ANCOVA, $F_{4,112} = 12.9$, $p < 0.01$). When the series are compared in pairs, Moggio, Gianico and Artogne were not different among themselves (ANCOVA, $F_{2,69} = 1.35$, $p = 0.26$), and Moggio, Gianico and Morterone were not different among themselves (ANCOVA, $F_{2,68} = 2.77$, $p = 0.07$). Alpe Gigiai was significantly different from all of the other series ($p < 0.01$), and Morterone and Artogne were different between themselves (ANCOVA, $F_{1,52} = 9.05$, $p < 0.01$). Statistical analysis recognizes the following groupings: (i) Moggio, Gianico and Artogne; (ii) Moggio, Gianico and Morterone; and (iii) Alpe Gigiai. The force ranking (in terms of corrected means of force) is as follows: Alpe Gigiai 147 N, Morterone 89 N, Moggio 77 N, Gianico 73 N, Artogne 63 N. For C. sativa, it was not possible to compare all of the four series because the variances were non-homogeneous (Levene's test, $p < 0.05$). The same problem occurred for the comparison of pairs because of non-parallelism (Tab. 2.1.4), except in the case of Villa di Chiavenna-Crandola and Villa di Chiavenna-Casargo, which were parallel (ANCOVA, $F_{1,49} = 1.53$, $p = 0.22$; ANCOVA, $F_{1,41} = 0.96$, $p = 0.3$) and statistically not different (ANCOVA, $F_{1,50} = 0.74$, $p = 0.1$; ANCOVA, $F_{1,42} = 1$, $p = 0.3$), and in the case of Casargo-Boario, which was parallel (ANCOVA, $F_{1,43} = 1.32$, $p = 0.26$) and significantly different (ANCOVA, $F_{1,42} = 10.6$, $p < 0.01$). The possible groupings are as follows: (i) Villa di Chiavenna and Crandola; (ii) Villa di Chiavenna and Casargo; (iii) Boario. For F. excelsior, it is not possible to consider all of the series together because the regression lines are not parallel (ANCOVA, $F_{2,67} = 4.96$, $p < 0.01$). When the series are compared in pairs, Pasturo and Oneta are significantly different (ANCOVA, $F_{1,41} = 16.6$, $p < 0.01$), and the log-transformed mean corrected value of F is higher for Pasturo (54 N) than for Oneta (35 N). From a cautious perspective, the Prestine and Oneta series can be considered to be not different (ANCOVA, $F_{1,48} = 6.63$, $p = 0.013$); they have mean corrected values of 53 N and 40 N, respectively. The Pasturo and Prestine series are not parallel. For A. pseudoplatanus, the series are parallel (ANCOVA, $F_{1,56} = 1.5$, $p = 0.22$) and significantly different (ANCOVA, $F_{1,57} = 24.2$, $p < 0.01$). The log-transformed mean corrected value of F is higher for Prestine (81 N) than for Oneta (49 N). For O. carpinifolia, the series are parallel (ANCOVA, $F_{1,50} = 0.23$, $p = 0.63$) and not different (ANCOVA, $F_{1,51} = 5.52$, $p = 0.022$). The mean corrected values were 58 N for Malegno and 80 N for Pasturo. For L. decidua, the series are not parallel (ANCOVA, $F_{1,36} = 6.19, p = 0.017$). If parallelism is forced (because the p value is very close to the significance level), the series are significantly different (ANCOVA, $F_{1,37} = 60.96$, $p < 0.01$), and the mean corrected force value is higher for Alpe Gigiai (69 N) than for Monte Pora (20 N).

Tab. 2.1.4 Coefficients and statistical parameters of power regressions F–d; superscript letters indicate statistically significant differences ($p < 0.05$) in corrected means (ANCOVA); (*,×, +) indicate non-parallelism while (◦) represents non-homogeneity of variances.

station	**N**	***a***	***b***	**p**	**R^2**	**se**	**F corrected means (N)**
PcBGFino	28	7.36	1.88	< 0.001	0.84	0.39	38^{c}
PcBGMnPo	29	9.76	2.02	< 0.001	0.93	0.29	59^{b}
PcBGPiur	29	5.09	2.12	< 0.001	0.80	0.51	34^{c}
PcBGViCh	26	6.01	1.96	< 0.001	0.82	0.43	34^{c}
PcBGIncu	46	4.93	2.12	< 0.001	0.82	0.48	33^{c}
PcBGAlGi	25	15.82	1.98	< 0.001	0.88	0.36	94^{a}
FgLCMort	27	19.74	1.78	< 0.001	0.89	0.28	89^{b}
FgLCMogg	15	19.11	1.66	< 0.001	0.83	0.39	77^{bc}
FgBSArto	28	12.06	1.94	< 0.001	0.77	0.55	63^{c}
FgBSGian	30	18.08	1.65	< 0.001	0.86	0.32	73^{bc}
FgCOAlGi	18	42.74	1.46	< 0.001	0.69	0.47	147^{a}
CsBSBoar	27	12.01	1.16	< 0.001	0.77	0.31	$28^{b*+\circ}$
CsLCCasa	18	14.51	1.44	< 0.001	0.71	0.41	$44^{a\circ+}$
CsLCCran	26	9.13	2.1	< 0.001	0.93	0.30	$49^{a*\circ+}$
CsSOViCh	27	9.73	1.79	< 0.001	0.69	0.52	40^{a+}
FeBGOnet	22	8.93	1.66	< 0.001	0.80	0.39	37^{b}
FeLCPast	22	16.43	1.43	< 0.001	0.88	0.30	54^{a*}
FeBSPres	29	8.48	2.03	< 0.001	0.69	0.52	53^{b*}
ApBGOnet	27	10.55	1.82	< 0.001	0.82	0.43	49^{b}
ApBSPrest	33	20.91	1.58	< 0.001	0.88	0.33	81^{a}
OsLCPast	26	17.37	1.58	< 0.001	0.79	0.40	80^{a}
OSBSMale	28	11.25	1.71	< 0.001	0.72	0.55	58^{b}
LxBGMnPo	23	9.93	0.99	< 0.001	0.53	0.48	20^{b*}
LxCOAlGi	17	21.49	1.68	< 0.001	0.84	0.44	69^{a*}

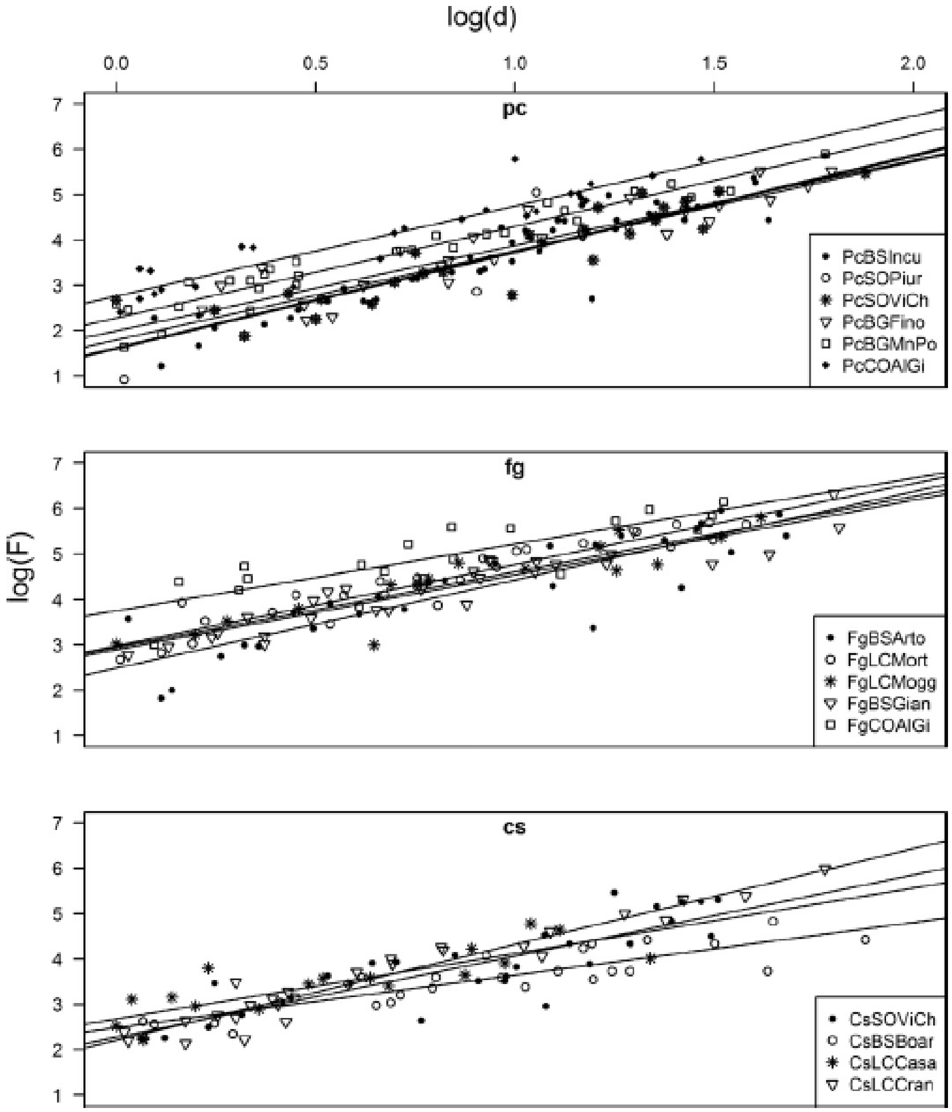

Fig. 2.1.3 log force–log diameter regression lines for each species and site Spruce fir (Pc), Beech (Fg), Sweet chestnut (Cs), Ash (Fe), Maple tree (Ap), Hornbeam (Os), Larch (Lx).

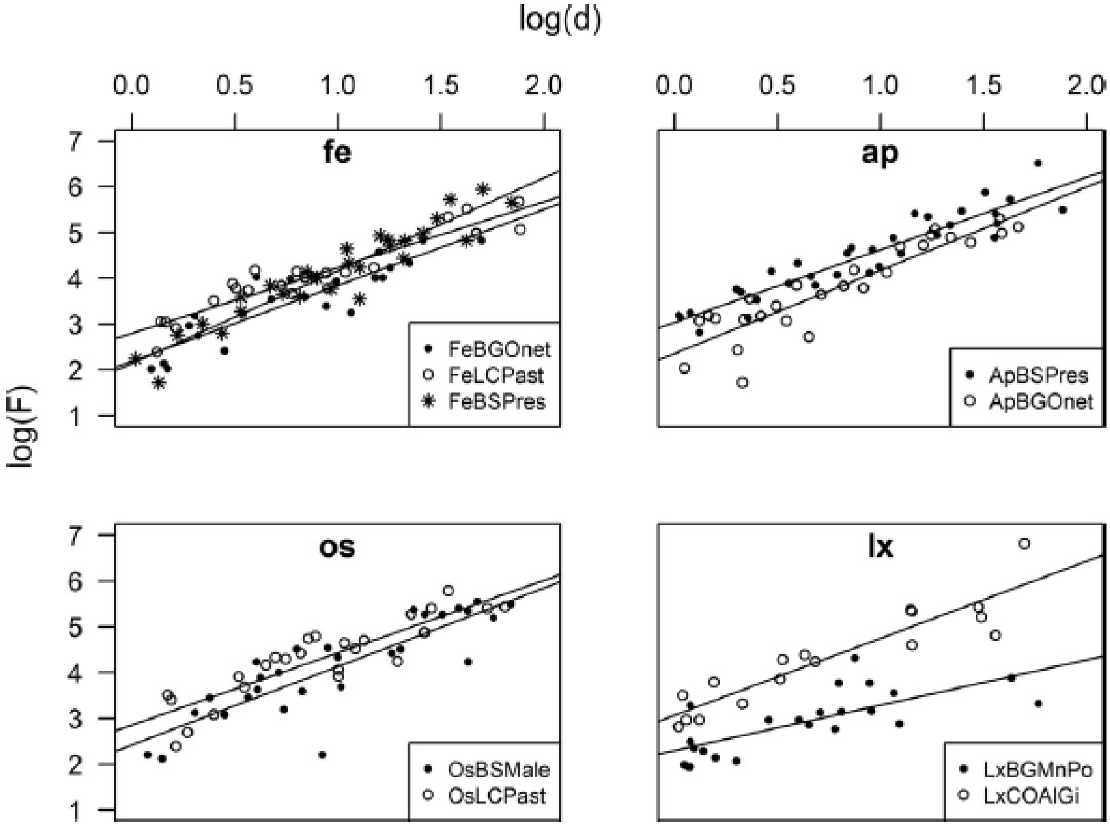

Fig. 2.1.4 (continued)

Environmentally driven variability

To evaluate the effects of environmental variables on root resistance, besides their effects on root size, multiple regression analysis was performed. The multiple regression analysis was performed using root force as a dependent variable and the following six environmental and stand variables, in addition to root diameter: elevation, mean slope, drained area, wetness index, mean distance of trenches from trees, and mean diameter of trees around the sampling trench (Tab. 2.1.1). For this analysis, only those species that had at least a certain number of observations related to various growing and stand conditions were considered: spruce fir, beech, and sweet chestnut. When simple regressions between each explicative variable and all of the available force values for each species were performed, non-significant relationships ($p > 0.01$) with low coefficients of determination ($R^2 < 10\%$) were always obtained. Such results were expected because of the great variability of force values for given environmental and stand variables resulting from the differing diameters of the sampled roots. However, when the site-averaged force values for each species were considered the amount of data was greatly reduced, making regression analysis unfeasible. Therefore, regressions were performed considering the mean values of root force for five diameter classes ($1 \leq d < 2$; $2 \leq d < 3$; $3 \leq d < 4$;$4 \leq d < 5$;≥ 5 mm) for each species and site. As described by Finér et al. (2011), because of the small number of observations, relationships with the explicative variable were considered significant for $R^2 > 30\%$. The selected variables (with $R^2 > 30\%$) were then used together with diameter to perform multiple regressions on all of the force values available for each species.

In the case of beech, the variables of drained area, wetness index, mean tree diameter, mean slope, and mean distance from tree did not show a significant relationship with log-force values ($p > 0.1$, $R^2 < 30\%$). A multiple linear regression of root diameter (log transformed values) and elevation was tested, taking into account all of the log-transformed force values. Force seems to increase with root diameter and elevation. The model is significant ($p < 0.001$) and explains 76% of the total force variability ($R^2 = 0.76$); all of the considered variables are significant for the regression model (Student's t-test and Fisher's Test, $p < 0.001$). However, it must be noted that most of the variability is explained ($R^2 = 0.73$) by using only log-transformed diameter values as the explicative variable in the linear regression model.

In the case of spruce fir, only root diameter (log-transformed values), elevation, and mean distance from trees showed any relationship with log-transformed force values. A multiple linear regression between force, root diameter (both log-transformed values), elevation, and mean distance from trees was considered.

With this model, the mean distance parameter resulted in a non-significant variable ($p > 0.05$) and was therefore excluded.

A regression model using only root diameter and elevation was adopted, and the results confirmed the increase of force with elevation.

The model is significant ($p < 0.001$) and explains 80% of the total force variability ($R^2 = 0.80$), and all of the considered variables are significant for the regression model (Student's t-test and Fisher's Test, $p < 0.001$). However, as in the case of beech, most of the total variability can be explained in terms of root diameter only ($R^2 = 0.73$, $p < 0.001$).

The findings for sweet chestnut confirm that the only significant variables are root diameter and elevation. The multiple linear regression model between log-transformed force values, log-transformed diameter values, and elevation is significant and explains 77% of the total variability; the considered variables are significant for the regression model (Student's t-test and Fisher's Test,

$p < 0.001$). Again, force increases with elevation, but diameter alone explains 72% of the total variability.

2.1.4 Discussion

The mean values of tensile stress presented in this study cover a range from 1 to 75 MPa, whereas force ranges from 2 to 900 N (Tab. 2.1.2) according to reported values (Norris et al., 2008). When all of the data obtained for a given species regardless of the sampling site are considered, statistically significant relationships are obtained for both root diameter vs. stress and root diameter vs. force, confirming the strong dependence of root resistance on root size (diameter). According to many other authors (Ziemer and Swanston, 1977; Nilaweera and Nutalaya, 1999; Kondo et al., 2004; Bischetti et al., 2009; Abdi et al., 2010; Genet et al., 2011), this relationship is well described, in terms of both stress and force, by power law regressions (Tab. 2.1.3 and Tab. 2.1.4).

Comparisons of F–d relationships for different species (ANCOVA, $F_{6,618} = 8.27$, $p < 0.001$;Fig. 2.1.2) confirmed that there are statistically significant differences in root resistance between species (Schiechtl, 1980; Genet et al., 2005, 2010; De Baets et al., 2008; Bischetti et al., 2009). In this regard, beech and maple can be considered to be the “strongest” species, while spruce, sweet chestnut, and larch are the “weakest”; specifically, the roots of beech are 25% stronger than those of maple and two times stronger than those of the other species. These findings are consistent with those of Genet et al. (2005) and Bischetti et al. (2009), who observed similar patterns for the stress–diameter relationships of beech, spruce and sweet chestnut, although the values obtained in those studies were higher.

Differences in root resistance within a given species can be ascribed primarily to environmental growing conditions (Genet et al., 2011). However, Hathaway and Penny (1975) observed significant difference among different clones of the same species grown in the same nursery, and genetic adaptations to the specific environment also cannot be ruled out.

Comparisons of site-specific relationships for a given species show that these relationships can differ significantly as a consequence of differing conditions in the growing environment, and not just as a consequence of differences in root size. The results obtained from ANCOVA indicate that the species exerts a general control over root resistance. On the other hand, the results from ANCOVA of a given species sampled in different sites show that for all species there are cases in which the root force is significantly different from one site to another.

These findings are consistent with those of other studies performed on a single species (Genet et al., 2011) or in a small area (Hales et al., 2009). These two groups both observed a difference within a given species and explained the difference in terms of the elevation and the sampling position on the hillslope (as an indicator of soil saturation), respectively. These two groups also suggested a link between root resistance and cellulose dynamics.

In the present study, multiple regression analyses performed with the consideration of several environmental factors showed a significant influence only for elevation (and distance from trunk, in the case of spruce) and a strongly predominant effect of root diameter, which by itself explains more than 70% of the variability.

Elevation seemed to weakly affect root resistance, apparently in contrast to the results of Genet et al. (2011). Actually, these authors observed for Abies georgei a decrease of root force with elevation when comparing roots of the same diameter taken at lower (3480 m a.s.l.) and higher (4330 m a.s.l.) elevations, whereas the difference in root force for lower (3480 m a.s.l.) vs. middle (3900 m a.s.l.) elevations is not statistically significant. The effect of elevation appears to reflect a change in cellulose dynamics that occurs at the altitudinal limit of the treeline (4330 m a.s.l.). In a range of less critical elevations, such as in the present study, the effect of elevation appears to be smaller or negligible.

In regard to the effect of position on the hillslope, our sites are relatively uniform (as indicated by the small range of the wetness index), in contrast to the study by Hales et al. (2009). This parameter therefore had little or no effect on the measured root forces.

The lack of a relationship between root force and distance from trunk, which is in contrast to the results of other studies (Abernethy and Rutherfurf, 2001; Docker and Hubble, 2008), is most likely due to the density of our forests; the root systems of the trees overlap, generating a dense and fairly uniform root network between the trunks regardless of the density and size of the trees. The above-mentioned studies, in contrast, involved sparse plantations or isolated plants on riverbanks.

The site-specific environmental factors considered and the very general criterion of broadleaves vs. conifers did not allow us to explain and generalize the differences and similarities among the force–diameter relationships obtained for a given species at different sites. We therefore attempted a different approach based on defined forest districts, which represent in a holistic manner relatively homogeneous growing conditions (Del Favero, 2002).

The results of ANCOVA (Tab. 2.1.4) were re-analyzed from this perspective, comparing root force–diameter regression relationships for a given species grown in different forest districts (Fig. 2.1.5).

In most cases, the force–diameter relationships within a given species that are not significantly different tend to occur within the same Forest District (Fig. 2.1.5 a). New force–diameter relationships were then obtained using the Forest District as a criterion to describe uniform growing conditions (Tab. 2.1.5). The R2 values for such relationships are always greater than 0.69, with the exception of European larch of the Middle Eastern Esalpic district (LxMnPo), and are always statistically significant at the 0.001 level.

These findings indicate that, with few exceptions, Forest Districts are a useful criterion for explaining the observed variability in root resistance and the more robust relationships (R^2 values higher than species-averaged values regardless of the sampling site). It should be noted that the sites that do not conform to the forest district criterion are located at the boundary between two Forest Districts. Because the definition and the mapping process of the Districts involved a certain degree of uncertainty (the map scale is 1:250.000) we excluded from the analysis all the sites that were near a boundary. The remaining sites, which could be assigned to different Forest Districts without ambiguity (with the exception of ash and the partial exception of sweet chestnut), conformed to the Forest District criterion (Fig. 2.1.5b).

Thus, the holistic approach to forest classification appears to be promising for studies of average root resistance. More detailed forest classification schemes, such as the “forest type,” which relates site characteristics (soil, altitude, steepness, exposure, climatic aspects) to stand characteristics (mean species, secondary species, management, etc.) in a more comprehensive manner, might be preferable in theory but are also more demanding of resources.

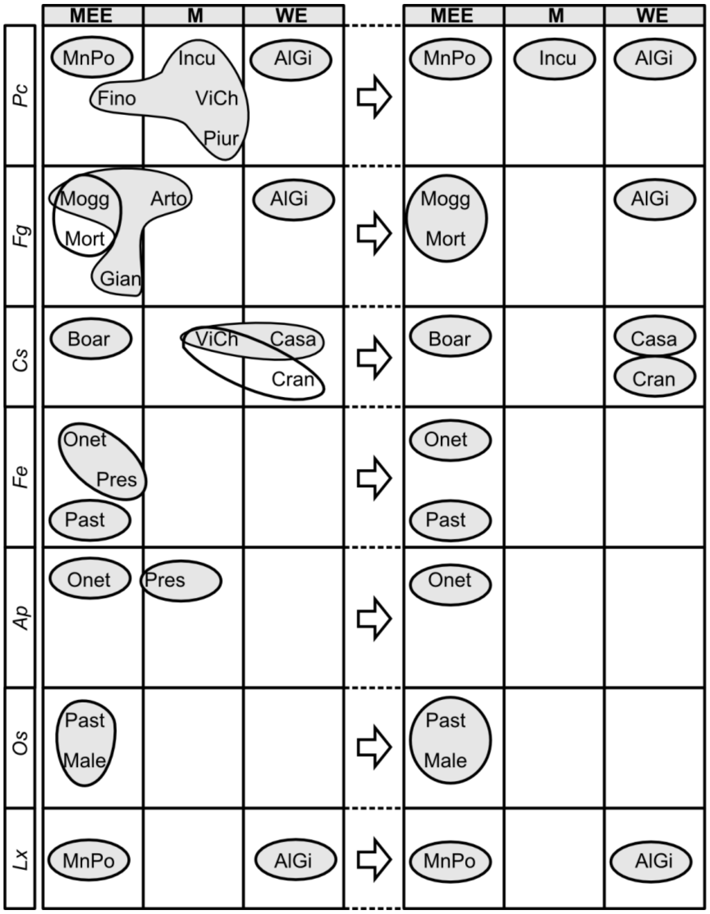

Fig. 2.1.5 similarity/difference at Forest District scale considering (a) all sites, (b) without near-boundary sites; the same species at different sites that are not statistically different are grouped within circles.

Tab. 2.1.5 Coefficients and statistical parameters of species and district-averaged F–d relationship.

species	**forest district**	**n**	**a**	**b**	**R^2**	**p**	**se**
Spruce fir	middle eastern esalpic	57	9.39	1.82	0.86	< 0.001	0.39
Spruce fir	mesalpic	101	5.22	2.08	0.81	< 0.001	0.47
Spruce fir	western esalpic	25	15.82	1.98	0.88	< 0.001	0.36
European beech	middle eastern esalpic	72	23.39	1.69	0.81	< 0.001	0.33
European beech	mesalpic	28	12.06	1.94	0.77	< 0.001	0.55
European beech	western esalpic	18	42.74	1.46	0.69	< 0.001	0.47
Sweet chestnut	middle eastern esalpic	27	12.01	1.16	0.77	< 0.001	0.31
Sweet chestnut	mesalpic	27	9.73	1.79	0.69	< 0.001	0.52
Sweet chestnut	western esalpic	44	11.01	1.88	0.85	< 0.001	0.37
Ash	middle eastern esalpic	73	10.63	1.74	0.83	< 0.001	0.39

Maple tree	middle eastern esalpic	27	10.55	1.82	0.82	< 0.001	0.43
Maple tree	mesalpic	33	20.91	1.58	0.88	< 0.001	0.33
Hornbeam	middle eastern esalpic	54	14.08	1.63	0.73	< 0.001	0.50
European larch	middle eastern esalpic	23	9.93	0.99	0.53	< 0.001	0.48
European larch	western esalpic	17	21.49	1.68	0.84	< 0.001	0.44

2.1.5 Conclusions

The results of the present study show that root resistance is strongly dependent on root size and can be well described by power law relationships as a function of the root diameter, both in the case of stress (decreasing) and force (increasing).

Root resistance differs significantly among species, although there is also a certain degree of similarity among different species. This issue, which was also mentioned by Hales et al. (2009), was not investigated here but merits future study.

Investigation of the variability within a given species sampled at different sites by multiple regression analysis using environmental and stand properties showed only weak relationships with elevation and with distance from trunk, in addition to the relationship with root diameter.

A promising approach to the interpretation of root resistance data is that involving the holistic perspective of Forest Districts. This approach may represent the appropriate balance between a macro- and a micro-vision of the root resistance process.

If it is confirmed by further studies, such an approach will lead to averaged force (or stress)–diameter relationships that are valid for large areas and facilitate the use of additional cohesion into hillslope stability models.

2.1.6 References

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2.2 Effects of the variability of tensile force and root distribution on root reinforcement estimation: the case study of *Picea abies* in the alpine region.

2.2.1 Introduction

Despite the large volume of research addressing root tensile strength and root distribution, few studies attempt a quantification of the influence of their variability on root reinforcement estimation. Mao et al. (2012) considered the effect of root area ratio variability and root tensile strength on the W&W and on the stress-step loading FBM models for a mixture of species in order to assess inter-species variability between different functional groups (trees-shrubs-grasses). Similarly, Genet et al. (2010b) investigated how tree species diversity influences the factor of safety of a slope, and found that not between all species there are significant differences in root mechanical properties. Intra-species variability, however, was not considered in both cases, as a common force diameter relationship was used for each species. In addition, there are no investigations on the sensitivity of Root Bundle Model to root distribution and root mechanical properties variability, despite the large quantity of data on root pullout and tensile tests and on root distribution. In particular, the effects of the mechanical variability within a diameter class (Schwarz et al., 2013) have never been considered yet.

As analyzing root systems in the field is difficult and time consuming, it is important to quantify how much root tensile/pullout forces and root distribution affects root reinforcement estimation, to plan at the best field campaigns. It is also important to estimate the magnitude of the uncertainty involved in the assumptions regarding tensile force and root distribution and its effects in numerical models.

In the following, the sensitivity of root reinforcement calculations by means of Root Bundle Model for a widespread alpine species, *Picea abies (*L.) Karst, will be assessed with specific reference to:

- ✓ the variability in measured root strength versus diameter (i.e. the variability in root mechanical properties), including the strength variability within a diameter class;
- ✓ the variability in root distribution (i.e. the variability in the number of roots per diameter class).

Such a work is based on a large dataset of root tensile tests and root distribution of one of the most important tree species for the alpine region. Data were collected in a wide range of altitudinal and climatic conditions on both the North and South side of the Alps. Different methods in sampling root distributions and in measuring root force-diameter relationships were also compared, covering the most common methods adopted in the last years. The final objectives of this analysis were: i) to have evidences about the effect of the use in root reinforcement estimation of data presented in literature (root force-diameter relationships and root distributions); ii) to assess which factors have to be considered to avoid errors in root reinforcement assessment and thus on the quantification of the stabilization effects of roots at the hillslope scale.

2.2.2 Material and Methods

Root distribution data

The root distribution of spruce (*Picea abies* (L). Karst) was measured by means of 116 trenches, dug in different sites in Lombardy, Italy, and in Switzerland (Fig. 2.2.1). In Lombardy, 33 trenches (30 cm wide and 50 m deep) were dug (Tab. 2.2.1) in six forest sites, choosing the sample points where the value of root density was expected to be the lowest. In Switzerland, 83 root distributions were obtained in five sites (Tab. 2.2.2), where 4 to 9 trees were selected and three trenches (50x50 cm large) were dug at increasing distances from each selected tree stem (0.5 , 1.5, 2.5 and 3.5 m). Sites in Lombardy and in Switzerland were chosen to sample a range of conditions (altitude, slope angle, climatic zone, tree size, see Tab. 2.2.1 and Tab. 2.2.2).

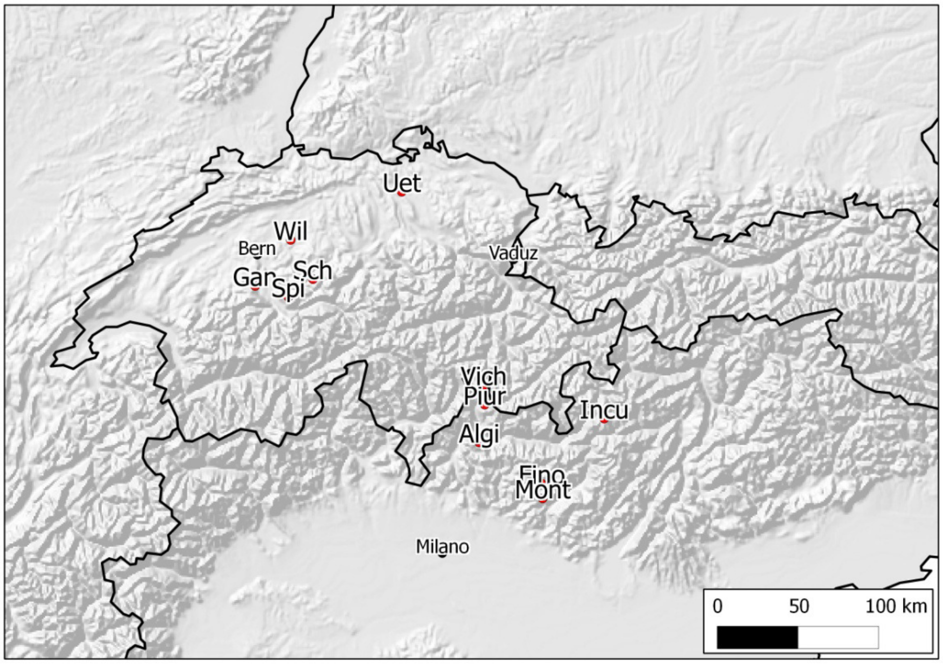

Fig. 2.2.1 Sampling sites map.

Two different methods for estimating the number of roots per diameter class were used. For the Lombardy dataset, this number was estimated through digital image analysis (Bischetti et al., 2009), whereas for the Swiss data roots were counted and measured directly on the wall trench just after digging (Schwarz et al., 2010). In the digital image method the trench walls were cleaned after digging to remove all the organic materials other than roots, and wetted to increase the contrast between roots and soil. A frame of known size was applied to the walls as spatial reference and several images were taken to reproduce the whole profile. Images were then corrected for geometrical distortions basing on the reference frame and merged using a image analysis software (GIMP 2; www.gimp.org). All roots visible on the image were manually selected and their diameter and coordinates measured by a GIS software (MapWindow 4.6, www.mapwindow.org).

Roots of both data sets were ranked in 1-mm diameter large class, from 0.5 to 5.5 mm. For the Italian dataset, the first diameter class consists only of roots between 1 and 1.5 mm because the digital method makes very difficult the identification of roots smaller than 1 mm. All root distributions are reported in the Appendix A.

Tab. 2.2.1 Sites characteristics in Lombardy.

sample site	short form	n. of trenches	elev (m asl)	mean slope (°)	mean tree diameter (cm)	mean distance tree-trench (m)	Climatic zone
Fino del Monte	Fino	5	961	27	34	2.13	Middle Eastern Esalpic
Monte Pora	Mont	10	1484	27	37	4.90	Middle Eastern Esalpic
Piuro	Piur	5	1097	35	46	2.50	Mesalpic
Villadichiavenna	Vich	5	1082	19	22	2.20	Mesalpic
Alpe Gigiai	Algi	3	1542	34	24	3.50	Western Esalpic
Incudine	Incu	5	1227	34	27	2.70	Mesalpic

Tab. 2.2.2 Sites characteristics in Switzerland.

sample site	short form	n. of trenches	elev (m asl)	mean slope (°)	mean tree diameter (cm)	mean distance tree-trench (m)	forest district
Schangnau	Sch	12	1000	25	39	0.5/1.5,/2.5/3.5	Northe Esalpic
Spisibach	Spi	11	1240	35	40	0.5/1.5,/2.5/3.5	Northe Esalpic
Gantrisch	Gan	18	1220	15	41	0.5/1.5,/2.5/3.5	Northe Esalpic

Wiler	Wil	17	1620	27	37	0.5/1.5,/2.5/3.5	Endalpic
Uetliberg	Uet	25	630	10	22	0.5/1.5,/2.5/3.5	North-Eastern Esalpic

Root force-diameter data

Concerning the force diameter relationships, we used the force-diameter data of the original studies of Vergani et al. (2012) for the considered six Italian sites and of Schwarz et al. (2011) for one site (Uetliberg) in Switzerland. These data were obtained by laboratory tensile tests of roots (for Italy) and by field pullout experiments (for Uetliberg). Results of these experiments are shown in Fig. 2.2.2 for each site and for all data together ("*all*").

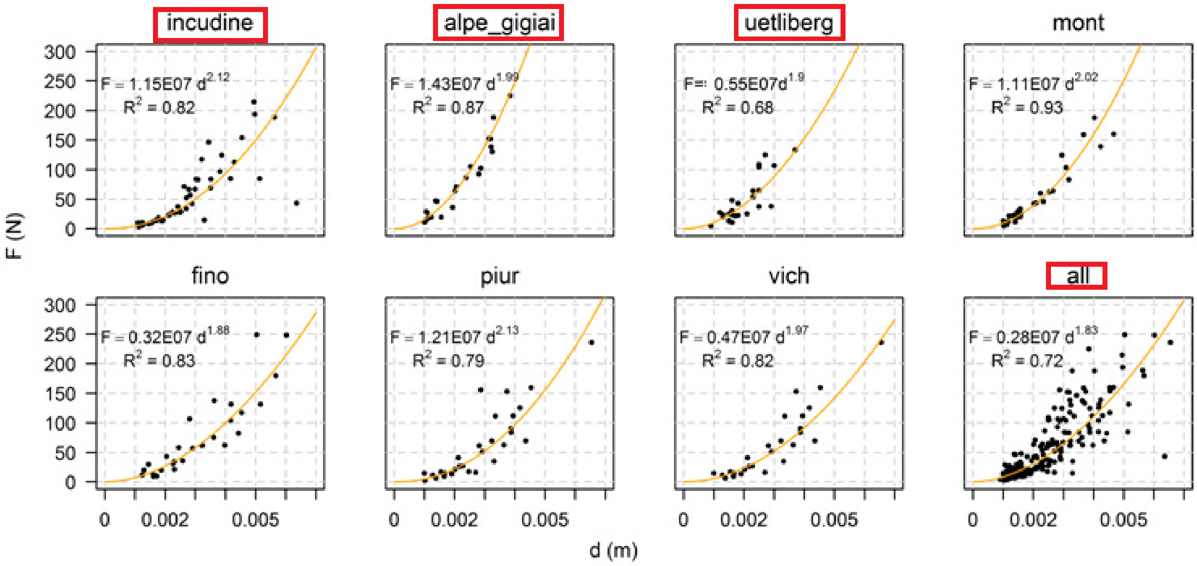

Fig. 2.2.2 Data set of force-diameter and power law relationships. The selected power laws for the sensitivity analysis (indicated by the red blocks) are: Incudine=*f_min*, Alpe Gigiai = *f_max*, Uetliberg = *f_field*, all = *f_all*.

To investigate the force variability exhibited by the data, we selected four power-law fits among the eight available (sites in red box in Fig. 2.2.2). Uetliberg was chosen because it is the only data set obtained by field pull out tests. Alpe Gigiai and Incudine sites were chosen as they represent the maximum and minimum force-diameter relationship (note that the Incu fit is smaller than the Vich fit for root diameters ranging between 0 and 2.5 mm). The fit of all data was selected as a representative average. These fits are named, respectively, *f_field*, *f_max*, *f_min*, and *f_all*.

F_max, f_min, f_field are highly different between them (Fig. 2.2.3, which also includes *f_all*). The comparison by means covariance analysis of the three linear functions derived by log-tansformation

(Fig. 2.2.3 b) of force and diameter values, indicates that they are parallel ($F_{2,90}$ = 0.17, p= 0.84) and highly different ($F_{2,92}$ = 44.54, p < 0.001). Mean fitted values of forces are 79 N for Alpe gigiai (*f_max*), 28 N for Incudine (*f_min*) and 49 N for Uetliberg (*f_field*). Variability exists not only between the two different measurement methods (field vs laboratory) but also within the laboratory data sets.

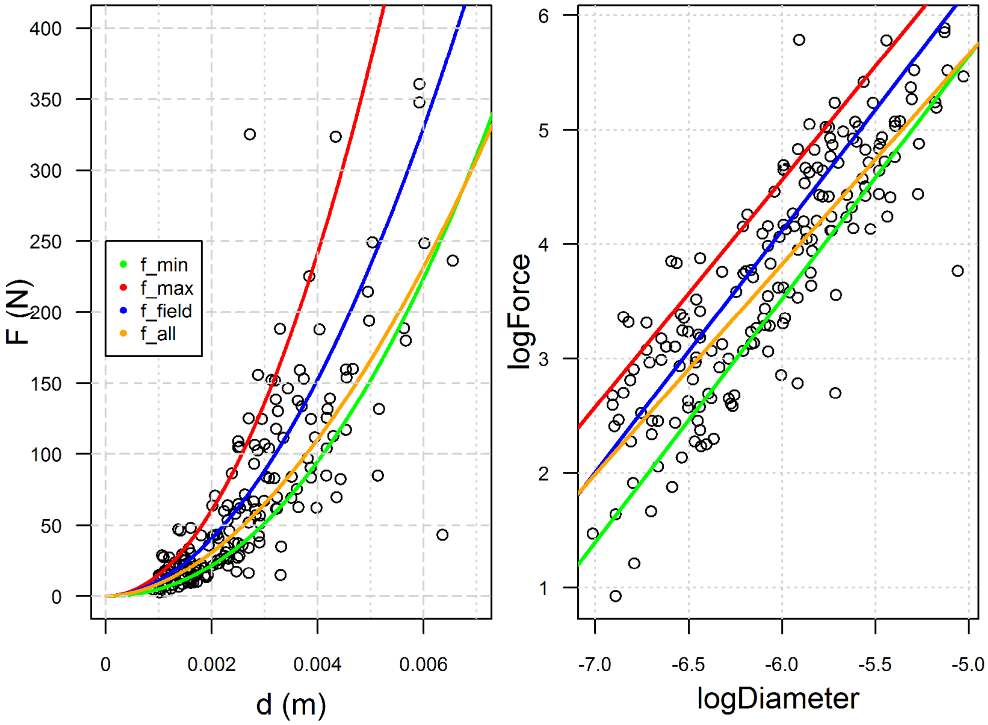

Fig. 2.2.3 Comparison between the force-diameter power law regressions and between the linear regressions obtained by the log-transformation of diameter and force values.

Model

The extended Root Bundle Model, RBMw (Schwarz, 2013), was used to calculate tensile force and displacement of a bundle of roots, according to the root diameter-force relationship and roots distribution. For a detailed explanation of the model see chapter 1.3. Root length was assumed constant for each root diameter class and was estimated from the model of Schwarz et al. (2013) basing on data reported by Schwarz et al. (2011). Parameter values for eq. 1.3.10 (see page 33) are $\gamma = 0.575$ and $L_0 = 18.5$. Young’s modulus was estimated using the relationship proposed by Schwarz et al. (2013), where $\beta = -0.3$ and $E_0=0.248*10^8$ Pa. Root tortuosity was set equal to 1 since eq.

1.3.10 was calibrated with data obtained from field experiments that implicitly consider the effect of tortuosity.

The Weibull exponent was calibrated by fitting the Weibull Survival function to the normalized displacement (see chapter 1.3, for details). For the Uetiberg site, the Weibull exponent resulted 2.4 (Schwarz et al., 2013). For the Italian sites values range between 3.2 and 6.4. Tab. 2.2.3 shows values for the all the sampling sites and Fig. 2.2.4 shows the Weibull survival functions for the four selected force-diameter relationships.

Tab. 2.2.3 Best fit parameters of the Weibull survival functions.

Site	**Algi (*f_max*)**	**Incu (*f_min*)**	**Uet (*f_field*)**	**Mont**	**Fino**	**Piur**	**Vich**	***f_all***
Best fit Weibull exponent *ω*	6.43	5.45	2.4	6.63	4.7	3.2	3.2	2.06

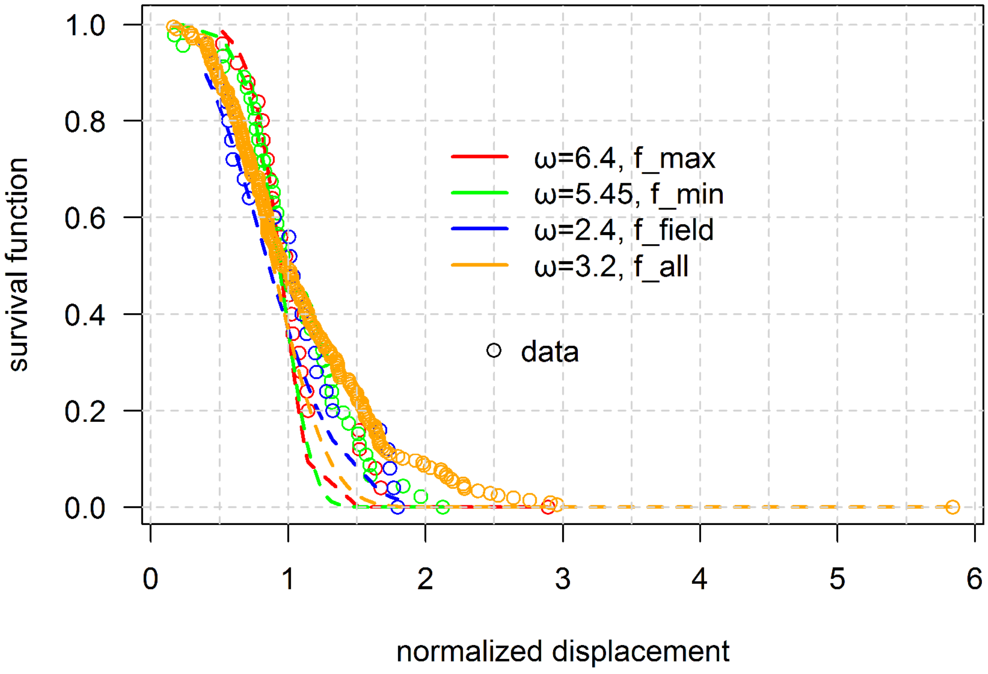

Fig. 2.2.4 Fitting of survival functions for the four dataset and for all data assuming the scaling factor constant to 1.

2.2.3 Results

The sensitivity of the RBMw was explored by four different steps:

1. Estimation of the root reinforcement in terms of force-displacement behavior of each measured root bundle using the best power-law fits and the best Weibull exponent fits for each study area;

2. Evaluation of the influence of the different force diameter function, by means of the estimation and comparison of the root reinforcement obtained by the different force-diameter power-law keeping other variables (root distribution and Weibull exponent) constant;

3. Evaluation of the influence of the Weibull exponent on the calculation of root reinforcement, by means of the estimation of the root reinforcement obtained by the different force diameter power law and the different Weibull exponent;

4. Evaluation of the influence of the different root distribution, by means of the estimation and comparison of the root reinforcement obtained by the different root distributions keeping other variables (power law and Weibull exponent) constant.

Root reinforcement estimation using site-specific power laws, Weibull exponents, and root distributions

Using the calibrated parameters of the force-diameter relationships (fig. 2.2.2), the site specific Weibull exponents (tab. 2.2.3), and the observed root distributions (Appendix A) we obtained 116 combinations of peak force and corresponding displacement value for the root bundles. Fig. 2.2.5 shows the average and standard deviations for each site. This represents the “best modeling” of computed root-reinforcement variability for the considered study areas. The peak values of reinforcement range between 75 and 3754 N. The highest values were obtained for the “algi” dataset, which has the highest force-diameter pre-exponential factor (a) and one of the highest Weibull exponent (see tab. 2.2.3). The minimum values were obtained for the Swiss distributions, which have the lowest number of roots (see Appendix A).

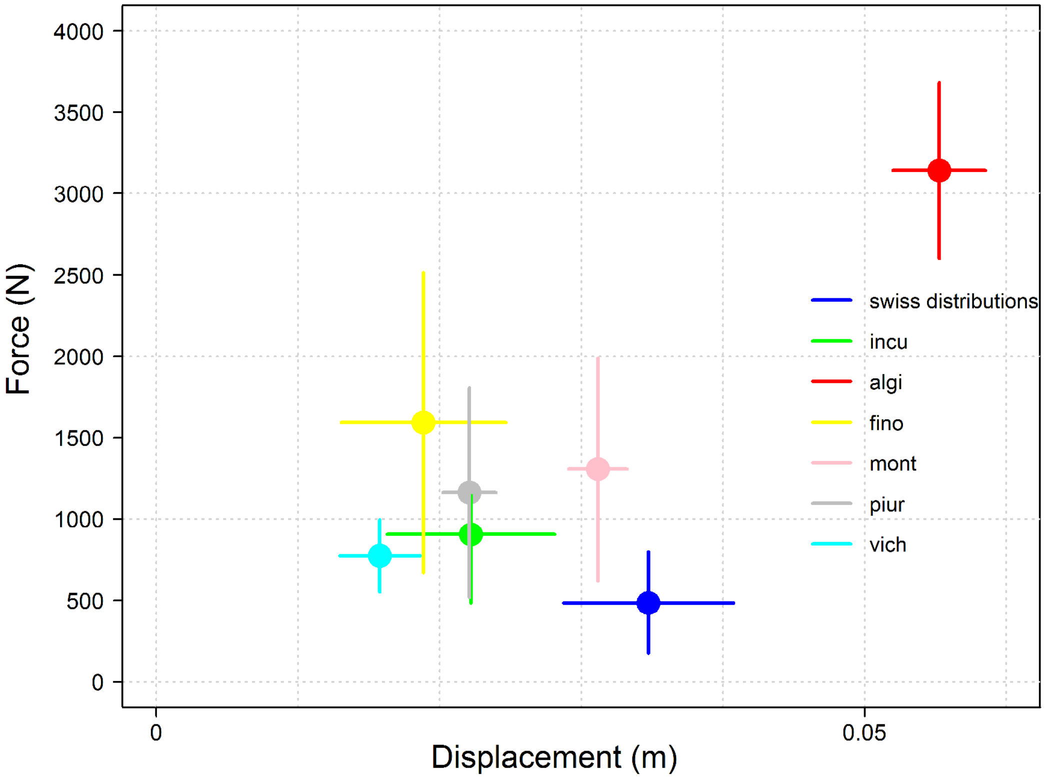

Fig. 2.2.5 Maximum force and corresponding displacement computed with the RBMw with site specific power law parameters, Weibull exponent, and root distribution. The number of roots for the Italian data set is scaled to a 0.5x0.5 m soil. Mean value (points) and standard deviations (lines) of the values of the maximum force and displacement at the maximum force are reported.

Influence of the different force-diameter functions application

The RBMw was firstly applied considering a bundle made by only one root of 3 mm; the four force-diameter power laws (*f_min*, *f_max*, *f_field* and *f_all*) were applied and the Weibull exponent was kept constant and equal to 2.4. Peak forces mobilized by roots are significantly different (Fig. 2.2.6). The peak force obtained using *f_max* is 62% higher than the peak force obtained with *f_min* and 35% higher than *f_field*. The peak force obtained with *f_all* is 24% higher than the one obtained with *f_min* and respectively 25% and 50% lower than the ones obtained with *f_field* and *f_max*. The same analysis carried out with a bundle composed of a root of different diameter lead to slightly different results, with percentages varying between 72% and 20% for a 1-mm root, and between 60% and 11% for a 5-mm root.

Considering a more realistic bundle made of several roots, RBMw was applied taking the real root distribution for the available sites, the four different power laws, and assuming a constant value of the Weibull exponent equal to 2.4 as in the previous case. Results are shown in Fig. 2.2.7, where the mean values of peak force and corresponding displacements are also reported.

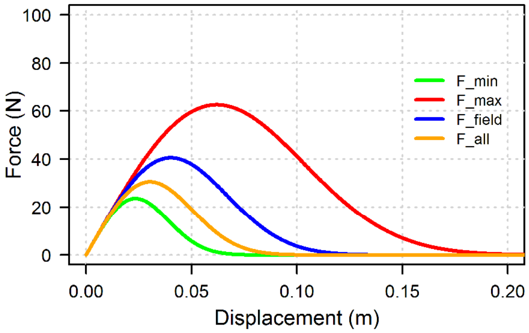

Fig. 2.2.6 Force-displacement curves using the RBMw with four different force-diameter curves and a constant Weibull exponent for a 3-mm diameter root.

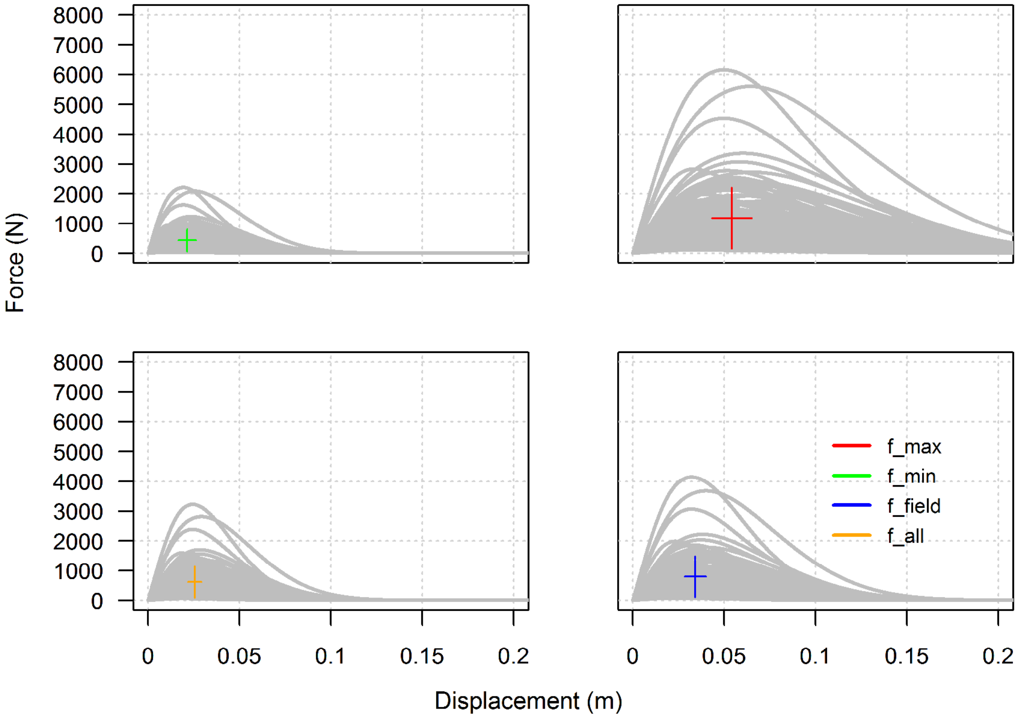

Fig. 2.2.7 Force-displacement for all root bundles obtained with the RBMw for each of the four power laws The Weibull exponent is kept constant. Root numbers are scaled to a 0.5x0.5 m soil profile.

To evaluate the differences in the peak force derived by using the different force-diameter relationships, both raw values and values normalized by *f_max* peak value are reported in Fig. 2.2.8 and Fig. 2.2.9. Results show that:

- using *f_min* the median peak force value is 60% lower than using *f_max*;
- using *f_field* the median peak value is 30% lower than using *f_max*;
- using *f_all* the median peak value is 50% lower than using *f_max*, 30% higher than using a *f_min*, and 20% lower than using *f_field*.

It must be noted that a great variability in the force values is evident even when the same force-diameter relationship is considered, and this has to be ascribed to the heterogeneity of the root distributions.

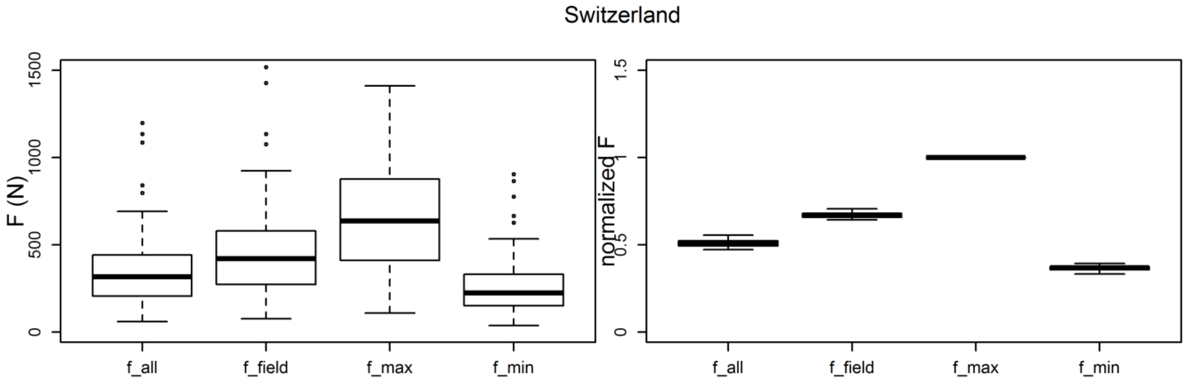

Fig. 2.2.8 Boxplot of peak force values of the bundle for each force diameter curve using Swiss root distributions. 0.5x0.5 m soil profile surface are considered.

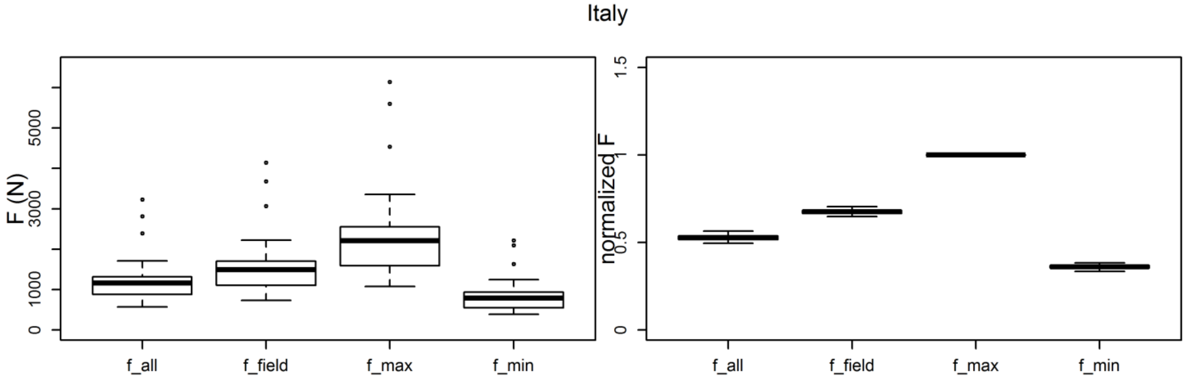

Fig. 2.2.9 Boxplot of peak force values of the bundle for each force diameter curve using italian root distributions. 0.5x0.5 m soil profile surface are considered.

Influence of the Weibull exponent values application

As shown by Schwarz et al, 2013 the reinforcement obtained through RBMw depends significantly on the Weibull exponent. In general, the higher is the value of the Weibull exponent, the higher the peak force is, as larger values of Weibull exponent imply a lower root strength variability within the same diameter class. To test the importance of the related variability we applied the FBMw by using the different site-specific Weibull exponents for a single 3-mm diameter root. The results are shown in Fig. 2.2.10. Comparing Fig. 2.2.10 and 2.2.6, it can be noted that the peak force is greatly increased in the case of *f_max*, and *f_min*, which has a great site specific exponent, whereas is not relevant in the other cases; this is due to the fact that the site-specific exponent of F-field is close to the one of *f_all*. If we apply the model to the measured root distributions, the peak force value derived from the application of *f_min* and *f_max* are up to 30% higher respect to ones of Fig. 2.2.7 due to the higher Weibull exponent used.

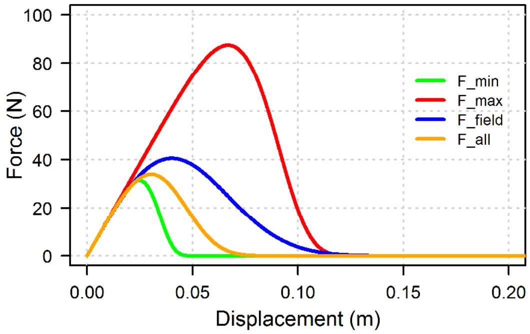

Fig. 2.2.10 Application of RBM with the four different force-diameter curves to a 3 mm root using site-specific Weibull exponents.

Influence of the different root distributions application

To assess the sensitivity of the model to the different root distributions peak forces for the different study areas were computed choosing arbitrarily the force-displacement function *f_min*.

Considering Switzerland, the mean values of peak force in the different sites range between 153 (UET) and 415 N (SCH), with a mean value of 286 N ± 96 N (standard deviation). Differences between the median values (Fig. 2.2.11) of peak force in different sites range between ±5% and ±56%, considering as reference the site with the highest peak of force (this is valid for all the percentage reported henceforth) In the Italian sites, mean values of peak force range between 682 N (Vich) and 1100 (Piur), with a general mean value of 875 N ± 191 (standard deviation). Considering the median peak force values in Italy, differences between the considered sites range between ±2% and less than ±40%.

Considering the differences observed in the same stand, and due to micro-variability of soil characteristics, nutrient and water availability, inter and intra specific competition, in Swiss sites the mean values and corresponding standard deviations resulted 280 ± 115 N (Gan), 415±214 N(Sch), 259±235 (Spi), 152±62 (Uet), 322±179 (Wil). Differences in the peak force values of the different root distribution within each site range from almost ±0% until ±80% (Uet), from ±1% to ±84% (Spi), from ±13% to ±73% (Gan),from ±14% to ±78% (Sch),from ±1% to ±70% (Wil).

In Italian stands instead, mean values and corresponding standard deviations resulted 1081±664 (Fino), 697 ±366 (mont); 750±213 (Incu); 939± 172 (algi); 1101±611 (Piur), 682±209 (Vich). Differences in peak force values ranged between ±10 and more than ±70% in Fino, between ±2 and ±70% in Mont, between ±1% and ±60% in Incu, between ±30% and ±60% in AlGi, between ±20 and ±70% in Piur, between ±3 and ±50% in Vich.

Considering the differences due to the distances from the trees, available only for Swiss sites, a decreasing of root reinforcement values with the increase of the distance from the trees can be observed in most cases, with the exception of Spi site (Fig. 2.2.12). Mean values of peak force at different distances at each site ranged between 200 N (Uet at 2.5 meters from the stem) and 1106 N (Sch at 0.5 meters from the stem). Mean values at each site considering all the distance and the relative standard deviations resulted: 265± 67(Uet), 593±13 (Wil), 560±173 (Gan), 748±329 (Sch), 434 ± 162 (Spi). Relative differences in median values between the different distances in each site range between ±20 and ±60%, but a certain variability can be observed also considering the same distance at the same site, due to the different tree diameter and small scale environmental patterns.

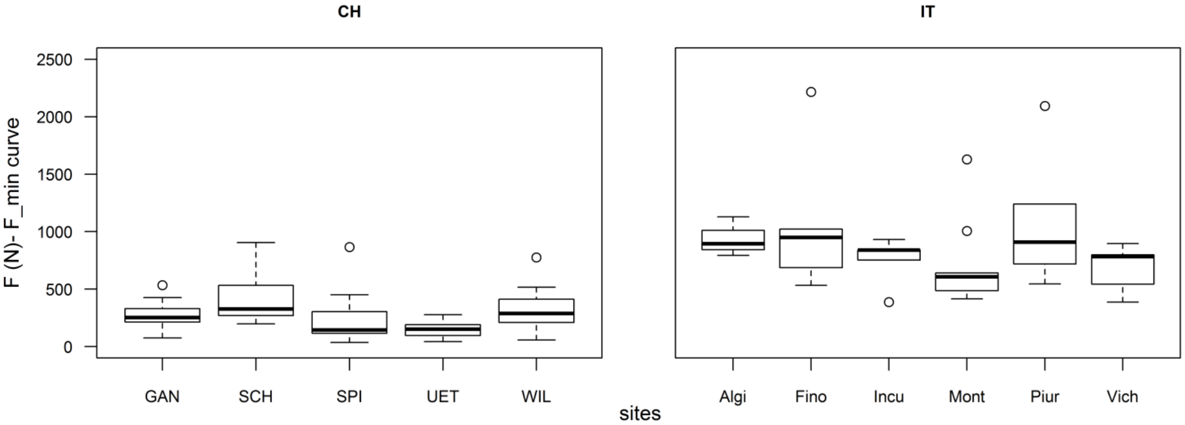

Fig. 2.2.11 Boxplot of peak force values in the different study sites, using a f_min force-diameter curve. 0.5x0.5 m soil profile surface are considered.

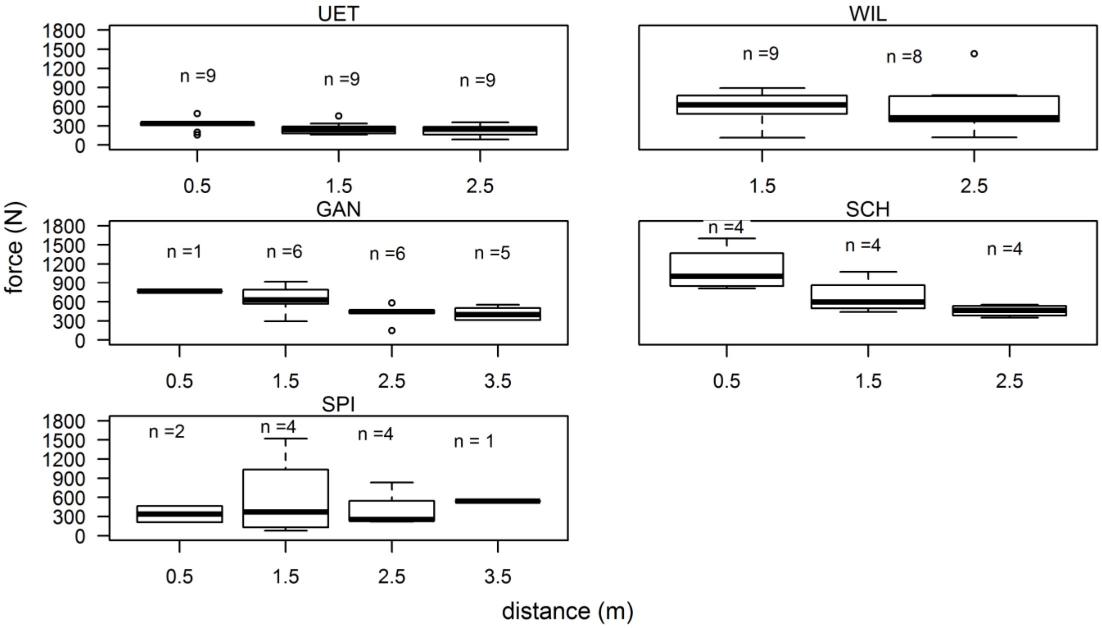

Fig. 2.2.12 Boxplot of peak force values in Swiss samples in function of the distance from tree stem; for each root distribution values coming from the application of the three different force-diameter curve are considered. 0.5x0.5 m soil profile surface are considered.

2.2.4 Discussion and Conclusions

Root reinforcement values obtained in this study fall in the range of values reported in literature for other species (Genet, 2010a, smith fir; Ziemer and Swanston, 1977, sitka spruce and hemlock). Considering root tensile force instead, differences within the considered species are higher than those reported by other authors between different species (Ji et al., 2012, Genet et al. 2005, Mattia et al. 2005). The variability we observed is high, even when the same procedure was applied to measure root properties.

In the considered case it has been showed that this force variability strongly affects root reinforcement estimation, with relative differences in peak force values calculated by the RBMw ranging between ±30 and ±-60%. When a single general power law was adopted, an underestimation of 50% and an overestimation of about 30% was observed with respect to values derived from a maximum and minimum power law. This is in contrast with the findings of Mao et al. (2012), who found that the use of different tensile stress curves for different plant functional groups (shrub, trees, grass) had a small effect on the estimation of root reinforcement. They therefore suggested the use of a general force-diameter equation when studying the stability of temperate forested slope with mixed species, and stated that differences in root distributions are a priority in studies about root reinforcement. Due to the large root strength differences we observed even within the same species and the relevance of the possible consequences of an overestimation of root reinforcement on slope stability, we deem that root tensile strength should be considered a critical factor in slope stability evaluation as did, for example, Ji et al. (2012).

Concerning the Weibull exponents, it can be noted that the lowest value of the Weibull exponent was obtained for the Swiss data that were obtained by field pullout dataset, indicating a higher within diameter class variability. Few studies have evaluated the differences between field and laboratory testing on root strength. Rienstenberg and Sovonick Dunford (1983) found that the force-diameter power law is not affected by the testing methods for roots between 1 and 8 mm. Tosi (2007) found a negligible difference for roots of diameter less than 5 mm. Hales et al. (2013) results are consistent with these studies showing that for roots smaller than 5 mm there is no difference between laboratory and field experiments. In this work with the available data it is not possible to draw any conclusion about the differences between data obtained by field and laboratory tests, because they come from different sites, but it is an issue that must be considered in the future.

According to Schwarz et al. (2013), the implementation of the Weibull survival function in root reinforcement modeling affects in a considerable manner (up to 30%) the results and this should be taken into account, especially when a non site-specific power law is adopted. The effect of using the fitted values of Weibull exponent for each power law curve on the output of RBMw is that the maximum peak force changes significantly, and also the displacement at which the maximum force is reached. Using a higher value of the exponent the peak of the force increases, while using a lower value of the exponent, which means higher variability, the curve becomes smoother and the peak force decreases. Using a Weibull exponent derived from field tests yields more cautionary estimates of root reinforcement.

The number of roots (see Appendix A) for which the lowest peak force was obtained was 8 in Switzerland and 42 roots in Italy (scaled to a 0.5 m x 0.5 meter soil profile). For the highest peak force, the total number of roots is 82 in Switzerland and 246 in Italy (same scaling for the soil profile). There is a consistent difference in the number of roots between Swiss and Italian distribution; this is not surprising considering the high variability that root distribution shows also in the same site. Our data do not allow to assess if the sampling method has an effect on the root density evaluation, but it would be important to carry out some further research on this point. If we consider root area ratio values, the ratio between the total area occupied by roots and the area of the soil profile, for the Italian distribution we have a minimum value of 0.06% and a maximum value of 0.32%, while for Swiss distribution a minimum value of 0.00006% and a maximum value of 0.13%. Literature data for the first 50 cm of soil and for roots diameters between 1 and 10 mm indicate values between 0.07% and 1.85% (Mao et al., 2012, mixed forest of spruce and silver fir) and between 0.1 % and 5% (Stokes et al., 2008, different tree species), results that are higher than data obtained in this study. The differences in the reported data underline the great variability in root distributions reported in literature; it would be opportune to develop more standardized method for the analysis of root distribution in order to allow a better comparison of different datasets in the future.

Analyzing the output of RBMw, a high variability has been found as a result of the combination of different sampling methods and different sampling sites, in fact the highest relative differences in peak force values of the bundle were found between Italian and Swiss distributions. Differences between Swiss median value and the highest Italian median value are comprised between ±85 and ±65%, while differences from the minimum median Italian value (mont) are comprised between ±75 and ±50%. These differences are to be ascribed to the differences in the number of roots, as described above.

Differences are however consistent if we consider the same sampling method and the same sampling zone (north and south of the Alps). Differences in root reinforcement between the considered sites reach ±50% in Switzerland and ±40% in Italy. The differences of root distribution within the same study area are also important, with values between 0 and ±70% in Italian sites and between 0 and ±80% in Swiss sites. However, it can be noted that in general maximum differences in percentage values are lower in Italian sites than in Swiss site due to the different approach adopted to locate the position of the analyzed soil profiles. In the Swiss sites sampling was conducted at a different and fixed distances from tree stems, while in the Italian sites soil profiles were dug in a position where the root reinforcement was expected to be the lowest within the forest stand.

For the Swiss sites, some considerations can be driven on the effects of the distance from the trees on root distribution variability (Fig. 2.2.12). In general, root reinforcement decreases with increasing distance from the trees (Schwarz, 2010). Differences due to distance are comprised between ±20 and ±60% and are even higher than the differences in median values between the different Swiss sites. Also considering the same site and the same distance, there is a certain variability that can be ascribed to different diameter of trees considered (table in the Appendix A) and micro-topography variability. Small scale variability of root distribution and its effects on root reinforcement estimation underlines the importance of modeling lateral root distribution.

Further considerations can be driven if we consider the role of fine (<2 mm diameter class) and coarse roots (>2 mm diameter class). Considering the root distribution and force-diameter power law of Algi_3, which give the highest real value of the peak force of the bundle (Fig. 2.1.2), a sensitivity analysis (Fig. 2.2.13) has been carried out to quantify the role of fine (1mm diameter) and coarse roots (5 mm diameter). To obtain the same value of peak force of the bundle (3754 N) 383 roots of 1 mm are needed, while 16 roots of 5 mm are needed. If we hypothesize to reach the same peak force with just one roots, we need one roots of 20 mm of diameter. In this case the displacement at which the maximum force is reached increases significantly, and this is important in relation to the tension cracks that are formed during a landslide triggering. If we consider the contribution of adding one roots to the bundle, we obtain an increase of the peak force of 1% if we add a root of 2 mm, 2% if we add a root of 3 mm, 3% if we add a root of 4 mm and 4% if we add a root of 5 mm. Considering the percent contribution of each single class of roots to the number of roots of the bundle and to the peak force of the bundle (Tab. 2.2.4), we can see that 1 mm diameter roots are the 33% of the total roots of the bundle but contribute just for the 8% to the peak force; on the other hand, 5 mm diameter roots are the 8% of the total roots of the bundle but contribute for almost the 30% to the peak force. If we consider the total energy of the bundle, the Algi root distribution has a total energy of 355 Nm; the 383 1 mm roots have a total energy of 91 Nm; 16 5 mm roots have a total energy of 375 Nm; 1 root of 20 mm has a total energy of 1227 Nm. On the basis of these results, it would be important to investigate the resistance of roots higher than 5 mm, which contribution has been demonstrated to be important in influencing the total force of the bundle.

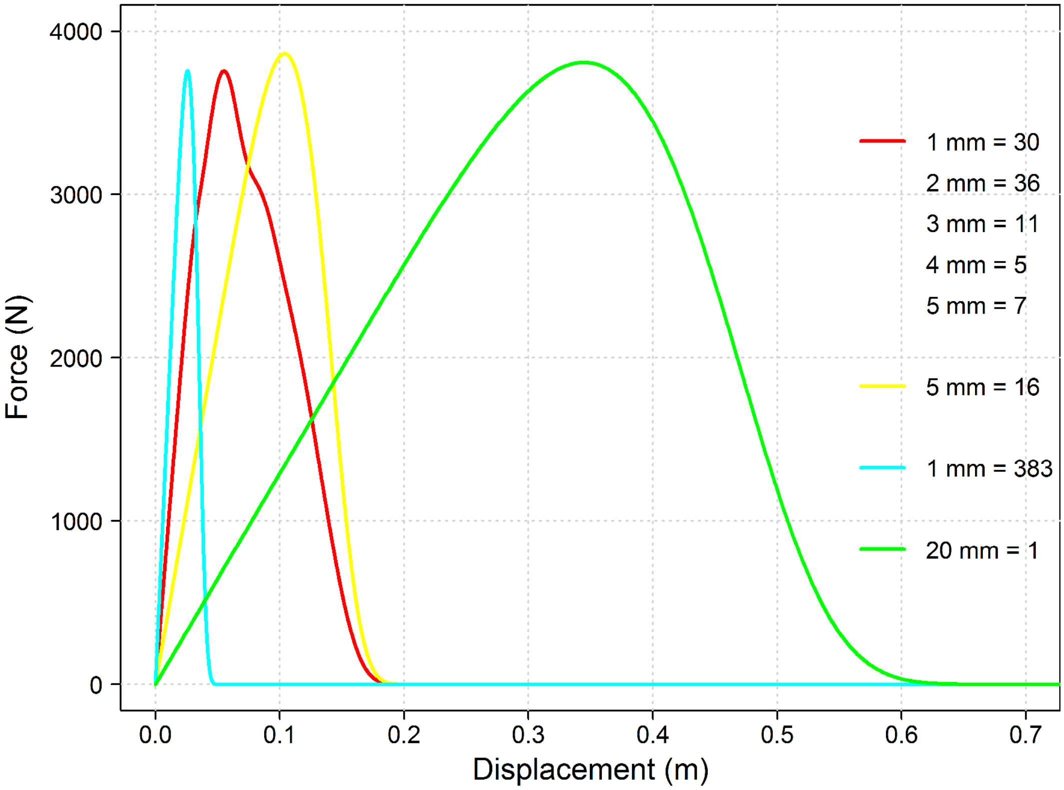

Fig. 2.2.13 RBMw output considering different compositions of the bundle of roots.

Tab. 2.2.4 Force values and number of roots for the different diameter classes used in the simulations.

diameter class	**1 mm**	**2 mm**	**3mm**	**4 mm**	**5 mm**	**tot**
n. of roots	30	36	11	5	7	89
force (N)	294	1109	800	536	1015	3754
% n. of roots	34	40	12	6	8	100
% force	8	30	21	14	27	100

2.2.5 References

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3 Root reinforcement dynamics after timber harvesting

Root reinforcement is one of the most important contribution against shallow landslides exerted by forest stands, and then is a key issue in the management of the protection forests against this kind of natural hazard. Providing data on the dynamics of root reinforcement after tree felling and silvicultural activities is therefore crucial for the definition of adequate management strategies in protection forests. As discussed in chapter 1, if the role of forest in protecting human settlements is well recognized from centuries, the quantification of root reinforcement is still a challenge, especially after logging and forestry operations. The literature concerning root reinforcement dynamics is scarce and providing data on such an issue is fundamental for defining adequate management strategies in protection forests.

After tree felling, roots start to decompose, causing gaps in the interlocking root systems of neighboring individual trees (Amman et al., 2009) and reducing the soil reinforcement effect (Ballard and Willington 1975; Burroughs and Thomas 1977; Swanson and Dyrness 1975; Ziemer and Swanston 1977; Wu et al. 1979; Abe and Ziemer 1991; Brooks et al. 1995). As root decomposition proceeds, it is generally assumed that the risk of landsliding increases as well (Ziemer and Swanston 1977; Ziemer 1981; Amman et al. 2009), at least until root systems are newly established due to seedlings, planting, or soil colonization by neighbor trees (Dhakal and Sidle, 2003; Imaizumi and Sidle, 2008).

Notwithstanding the worldwide relevance of the issue, data on root decay after felling are still scarce, especially when the last modeling improvement and the alpine environment are considered. Several studies attempted to describe the behavior of root decomposition, but further work is needed to extend and generalize these findings. Field data, in particular, are limited and collected several decades ago (Burroughs and Thomas 1977; Ziemer and Swanston 1977; O’Loughlin and Watson 1979; 1981; Ziemer 1981; Watson et al. 1997), when, for example, the relationship between roots resistance and diameter was not so clear. Consequently, the values concerning root decay were averaged regardless of their diameter (O’Loughlin and Watson 1979; 1981), or adopting broad diameter classes (Ziemer and Swanston 1977), or still additional root cohesion values were averaged for the whole profile regardless of root density distribution with depth (Burroughs and Thomas 1977). Finally, the data currently available were obtained for North American species (Douglas fir -*Pseudotsuga menziesii* (Mirb.) Franco, Sitka spruce - *Picea sitchensis* (Bong.) Carrière- and Western hemlock - *Tsuga heterophylla* (Raf.) Sarg. or New Zealand species (Radiata pine - *Pinus radiata* D.Don-, Red beech -*Nothofagus fusca* (Hook.f.) Oerst.- and hard beech -

Nothofagus truncata (Colenso) Cockayne), whereas minimal and more recent research concerned sub-Alpine and Alpine forests in Europe (Amman et al., 2009).

In the following two chapters two different case study are considered to partially fill this gap: one in the Italian Alps (chapter 3.1), where the decay of root cohesion after a recently introduced forest management technique is investigated, and one in the Swiss Alps (chapter 3.2) where there was the possibility to consider a larger time span after cutting. Differently from previous research, much attention was paid to the dependency of root force from the diameter and to the decay in the number of roots, which significantly affect the dynamics of root reinforcement. In particular, in chapter 3.2 also the spatial dynamic of root distribution (i.e. horizontal distribution of roots) in the forest stand was considered, to model both the spatial and temporal variability of root reinforcement.

3.1 Root reinforcement decay after felling in two Silver-fir-Norway spruce stands in the Italian Alps (BG)

3.1.1 Introduction

Gap cutting system has been reconsidered in the last years in the management of alpine and subalpine conifer forests. In fact it allows to combine economic needs with the principles of ecological forestry, emulating periodic, intermediate severity natural disturbances such as fire, windthrow, and insects attacks (Mercurio, 2009; Gugliotta 2006). The regime of disturbances is an integral component of forests ecosystems (Klopcic, 2009) and has an important influence on forests dynamics (Firm, 2009), especially on forest regeneration. Disturbances that open canopy gaps create environmental heterogeneity, increasing the amount of light penetrating to the forest understory, thus providing a range of regeneration niches for species with different ecological needs (Nagel, 2010). Gap cutting seems therefore to be an effective tool to improve natural regeneration and to diversify tree species, especially in conifers' monocultures (Mercurio, 2009). On the other hand, this type of management seems to guarantee economic sustainability to forest enterprises, because it ensures greater performances and reduces costs. This is an important aspect especially if we consider Lombardy subalpine valleys where forestry activities tend to be abandoned because of economic difficulties, leaving forests unmanaged and inducing the abandonment of mountainous lands.

To expand our knowledge in root strength and density deterioration along with the related consequences in terms of additional root cohesion, two Silver Fir-Norway Spruce (*Abies alba* Mill.. *Picea abies* (L.) Karst.) mixed stand in Lombardy (Central Alps, Northern Italy) where forest was harvested by gap cutting approach, was monitored for three years after felling. In contrast to previous research, attention was paid to the root strength variability with regard to diameter distribution and root density distribution along the soil profile. Field and laboratory data were used to estimate the additional root cohesion, cr, by means of the Fiber Bundle Model (Pollen and Simon, 2005), considering equal load sharing (each surviving root was subjected to the same tensile force regardless of root diameter; Bischetti et al. 2009, see paragraph 1.3).

More specifically the goals of this study were as follows: i) investigating the rate of root rot after gap cutting in subalpine forests, considering both the effects on root tensile resistance and root density and size distribution; and ii) estimating root reinforcement at different times after cutting to underline the critical time span where root cohesion is minimal.

3.1.2 Material and Methods

Study area

We considered two different stands in high Brembana Valley, in the subalpine catchment of high Brembo river, in Northern Italy (Cusio and Averara municipalities, Fig. 3.1.1). Gap cuttings have been reintroduced in the last decade in the study area as forest management system, while in the past the main forestry practice was single tree selection cutting. Selection cutting doesn't allow effective analysis on root rotting processes because of the interlocking mass of neighbor tree healthy roots, which can prevent the understanding of root rotting processes of logged trees.

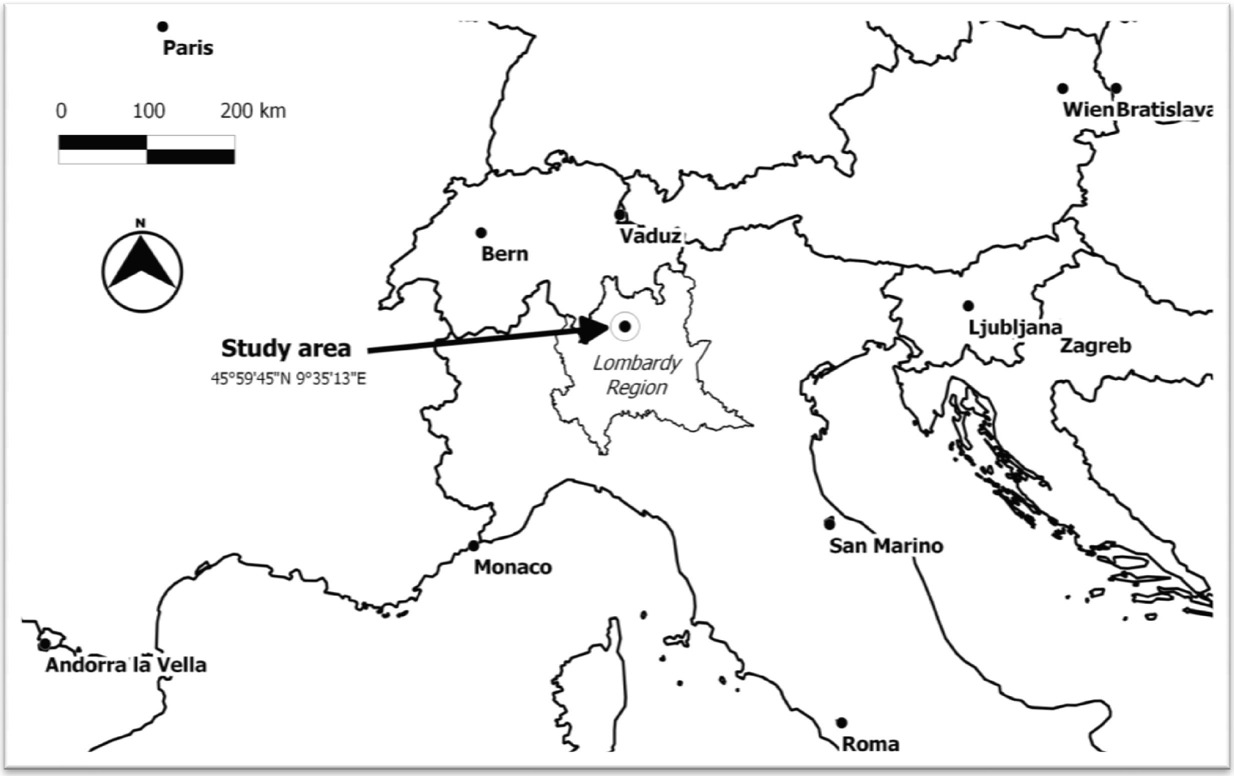

Fig. 3.1.1 Study area localization.

In both cases we have the same forest type (Del Favero e al., 2002), a mixed forest of *Abies Alba* (predominant species, 60-70%) and *Picea abies* (20-30%), with the sporadic presence of some broadleaves such as *Fagus sylvatica* in Cusio, *Fagus Sylvatica* and *Castanea sativa* in Averara. Stands are aged between 90 and 120 years (Averara) and 80 and 120 years (Cusio) in the logged areas (mature high forest), while in the undisturbed areas we find both mature high forest zones and zones with younger trees.

Both the study areas fall within the mesalpic forest region, characterized by high precipitations and cold temperature, and consequently in this area broadleaves are less competitive than conifers (especially *Picea abies* and *Abies alba*), which are favorite. Mean annual rainfall height is over 1400 mm, with two peaks in autumn and spring. Stands are located at an altitude of 1200 m asl (Cusio) and 1000 m asl (Averara), and both are on a middle hillslope position. In both the sites the bedrock belongs to Collio formation, which is grouped in the category of siliceous substrate, group of sandstone. This type of bedrock is semi-permeable and characterized by high weathering; it originates siliceous soils. The soil in Cusio is umbrisol, according to the WRB classification, and it is characterized by a fine matrix, mainly low permeable silty-clay, with a surface layer characterized by an organic matter of type "moder" and low basis saturation (Soil map of Lombardy Region). In Averara, instead, the soil is classified as cambisol, characterized by a sandy loam texture. Cobbles and stones are frequent in deeper soil layers in both sites.

In both sites the undisturbed stand adjacent to the gap was characterized by the method of "areas of sample": a circular area with a radius equal to 15 m was delimited in the undisturbed forest adjacent to the gap, and all diameters at breast height were measured, together with some representative heights (Fig. 3.1.2). In Cusio the basal area of the living stand is 30.36 m^2/ha, and the mean tree height and diameter are 31 m and 0.31 m, respectively. In Averara the basal area of the living stand is 33.26 m^2/ha , and the mean tree height and diameter are 30 m and 0.33 m, respectively.

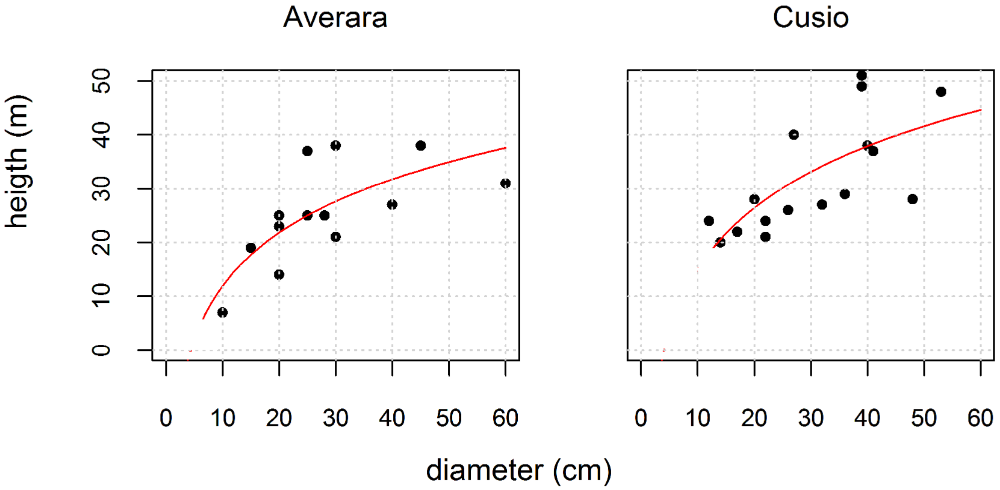

Fig. 3.1.2 Ipsometric curve of the undisturbed forest stand in Averara and Cusio.

Gap-cutting was carried out in Cusio in summer 2009, and the harvested area was about 1000 m^2; in Averara gap cutting was carried out in winter 2010 with a harvested area of about 600 m^2.

Field surveys and sampling have been carried out in each site at the centre of the gap (Fig. 3.1.3) for three years: 2010, 2011 and 2012. In 2010 monitoring was also conducted in the undisturbed adjacent forest.

Fig. 3.1.3 Gap cutting in Cusio (a) and Averara (b).

Root reinforcement modeling

The estimated values of root reinforcement resulting from the application of the different models developed in the last 30 years (Wu and Waldron, 1976,1977; Pollen and Simon, 2005; Schwarz 2010,2013, see chapter 1.3) can significantly differ (Ji et al. 2012; Mao et al. 2012) as absolute values, although the differences decrease with depth as consequence of the reduction of the number of roots in deep layers (Bischetti et al. 2009; Mao et al. 2012). Ji et al. (2012) compared root cohesion values given by the W&W model and the three different types of FBM and RBM, concluding that the W&W model provides the greater values of *Cr* (and likely overestimates it), RBM always provides values greater than those estimated by FBMs, and the three type of FBMs give similar results. In the case of *Cr* values after felling, which are generally defined in terms of ratio with regard to *Cr* value in undisturbed conditions (e.g. Ziemer 1981; O'Loughlin and Ziemer 1982; Sidle 1991;Dhakal and Sidle 2003), the choice of model is of less importance. Of course the absolute values of *Cr* here estimated must be taken with caution and related to the uncertainty still involved in root reinforcing modeling.

All of the above considered, in our case, the FBM was implemented, under the static fibre bundle approach and equal load sharing, as described in detail in Bischetti et al. (2009) and Ji et al. (2012).

The additional root cohesion values at depth Z, cr^Z , consider both the resistance due to those roots crossing the basal shear surface, $cbas^Z$ and the resistance due to those roots intersecting the vertical plane at the detachment scarp clat^{Z} (Riestenberg and Sovonick-Dunford 1983; Terwillinger and Waldron 1991; Schmidt et al. 2001; Keim and Skaugset 2003; Roering 270 et al. 2003; Schwarz et al.,2010a). In case of small volume landslides in shallow forested soils, the lateral root reinforcement, in fact, has proven to be important for landslides with areas up to 1000 m^{2} (Schwarz et al. 2010b).

For each case (undisturbed, 1 yr, 2 yrs and 3 yrs) the cr^{Z} distribution at each trench was calculated, considering roots in the range 1-10 mm. Roots smaller than 1 mm in diameter were excluded because their role in soil reinforcement is uncertain (Waldron 1977) and they are subject to rapid turnover (Stokes et al. 2009; Gan et al. 2010; Mainiero et al. 2010; Finér et al. 2011; Garkoti 2011). Finally, the measure of very fine roots involves great errors due to both the testing device accuracy and diameter measurement errors. The 10 mm-threshold is generally adopted in root cohesion estimation (Tosi 2007; Genet et al. 2010; Abdi et al. 2010; Bischetti et al. 2009), even if roots up to 20 mm and even up to 40 mm are considered important in root reinforcement (De Baets et al., 2007); in any case roots higher than 10 mm are really difficult to test with laboratory tensile test and the measurement of their force still represents a challenge.

Tensile tests

Most of previous work on root strength decay considered root tensile stress values (Burroughs and Thomas 1977; Ziemer and Swanston 1977; Ziemer 1981; O'Loughlin and Ziemer 1982; Amman et al. 2009). According to several other authors, the present study considers root tensile force at rupture, which is the experimentally measured variable (Hathaway and Penny 1975; Ziemer and Swanston 1977; Nilaweera and Nutalaya 1999; Schmidt et al. 2001; Kondo et al. 2004; Norris 2005; Tosi 2007; Hales et al. 2009; Genet et al. 2011; Vergani et al. 2012). This avoids introducing a possible additional source of variance, being the tensile stress of roots calculated as the ratio between breaking force (N) and root area (mm) which, in turn, depends on root diameter (Vergani et al. 2012). Roots were collected, both in organic and mineral horizons, by digging pits in the middle between adjacent stumps within the gaps, or live trees within the undisturbed forest, taking care not to damage them and sampling to cover the whole diameter range of 1-10 mm (see the following sections for the diameter range justification). Samples were preserved from deterioration by putting roots in plastic containers filled with a 15% alcohol solution (Meyer and Gottsche 1970; Bischetti et al. 2003), until tensile tests were carried out following the methodology described by Bischetti et al. (2005, 2009). Tensile tests were carried out within one month after root collection, by means of a self-designed and self-built device (Bischetti et al., 2009) consisting of a strain apparatus controlled by an electrical motor Fig. 3.1.4. Roots were attached to specifically developed clamping devices that avoid root damage at the clamping points; tensile force was exerted by a system of gears at a rate of 10 mm/min (Bischetti et al., 2009). The distance between the centre of the jaws of the clamping device was 50 mm, and all the tested specimens had a constant length of 15 mm. Tensile force was recorded by a load cell (Full Scale, F.S. = 500 N, accuracy = 0.1% of F.S.) connected to an acquisition system.

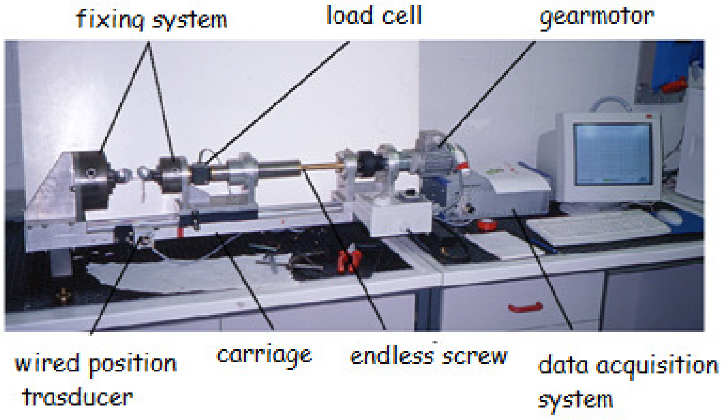

Fig. 3.1.4 Tensile tests machine.

Only specimens that broke near the middle of the root between clamps were considered, in order to ensure that the rupture was due to the force applied in tension and not induced by root structural damage or stress concentration near the clamps. Root size was estimated as the average of three values taken with an electronic caliper at three points near the section of potential breaking (Abdi et al. 2010; Vergani et al. 2012). It is well known that the tensile resistance of roots, in addition to the plant species, is strongly dependent on their size and generally follows a power-law relationship (Ziemer and Swanston 1977; Nilaweera and Nutalaya 1999; Kondo et al. 2004; Genet et al. 2010; Abdi et al. 2010;Vergani et al. 2012). Thus, over 50 force-diameter values in the whole diameter range were taken for each case.

Root diameter distribution estimation

Root density was analyzed in terms of number of roots per root diameter class by means of the trench wall method (Bohm, 1979; Abernethy and Rutherfurd 2001; Schmid and Kazda 2002; Abdi et al. 2010; Douglas et al. 2010) and image analysis (Bischetti et al. 2009; Hales et al. 2009). In each site and in each year of sampling (in the paper noted as 1yr, 2yrs, 3yrs and undisturbed) a 0.9 m long trench, allowing analysis of related profiles in terms of root density. Trenches were dug nearly at equal distance from adjacent stumps in the gap or living trees in the undisturbed forest, and in the middle of the group of stumps, where the point of minimum cohesion is likely to appear. Clearly, it was impossible to sample the exact same point year after year due to the destructive nature of the trench method, but the distance from the stumps was maintained homogeneous as more as possible. Distances from stumps or trees and surrounding stumps/trees diameters are reported in Tab. 3.1.1 and Tab. 3.1.2 (respectively Averara and Cusio) for each trench in each treatment. Note that in the undisturbed forest, tree diameter refers to DBH, and trees are generally younger that the ones in the gap which have been cut. This is the only characteristic that varies between the undisturbed forest and the gap; type of soil, slope, exposure and type of stand are similar and comparable. The depth of the trenches varies between 0.70 and 1.20 m depending on the abundance of stones and cobbles, which prevented further excavation; by spot deeper excavation, in any case, we observed that only very few and negligible roots can be found beneath the depth reached by trench excavation. This is confirmed by several studies showing that in northern forests roots are generally restricted to the upper soil layers, with most roots occurring within the first 0.30 to 0.50 m of the soil profile (Persson, 1980, 1983; Comeau and Kimmins, 1989; Finer et al., 1997; Millikin and Bledsoe, 1999; Püttsepp et al., 2006).

Tab. 3.1.1 Main characteristics of each sample site and each trench in Averara sample site. # = number; diameters in the gaps refers to the stumps, diameters in undisturbed forest are measured at breast height (*); the distance is the trench-stumps (or trees) distance.

treatment	**understorey cover (%)**	**understorey species**	**# surrounding trees or stumps (*Abies alba*)**	**mean diameter (m)**	**mean distance (m)**	**max distance (m)**	**min distance (m)**	**depth of trench (m)**
undisturbed forest	<5	Felci	7	0.30*	3.2	5.3	2	0.90
6 months old gap cutting	5	*Luzula nivea* (L.)*; Rubus* spp. (L.); Felci	4	0.50	3.2	4.2	2.2	0.80
1 year old gap cutting	50	*Luzula nivea; Rubus* spp., Felci	9	0.45	4.7	6.9	2.3	1.30
2 years old gap cutting	90	*Luzula nivea (L.); Rubus* spp.,; *Poa pratensis* (L.), *Vinca Minor, Abies alba* regeneration	7	0.49	3.3	5.5	2.3	0.90

Tab. 3.1.2 Main characteristics of each sample site and each trench in Cusio sample site. #=number; diameters in the gaps refers to the stumps, diameters in undisturbed forest are measured at breast height (*); the distance is the trench-stumps (or trees) distance.

treatment	understorey cover (%)	understorey species	# surrounding trees or stumps (*Abies alba*)	mean diameter (m)	mean distance (m)	max distance (m)	min distance (m)	depth of trench (m)
undisturbed forest	5	*Vaccinium myrtillus* (L.)*; Picea abies* regeneration	5	0.30*	3.2	5.3	2	0.70
1 year old gap cutting	10	*Luzula nivea* (L.)*; Rubus* spp. (L.)	4	0.46	3.1	4.9	1	0.90
2 years old gap cutting	50	*Luzula nivea; Rubus* spp., *Vaccinium myrtillus; Pteridium aquilinum* (L.)	8	0.50	3.3	5.2	2	1.10
3 years old gap cutting	90	*Luzula nivea; Rubus* spp., *Vaccinium myrtillus* (L.)*; Pteridium aquilinum; Poa pratensis* (L.)	6	0.57	3.2	5.0	2	0.90

After digging, each trench wall was cleaned of all organic materials different from roots and wetted in order to provide better quality camera images. A frame of known size (0.30X0.30 m) was applied to each trench, obtaining three vertical profiles for each trench. Pictures were then rectified and assembled through specific software to correct geometrical deformations (GIMP 2 www.gimp.org); root diameter and position were measured through the manual digitalization of each root using GIS software (MapWindow 4.6 www.mapwindow.org), figure 3. The number of roots per diameter class was determined for depth increments of 0.10 m; the considered diameter classes were 0-1 mm, 2-5 mm, 5-10 mm, > 10 mm (Genet et al., 2008; Ji et al.,2012). For completeness, roots with diameter < 1 mm and > 10 mm were also considered in the root analysis, even if these roots were not included in the cohesion calculation, as explained later.

Statistical analyses

Statistical analysis was performed on tensile force data. The relationship between root tensile force F (N) and root diameter d (mm) were obtained by regressions analysis of log-transformed values of F and d. Its goodness was evaluated through the coefficient of determination (R^2) and the coefficient of significance (*p-value*) from the Fisher Test, considering a level of significance of

0.01. The Fisher Test was applied to linear regressions obtained from log-transformed values of *F* and *d*. As a consequence of the dependence of tensile force and strength from diameter, ANCOVA frequently is adopted in comparing values obtained from different species, sites, etc. (Genet et al. 2005; Bischetti et al. 2009; Genet et al. 2010; Ji et al. 2012; Vergani et al. 2012). In the present study ANCOVA has proven to be unsuitable because the parallelism hypothesis was not verified, especially for the 3-yrs case (as afterwards described). To compare force values of roots coming from different treatments, taking into account diameter as a covariate, a multiple regression was carried out (Soliani, 2005), considering the log-force values of all the considered treatments (undisturbed and 1 yr, 2 yrs, 3 yrs) as the dependent variable.

In this analysis, the logarithm of force was used as a dependent variable, the logarithm of diameter as an independent variable and the four (n) treatments are represented by three (n-1) dummy independent variables: the 1 yr values are identified by dummy 1; the 2 yrs by dummy 2; and the 3 yrs by dummy 3. Each dummy variable assumes the value of 1 for the values of force belonging to the considered treatment and the value of 0 for the values of force belonging to all other cases. The values belonging to the undisturbed condition are therefore identified by having a value of zero for each independent dummy variable. Finally, a multiple linear regression model was implemented. The significance of the whole model was evaluated through the Fisher test and the adjusted coefficient of determination (adjusted *R2*), whereas the significance of each independent variable was evaluated through T-Student test and partial Fisher test, with a level of significance of 0.05. Force values of a treatment can be considered significantly different from force values of the reference case (undisturbed forest) if the corresponding dummy variable is significant. Requirement of normality and uncorrelation of residuals were verified through Kolmogorov Smirnov and Breush-Godfrey test, considering a level of significance of 0.05. All statistical analyses were performed using the software program R (http://www.r-project.org/).

3.1.3 Results

Root mechanical properties: root tensile force

The statistical parameters of tensile tests are reported in Tab. 3.1.3. The number of valid tests range between 46 and 60, and the mean diameters of roots tested between 2.35 and 3.25 mm. Observing the mean force values, we can’t observe a decrease as the years after cutting increase: without considering the diameter distribution of tested roots, as in the past literature, such results should be misleading. Even if the mean values of root diameter for the different treatments seem similar (table 3), the root diameter distribution is quite different (Fig. 3.1.5). In the case of Cusio, the 20% of roots of 3 yrs treatment have a diameter higher than 5 mm, while only the 7% of roots in the undisturbed condition is greater than 5 mm. Considering Averara, the 20% of roots have a diameter higher than 2.5 mm in the undisturbed case, while in 3 yrs case the 20% of roots have diameter higher than 4 mm. These differences influence the average root force and explain why we can't appreciate a reduction in the mean force of roots after cutting. This supports the necessity to take into account the diameter as covariate.

Tab. 3.1.3 Parameters of tested roots (stress values as are reported for comparison with previous literature).

site	case	# valid tests	diameters (mm)				force(N)				stress (Mpa)			
			mean	max	min	SD	mean	max	min	SD	mean	max	min	SD
Averara	und	46	2.40	5.53	0.89	1.12	38.13	191.06	4.91	39.24	7.45	12.89	3.95	1.95
	1-yr	57	2.35	5.83	0.83	1.29	48.95	277.54	2.10	60.38	9.44	37.23	1.08	7.50
	2-yrs	49	2.60	5.60	0.87	1.11	40.48	344.12	2.29	52.31	6.81	25.13	2.00	4.09
	3-yrs	63	2.80	6.71	0.43	1.51	23.72	108.30	2.86	23.38	4.11	20.03	0.39	3.22
Cusio	und	51	2.74	5.7	1.21	1.11	46.45	203.75	8.07	46.95	6.54	11.28	3.32	1.77
	1-yr	54	2.4	4.61	1.03	0.88	30.96	113.55	2.95	22.79	6.64	20.64	2.09	4.12
	2-yrs	52	2.37	4.94	1	1.12	34.66	144.26	0.53	29.89	7.57	33.31	0.67	5.41
	3-yrs	60	3.25	7.87	0.85	1.66	46.95	145.44	3.52	37.85	6.64	28.5	1.35	4.75

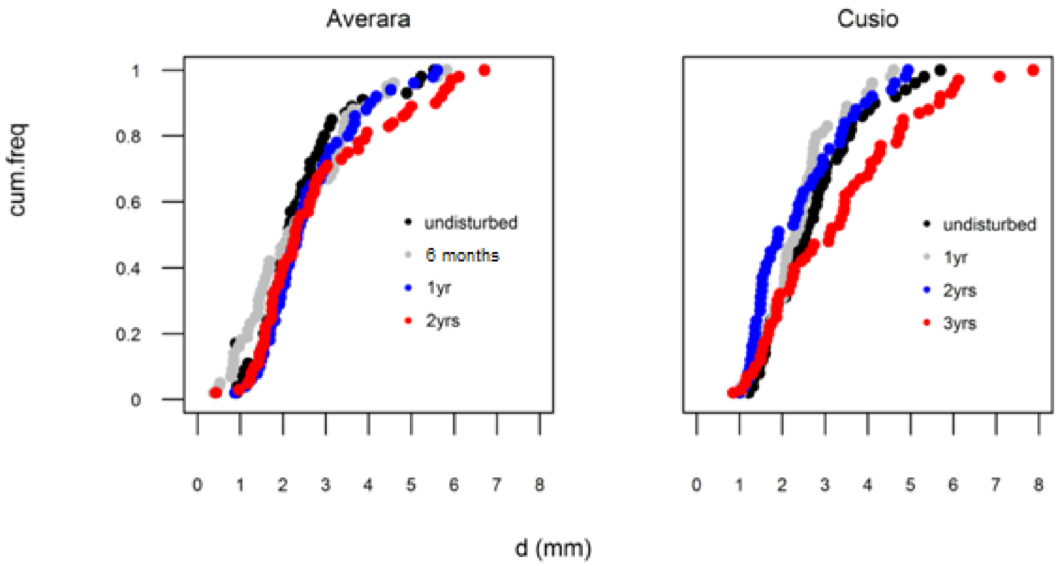

Fig. 3.1.5 Diameter distribution of roots submitted to tensile test in the two study areas.

The relationships between force values and the related diameter were interpreted through a regression, which has been proven to be a power–law type (Fig. 3.1.6 and Fig. 3.1.7) as found by several authors (Ziemer and Swanston 1977; Nilaweera and Nutalaya 1999; Kondo et al. 2004; Genet et al. 2010;Abdi et al. 2010; Vergani et al. 2012). The force-diameter power regressions were consistent (Table3). The R^2 values were always higher than 60%, with the exception of Averara 2 yrs, and the regressions were highly significant in all cases ($p < 0.001$).

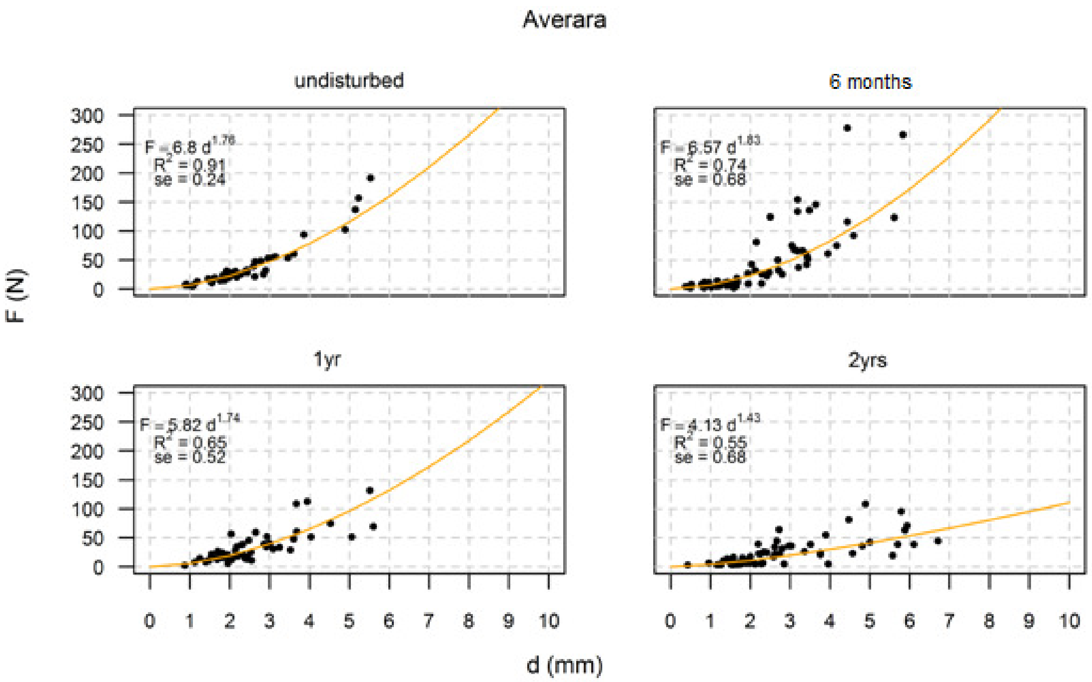

Fig. 3.1.6 Force-diameter power laws, Averara site.

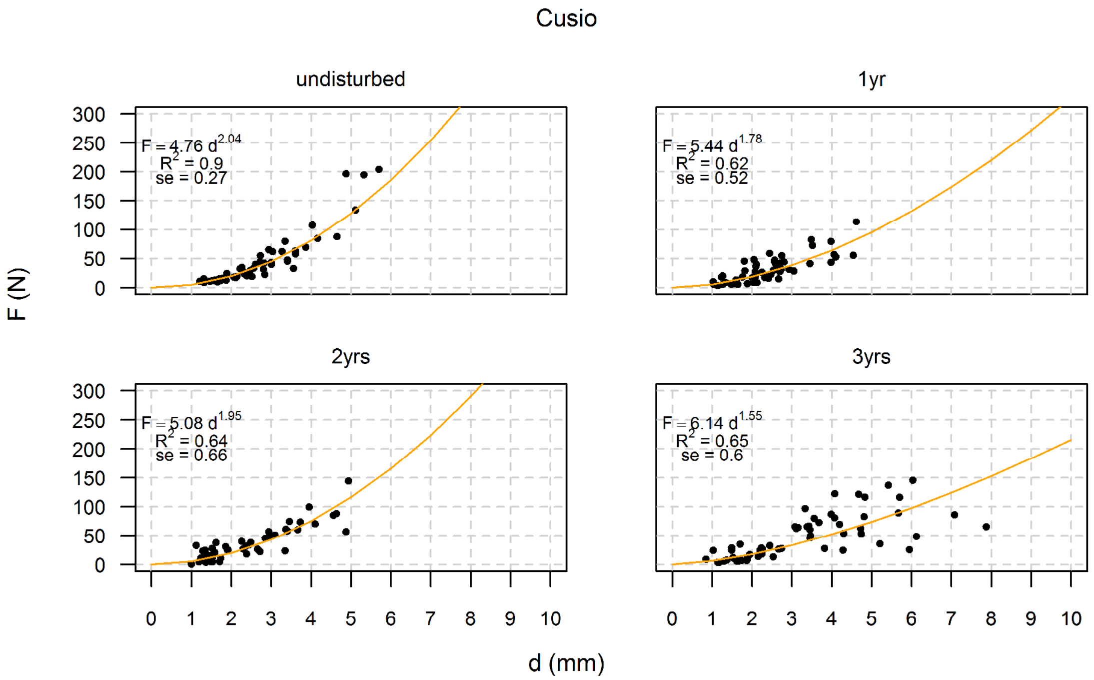

Fig. 3.1.7 Force – diameter power laws, Cusio site.

Tab. 3.1.4 Coefficients and statistical parameters of power regressions F-d

site	case	a	b	p	R^2	se
Averara	undisturbed	6.8	1.76	< 0.001	0.91	0.24
	6 months	6.57	1.83	< 0.001	0.74	0.68
	1 years	5.82	1.74	< 0.001	0.65	0.52
	2 years	4.13	1.43	< 0.001	0.55	0.68
Cusio	undisturbed	4.76	2.04	< 0.001	0.9	0.27
	1 year	5.44	1.78	< 0.001	0.62	0.51
	2 years	5.08	1.95	< 0.001	0.64	0.66
	3 years	6.14	1.55	< 0.001	0.65	0.60

It can be noted from standard error values (Tab. 3.1.4) that after felling, data progressively spread out, possibly due to an increasing number of deteriorated roots; this is particularly evident when drawing the data on the same diagram (Fig. 3.1.8). This can also be noted by the getting worse of the R^2 values.

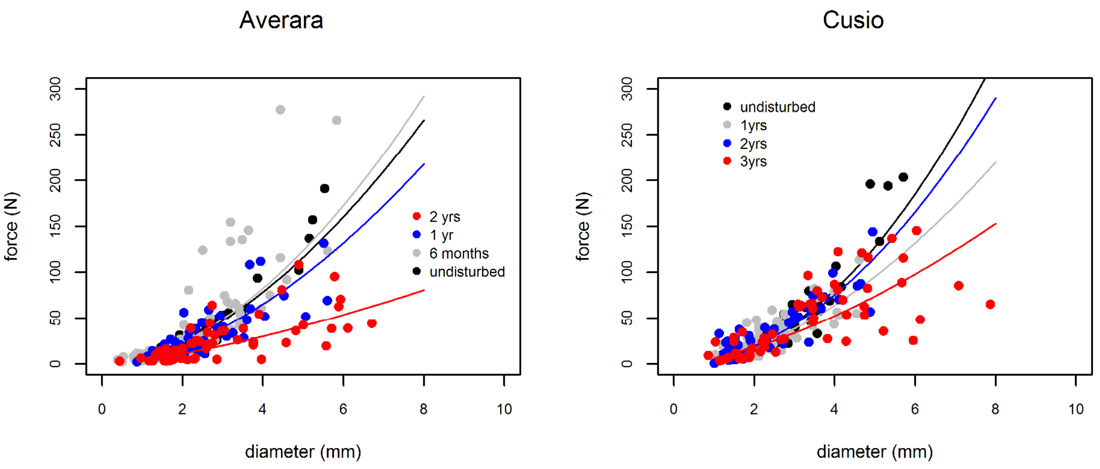

Fig. 3.1.8 Comparison between the force diameter power laws in each site.

The different force-diameter relationships (Fig. 3.1.8) are compared to assess the possible significant difference with time after felling by means of a multiple regression. This analysis also seeks to take into account the diameter distribution effect; diameter is introduced as an independent variable, while the effect of the different treatments is introduced with three dummy variables (Tab. 3.1.5). The adopted model is in both case highly significant ($p < 0.001$) and explains force data variability quite well (adjusted $R^2 = 0.70$ and 0.69 in Averara and Cusio respectively). Diameter is in both cases highly significant as an explicative variable, as expected, whereas dummy variables are not always significant. In particular, dummy 1 (related to 1 yrs condition) and dummy 2 (2 yrs condition) are not significant ($p > 0.05$) in Cusio site, while dummy 3 (3 yrs) is significant in explaining force values variability ($p < 0.05$, $f = 5.2$). In Averara just dummy 3 (2yrs) is highly significant in explaining force variability. Accordingly, the tensile force values of roots collected three years after felling were statistically different from those in the undisturbed condition, whereas the difference was not statistically significant between roots of undisturbed forest and roots collected one and two years after felling.

Tab. 3.1.5 Results of multiple regression models (* significant at 0.05, ** significant at 0.01)

site	**indipendent variable**	**coefficients**	**se**	**t test**	**p (>ltl)**	**partial F test**	**p (> F)**
Averara	diameter	1.68	0.08	21.76	< 0.001**	441.46	< 0.001**
	dummy 1 (6 months)	0.0002	0.11	0.002	0.99	15.59	< 0.001 ?
	dummy 2 (1 year)	-0.17	0.12	-1.38	0.17	8.35	0.004**
	dummy 3 (2 years)	-0.79	0.11	-6.94	< 0.001**	48.12	< 0.001**

Cusio	diameter	1.77	0.08	21.4	< 0.001**	472.25	< 0.001**
	dummy 1 (1 year)	-0.11	0.1	-1.07	0.28	0.02	0.89
	dummy 2 (2 years)	-0.06	0.11	-0.52	0.6	0.5	0.48
	dummy 3 (3 years)	-0.23	0.1	-2.28	0.02 *	5.2	0.02 *

Number of roots per diameter classes

For each trench, the number of roots in each diameter class per each depth class has been considered (Fig. 3.1.9 and Fig. 3.1.10). Roots smaller than 0.5 mm were excluded from the analysis, due to the difficulty in correctly detecting and recognizing them through the image analysis technique. In general, data regarding very fine roots (smaller than 1 mm) have to be taken with caution due to the difficulty in distinguish roots of silver fir and from the ones of understory vegetation in the images. Soil profiles are shown until 120 cm both in Cusio and Averara even if the excavation in some cases reaches shallower depths due to presence of stones and cobbles. As a consequence, maximum rooting depth is different between treatments due to spatial heterogeneity in soil characteristics, which caused practical problems in excavation.

Considering Cusio sample site, in spite of a difference in the maximum rooting depth between treatments due to spatial heterogeneity of soil, the general decreasing trend in the total number of roots with the increasing time after felling is quite clear. The total number of roots per trench is 352 in the undisturbed condition, 296 in 1 yr, 309 in 2 yrs and 113 in 3 yrs (Tab. 3.1.6); in the 1 yr condition, there is great number of 1 mm roots in the 0-10 cm layer. According to Silver and Miya (2001) and Stokes et al. (2009), roots with diameter < 2 mm can be classified as fine roots, whereas roots with diameter > 2 mm are thin roots. From such a view, fine roots (< 2 mm) are the most frequent in all the conditions (Tab. 3.1.6 and Fig. 3.1.9), even if there was a drastic reduction in the 3 yrs condition. In undisturbed, 1 yr and 2 yrs conditions, the predominant root diameter class is 0-1 mm for each considered depth, followed by the 1-2 mm class. For the 3 yrs condition, the most represented diameter class is 1-2 mm. Concerning thin roots, the most represented diameter class is always 2-5 mm; roots of 5-10 mm and > 10 mm roots are scarce.

In the undisturbed condition (Fig. 3.1.9 a) there is a decrease of roots with depth mainly due to the trend of very fine roots. The total number of roots ranges between more than 100 in the first soil layer, due especially to very fine roots, and some units at the maximum depth. Roots comprised between 0.5 and 1 mm are the half of the total number of roots; roots between 1 and 2 mm are 33% (fine roots as a whole are 83% of total roots); roots between 2 and 5 mm are 15%; roots between 5 and 10 mm are about 3%; no roots thicker than 10 mm were found. Also in 1 yrs condition (Fig. 3.1.9 b), the decreasing number of roots with depth is evident, mainly because of the high number of 0-1 mm class roots in the first layer. The fine roots are 84% (52% were very fine roots and 32% were roots between 1 and 2 mm) of the total roots, similar to the undisturbed condition.

In 2 yrs condition (Fig. 3.1.9 c), the reduction with depth is less evident. No significant reduction in the number of very fine roots (< 1 mm) can be observed; the total number of very fine roots is 161 and the number of roots between 1 and 2 mm is 95, similar to the undisturbed and 1 yr conditions. As a whole among size classes, the distribution of fine roots do not change (about 83%). In the 3 yrs condition (Fig. 3.1.9 d), the reduction with depth is not evident, probably due to the low number of remaining roots. Considering the absolute values the reduction is dramatic in fine roots, both less than 1 mm in diameter and comprised between 1 and 2 mm; very fine roots are only 11% of roots of the same class of the undisturbed forest, whereas roots with diameters between 1 and 2 mm are about the 33 per cent of the undisturbed condition. Fine roots as a whole are 67% of the total (only 17% of very fine roots). Considering thin roots, there is no reduction in the first two years after felling, a reduction can be observed after 3 years: there are 62 thin roots in the undisturbed condition, 48 in the 1 yr, 52 in the 2 yrs, and 36 in the 3 yrs condition.

Considering Averara sample site, still there are differences in the maximum rooting depth between the different treatments, but a decreasing trend in the total number of roots can’t be observed, especially if we consider roots with diameters higher than 5 mm. The total number of roots per trench is 203 in the undisturbed condition, 224 in 6 months, 220 in 1 yrs and 209 in 2 yrs (Tab. 3.1.7). Fine roots (< 2 mm) are still the most frequent in all the conditions, after two years there is an important reduction in roots < 1mm, while no reduction for roots > 1 mm. In undisturbed and 1 yrs conditions, the dominant root diameter class is 0-1 mm for each considered depth, followed by the 1-2 mm class. For the 6 months conditions, very fine and fine roots are almost equal. For the 2 yrs condition, the most represented diameter class is 1-2 mm. Concerning thin roots, the most represented diameter class is always 2-5 mm; the presence of 5-10 mm and > 10 mm roots is scarce. The decrease of roots with depth is evident in all the conditions.

In the undisturbed condition the total number of roots ranges between more than 60 in the first soil layer, due especially to very fine roots, and some units at the maximum depth. Roots comprised between 0.5 and 1 mm are the half of the total number of roots; roots between 1 and 2 mm are the 37% (fine roots as a whole are the 87% of total roots); roots between 2 and 5 mm are 11%; roots between 5 and 10 mm are 2.5%; no roots thicker than 10 mm were found. In 6 months condition

(Fig. 3.1.10 b), the fine roots are 83% (82% were very fine roots and 11% were roots between 1 and 2 mm) of the total roots, similar to the undisturbed condition.

In 1 yr condition (Fig. 3.1.10 c) no reduction in the number of very fine roots (< 1 mm) and fine roots can be observed; the total number of very fine roots is 112 and the number of roots between 1 and 2 mm is 85, similar or even higher than the undisturbed and 6 months conditions. As a whole among size classes, the distribution of fine roots do not change (about 88%). In the 2 yrs condition (Fig. 3.1.10 d), the only reduction in the number of roots is related to roots with diameter less than 1 mm, which in absolute value are 38, 40% respect to the ones of the undisturbed condition. Fine roots as a whole are 70% of total roots. No reduction in roots higher than 1 mm can be appreciated two years after felling.

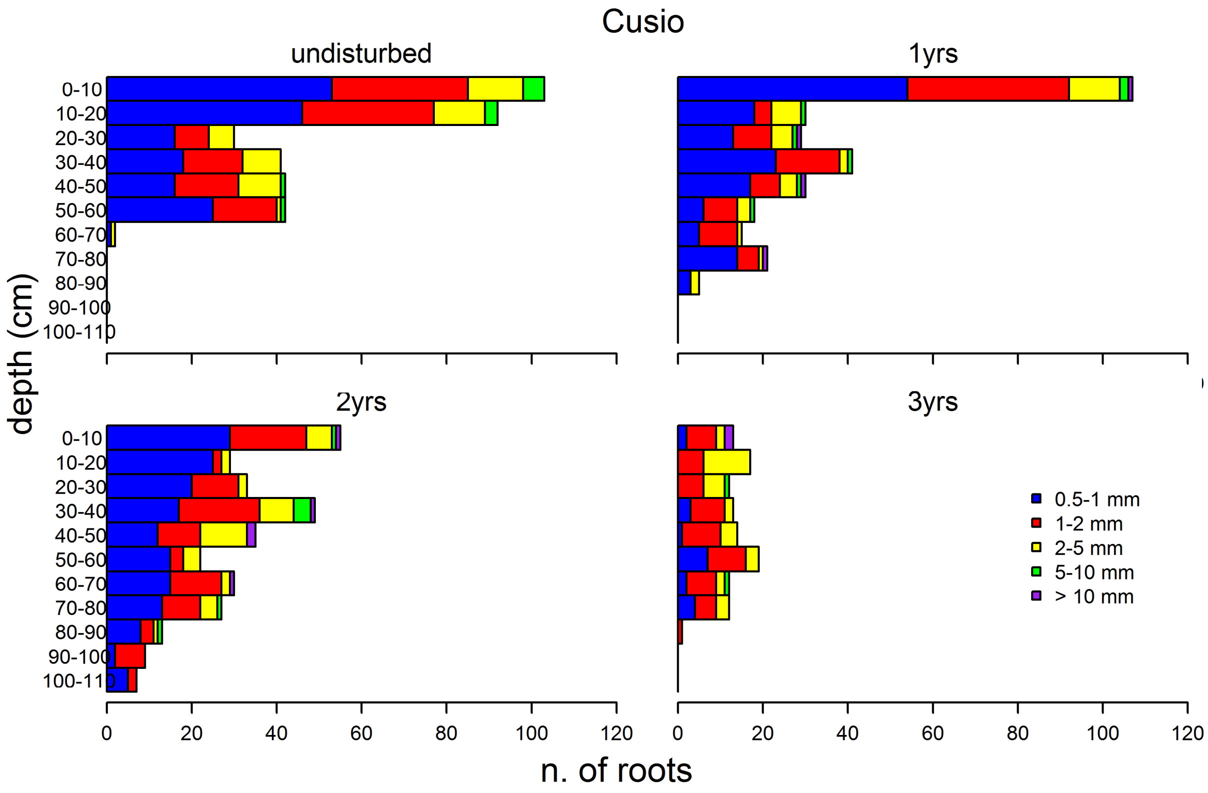

Fig. 3.1.9 Root distribution with depth in Cusio sample site.

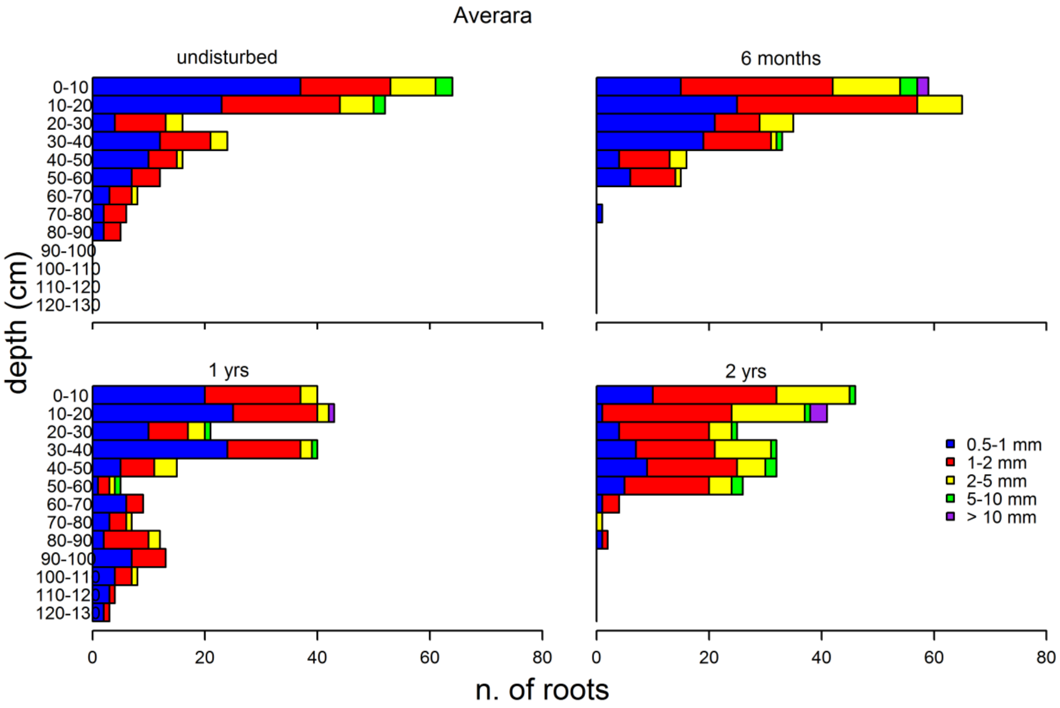

Fig. 3.1.10 Root distribution with depth in Averara sample site.

Tab. 3.1.6 Number of roots in each diameter class in each treatment at Cusio sample site.

Cusio				
treatment	**total number of roots**	**diameter class (mm)**	**number of roots**	**% on total**
undisturbed	352	0.5<d<=1	175	49.7
		1<d<2	115	32.7
		2<d<5	52	14.8
		5<d<10	10	2.8
		>= 10	0	0.0
1 yrs	296	0.5<d<=1	153	51.7
		1<d<2	95	32.1
		2<d<5	37	12.5
		5<d<10	7	2.4
		>= 10	4	1.4
2 yrs	309	0.5<d<=1	161	52.1
		1<d<2	96	31.1
		2<d<5	40	12.9
		5<d<10	7	2.3

		>= 10	5	1.6
3 yrs	113.0	0.5<d<=1	19	16.8
		1<d<2	58	51.3
		2<d<5	32	28.3
		5<d<10	2	1.8
		>= 10	2	1.8

Tab. 3.1.7 Number of roots in each diameter class in each treatment at Averara sample site.

Averara				
treatment	**total number of roots**	**diameter class (mm)**	**number of roots**	**% on total**
undisturbed	203	0.5<d<=1	100	49.3
		1<d<2	76	37.4
		2<d<5	22	10.8
		5<d<10	5	2.5
		>= 10	0	0.0
6 months	224	0.5<d<=1	91	40.6
		1<d<2	96	42.9
		2<d<5	31	13.8
		5<d<10	4	1.8
		>= 10	2	0.9
1 yrs	220	0.5<d<=1	112	50.9
		1<d<2	85	38.6
		2<d<5	19	8.6
		5<d<10	3	1.4
		>= 10	1	0.5
2 yrs	209	0.5<d<=1	38	18.2
		1<d<2	110	52.6
		2<d<5	50	23.9
		5<d<10	8	3.8
		>= 10	3	1.4

Root reinforcement estimation

Root cohesion was calculated for each soil layer in each considered conditions. Total root cohesion values (considering the sum of basal and lateral cohesion) are reported in Tab. 3.1.8. Considering Cusio, in undisturbed condition values decreased from about 20 kPa at the shallow layer to about 5 kPa at 0.7 m (the maximum explored depth); in 1-yr case from about 7 kPa to 2.5 kPa at 0.9 m; in 2-yrs case from 6kPa to 2 kPa at 1.1 m; in 3-yrs case from 3.5 kPa in the second soil layer to 0.9 kPa at 0.9 m (Tab. 3.1.8 and Fig. 3.1.11). The average values of additional root cohesion for the reference profile of 70 cm passed from 11kPa in undisturbed conditions to 5 kPa at one and two years after felling, and then to 2kPa after three years. The loss of additional root cohesion was about the 60% in the first two years and another 20% in the third year. Considering Averara, in undisturbed conditions values decreased from about 11 kPa at the shallow layer to about 2 kPa at 0.90 meters; in 6 months conditions from about 12 at the shallow layer to about 2 kPa at 0.80 meters; in 1 year conditions from about 4 kPa at the shallow layer to about 1 kPa at 1.30 meters and in 2 years conditions from about 4 to about 1 at 0.90 meters. The average values of additional root cohesion for the reference profile of 90 cm passed from 5 kPa in undisturbed conditions to 2.60 kPa at one years after felling and to about 3 kPa after two years. The loss of additional root cohesion was about 50% two years after felling.

Tab. 3.1.8 Total root cohesion values (kPa).

	Cusio				Averara			
z (cm)	undisturbed	1 yrs	2 yrs	3yrs	undisturbed	6 months	1 yrs	2 yrs
10	19.38	7.50	5.66	0.61	10.54	11.61	3.76	3.70
20	17.05	5.86	3.02	3.16	11.06	10.31	2.84	4.26
30	8.51	4.92	2.50	3.02	5.93	6.21	2.59	2.68
40	8.07	4.40	12.57	1.74	5.29	5.40	2.71	3.03
50	10.41	3.62	6.43	2.09	3.49	4.62	2.42	3.53
60	9.78	6.12	3.99	1.68	2.95	3.90	2.73	3.31
70	4.94	3.09	3.90	1.47	2.80	2.43	1.53	1.65
80	nd	2.49	5.45	1.41	2.41	2.12	2.23	1.45
90	nd	2.42	4.78	0.92	2.33	nd	1.95	1.26
100	nd	nd	2.87	nd	nd	nd	1.71	nd
110	nd	nd	2.35	nd	nd	nd	1.38	nd
120	nd	nd	nd	nd	nd	nd	1.11	nd
130	nd	nd	nd	nd	nd	nd	0.97	nd
mean at 70 - 80cm	11.16	5.07	5.44	1.79	5.56	5.83	2.60	2.95

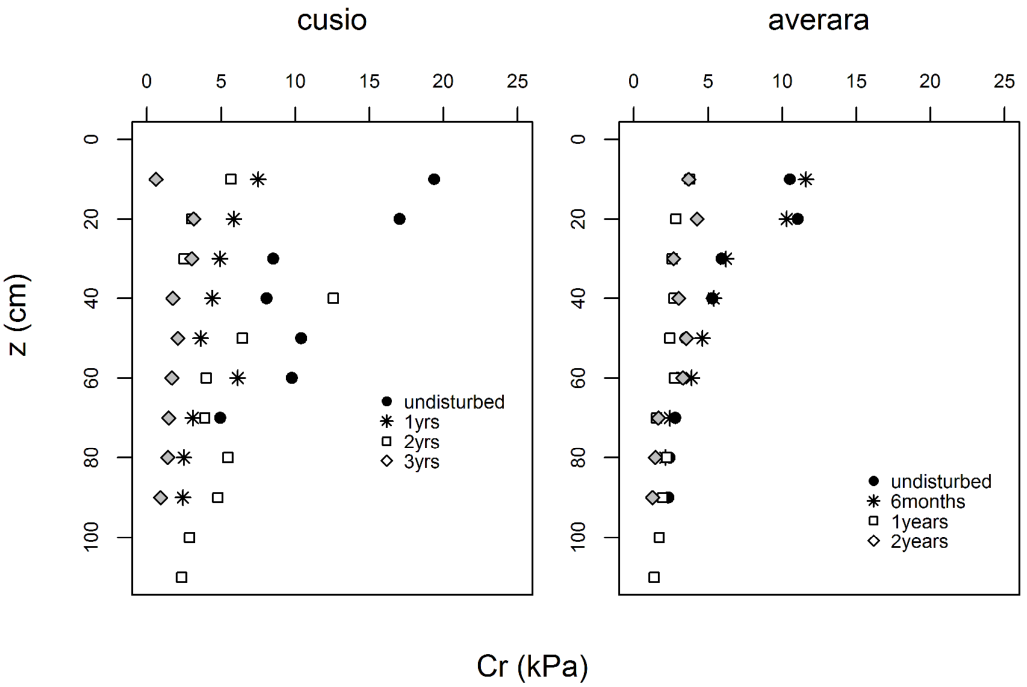

Fig. 3.1.11 Total root cohesion values.

3.1.4 Discussion

Root mechanical properties: root tensile force

Root tensile resistance in terms of force at rupture is dependent on root diameter, following a power law as well known in the case of live roots (i.e. Genet et al. 2010; Vergani et al. 2012). The obtained results show that such relationship is substantially valid also in the case of roots sampled from felled trees (Tab. 3.1.4), although its robustness seems to decrease with the time. After one, two and three years in the case of Cusio and 6 months, one and two years in the case of Averara, some force values progressively tend to move from the live root line (Fig. 3.1.8) to lower resistance values for the same diameter. In particular, we can observe a greater data dispersion after two years, both in Averara and Cusio sample sites. This can be ascribed to a process of progressive degradation that affects roots of the same size in a different way, with and possible random effects. First of all we can observe that mechanical degradation in the first three years after cutting seems not to depend only on root diameter, at least considering roots > 1 mm : for each diameter class greater than 1mm we find, after 2 and 3 years from logging, roots degraded and roots not degraded, and this determines an high data dispersion . From a mechanical point of view, finer roots do not seem to have a faster degradation than thicker roots. Silver and Miya (2001) found no significant statistical differences in decomposition rate of fine (< 2 mm) and medium (2-5 mm) roots, while roots bigger than 5 mm decomposed slower than fine roots. The presence of both degraded and not degraded roots in each diameter class can be explained with a difference in root degradation rate as function of root position in soil profile: roots in the shallower layer of soil are subjected to higher degradation rate than roots in deeper layer. The influence of root position in soil profile on root degradation rate has to be better explored in future works. It's worth to underline that, considering Cusio sample site, in two yrs condition the dispersion in roots of diameter class < =2 mm is higher than in three yrs condition, while in the 3 yrs condition spreading of data is more relevant than two yrs condition for roots > 2 mm as shown by standard error values (Tab. 3.1.9). This could be explained with the hypothesis that the most of degraded roots < 2 mm cannot be found after three years from logging, and the most of fine roots collected are not degraded, while two year after cutting both degraded and not degraded fine roots can still be found. This hypothesis is confirmed by the drastic decrease of the number of roots <= 2 mm in three yrs condition, especially in shallower soil layers. On the other hand, the number of thicker roots does not show degradation after two years from logging, and start to show any rotting process only after three years. After three years there is a greater number of deteriorated roots > 2mm than after two years from logging, influencing force values and standard error. In Averara any reduction in the number of roots can be appreciate just two years after felling, and only for roots < 1 mm, so two years after felling the standard error is higher than one year after felling in both the diameter classes, because the collected roots were both degraded and not degraded (Tab. 3.1.10).

Tab. 3.1.9 Standard error values at Cusio sample site.

treatment	**diameters of roots considered**	**se**
2 years after felling	<= 2 mm	0.87
	> 2 mm	0.32
3 years after felling	<= 2 mm	0.68
	> 2 mm	0.51

Tab. 3.1.10 Standard error values at Averara sample site.

treatment	**diameters of roots considered**	**se**
1 year after felling	<= 2 mm	0.47
	> 2 mm	0.56
2 years after	<= 2 mm	0.56

felling		
	> 2 mm	0.74

The degradation process in the considered cases becomes significant and affects root mechanical properties after three years from felling (Tab. 3.1.4) if we consider Cusio, and after more than two years from felling in Averara, in partial agreement to the available pioneering literature. O'Loughlin and Watson (1979), who did not find a significant influence of diameter on tensile strength, for Radiata pine (*Pinus radiata* D. Don), and O'Loughlin and Watson (1981) for Red and Hard beech (*Nothofagus fusca* (Hook.f) Oerst., and *Nothofagus truncata* Col.), observed a continuous reduction of average tensile stress after felling in the order of 30-35% for the first year. Watson et al. (1997) for *Kunzea ericoides* (A. Rich.) (Kanuka) and for *Metrosideros umbellata* (Cav.) (Southern rata), instead, observed an increase of strength values in the first year after felling and a decrease departing from the second year, explaining such behavior as the consequence of a reduction in roots diameter due to moisture loss (Watson et al. 1997). We observe the same phenomena in the roots collected in Averara 6 months after felling (fig. 4).

Actually, all these findings should be taken with caution because they are based on averaged values obtained from samples having different diameter distributions (as result from the diameter statistics reported by the authors), and this can lead to distorted trends (as evident in the present case). As herein showed, moreover, deteriorated and intact roots coexist for several months after cutting, making averaged values uncertain also for the same diameter. In any case the general trend observed in these studies can be considered consistent with the results here presented.

In a similar way the data of root tensile force presented by Ziemer and Swanston (1977), who accounted for root size heterogeneity by averaging the strength values in six diameter classes, showed a general decrease with the time after felling. The trend, however, likewise the works previously cited, presented fluctuations that are most likely related to the averaging operation and to the coexistence of roots with different degree of degradation, as already mentioned. Within a range of diameter similar to that here adopted (0-10 mm), however, the trend was consistent with the results of the present study.

Burroughs and Thomas (1977), who worked among the first on root strength deterioration, did not present the experimental data but stated that 10 mm diameter roots loss 49% of their strength (in terms of stress) after one year and 74% after two years from felling in the case of Coast Douglas Fir and only 30% after twelve years in the case of Rocky Mountains variety of the same species, introducing another relevant point that is the site variability of the degradation rate.

Amman et al. (2009), finally, studying root rotting process after felling and bark beetle attacks, found for Norway spruce a decrease in tensile strength after felling in the order of 60% of the original values after eight and ten years from cutting, and 30% after twelve years.

Root number per diameter classes

In Cusio site the total number of roots shows a decreasing shape with depth (Bischetti et al. 2005; Abdi et al. 2010; Genet et al. 2010; Mao et al. 2012) in undisturbed and one yr condition, as a consequence of the reduction of fine roots (< 2 mm) with depth (Zewdie e al., 2008), while in two yrs and three yrs condition root distribution is more homogeneous between soil layers.

No reduction in number of roots can be observed one year after felling, on the contrary there is an unexpected increasing in very fine roots number. This observation can be explained considering two different aspects. On one hand, we can observe from force data that a significant degradation cannot be noted after one year: roots do not show any decreasing in their mechanical properties. We can therefore hypothesize that after one year the degradation is minimal and do not affect both the number and the mechanical characteristics of roots, considering roots with diameter higher than one mm. On the other hand, number of roots and especially fine root biomass is proportional to diameter at breast height of the trees (Schwarz et al., 2010). In undisturbed forest trees surrounding the excavated trench have relatively lower diameter that, on the other hand, can induce important differences between the two stands. This can explain while the number of fine roots is higher in one year condition than in undisturbed forest. This lack of homogeneity between forest age between undisturbed and gap condition could not be removed because the gap interested the oldest portion of the forest stand considered.

Something similar happens in Averara where six months and one year after felling is not possible to see any reduction in the number of roots, and the total number of very fine and fine roots slightly increase in the six months and one yrs condition respect to the undisturbed conditions. Also in this case the variability in root distribution between the gap and the undisturbed forest (where diameter of the trees are smaller) is predominant respect to any eventual degradation, which in any case is still not significant as force data show.

Two years after felling in Cusio it is still not possible to appreciate a reduction in very fine roots, as in roots greater than 1 mm in diameter, with the exception of the first soil layer. This is supported also by force analysis: after two years roots with diameter > 1 mm don’t show a significant degradation of their mechanical properties. Considering two yrs condition, it is interesting to note that fine roots are more uniformly distributed along the soil profile. The decrease in the number of roots < 1 mm respect to the undisturbed and one yrs condition in fact occurs only in the first layers of soil, while the phenomenon can not be observed in the deeper layers; the same can be observed for 1-2 mm roots in the first 20 cm of soil. On the other hand two years after felling it is possible to appreciate a reduction in roots < 1 mm in Averara, while also in this site no reduction occurs in roots greater than 1 mm.

After 3 years from felling, the majority of very fine roots are degraded with the exception of the deeper layers; 1-2 mm roots show any degradation in the first 40 cm of soil. In 3 yrs condition no roots degradation can be observed for thick roots (diameter >2 mm).

Root decomposition, due to its relevance for carbon balance, is the object of an increasing number of papers (King et al. 1997; Janisch et al. 2005; Olajuyigbe et al. 2011; Garret et al. 2012). Although these studies measured root density degradation in terms of dry mass loss and deal with the shallower soil layers and hardly consider vertical trends, they can provide useful data for comparison.

The decay rate of roots depends on several factors, some related to root size and chemical composition (King et al. 1997; Silver and Miya, 2001; Fujimaki et al., 2008; Mao et al. 2011) and others climatic and environmental factors (temperature, precipitation, oxygen and nutrient availability, etc.). Chemical root composition is the driving variable that affect root decomposition rate (Silver and Miya, 2001; Fujimaki et al., 2008) and it is a function of root diameter (Silver and Miya, 2001). .In fact, different studies showed faster degradation for fine roots than for thicker roots (Fahey et al. 1988; 1991, King et al., 1997, Lin e al., 2011). This is consistent with our finding that after three years can be appreciate a reduction of the number of roots < 2 mm, and not of thicker roots, even if mechanical degradation begins also for roots > 2 mm. On the other hand basing on our findings the speed of mechanical degradation is not just a function of the diameter because both degraded and not degraded roots are found after two and three years of felling in all the diameter classes.

Climate and environmental factors has a secondary role in driving root degradation (Silver and Miya, 2001) affecting the activity of microbe and fungi which are responsible for root deterioration and which abundance and efficiency are known to strongly decrease with depth (Ekelund et al. 2001; Ros et al. 2006). As a consequence, greater and faster root degradation must be expected in superficial soil layers The results here presented can be therefore considered consistent with these finding concerning the decomposition dynamics of roots within the soil.

Decay rate, moreover, might not be a regular process consisting in an initial colonization, followed by more rapid decomposition and, in turn, followed by a slower phase of humification (Olajuyigbe et al. 2011).

Fahey et al. (1988) showed that fine roots decay is rapid in the first year and then it decreases, and Fahey et al. (1991) demonstrated that most of fine roots in the forest floor decompose during the first season after cutting, whereas fine roots in the mineral soil decompose more slowly. The same trend has been observed by McClaugherty et al. (1984) for red pine roots and by King et al. (1997) for Loblolly pine (Pinus taeda L.) roots. We can't observe such a trend for our data because of the non-homogeneity of trees diameter between undisturbed and first year after cutting, which influence especially the number of fine roots.

Concerning the rate of decay in terms of absolute and relative values, it must be noted that these vary greatly with the environmental conditions (soil and climate) and with root chemical composition (McClaugherty et al. 1984; King et al. 1997; Lin et al. 2011).

Root cohesion decay

As additional root cohesion is calculated from root strength which is a function of diameter of roots, cohesion values followed the combination of these two variables. Considering Cusio, notwithstanding the tensile force of roots is not significantly different for the first two years with respect to the values of live roots, *Cr* decays as a result of the reduction in root density, especially in the first 0.5 m of the soil profile. In terms of mean cr value for the whole profile (0-70 cm, to allow comparison), the values of 1-yr were 45% of the undisturbed conditions; such values are substantially maintained for another one year, and decreased to 16% during the third year. It is however important to underline that root cohesion decreasing after one year and two years is not due to root decomposition. No mechanical degradation has been observed and there is not a decrease in root number; root cohesion values are inferior than undisturbed because of the inferior number of roots > 2 mm in 1 and 2yrs condition, and so the difference in root reinforcement are mainly due to the spatial variability of root distribution. Reduction of additional cohesion in three yrs condition is on the contrary attributable to root degradation, since there is a reduction in fine roots and in roots mechanical properties after three years from felling. Considering Averara, after 1 and 2 years there is a reduction in terms of mean *Cr* values of 50% respect to the root reinforcement values of the undisturbed forest. Also in this case the reduction in root cohesion can be attributed to root degradation just two years after felling, and is due just to mechanical degradation since there is a reduction just in the number of roots inferior than 1 mm.

The decreasing rates are more severe than those reported by Ziemer (1981), but consistent with those reported by Sidle and Terry (1992).

Ziemer (1981), in fact, estimated that about half of the original reinforcement was gone within two or three years, two third within eight years and all within 25 years, whereas from decay curves reported by Sidle and Terry (1992) the ratio between additional root cohesion at 2-3 years and the initial values were about 30% for Radiata Pine (data from O'Loughlin and Watson 1979), about 35% for coastal Douglas Fir (data from Burroughs and Thomas 1977), about 50% for white fir-mixed conifer (data from Ziemer 1981) and for Rocky Mountain Douglas Fir (data from Burroughs and Thomas 1977), about 60% for Japanese cedar (data from Kitamura and Namba 1981 and from Abe and Iawamoto 1985), and about 80% for Spruce-Hemlock (data from Ziemer and Swanston 1977).

3.1.5 Conclusive remarks

New and comprehensive data concerning the deterioration of roots and its consequence in terms of additional cohesion were presented for a three-year period after felling in two Silver Fir-Norway Spruce stand in the Italian Alps.

Tensile strength of roots sampled after tree cutting, in terms of rupture force, was proven to be related to root diameter by a power law relationship as in the case of live roots, although the force values showed an increasing spread with time from cutting as consequence of the contemporary presence of decomposed and healthy roots.

In the considered cases root deterioration did not affect root strength for the first two years, whereas the reduction became statistically significant at the third year in one case and after two years in the other case.

Root density reduction, becomes important three years after cutting, even if interest only fine roots. The root degradation process due to bacteria and fungi is not uniform, and root degradation has been showed to decrease more rapidly in the shallower layer and for thinner roots, again accordingly to literature on decay studies.

The additional root cohesion, being a combination of root strength and root diameter distribution, starts to reduce as a consequence of root degradation between two and three years after cutting. Variability in root distribution in the stand is high and hides the effect of the degradation especially in the first year after cutting; it's therefore important to consider the spatial root distribution in function of the distance from the stem and the diameter of the stem in the future studies concerning root degradation.

The present work, investigating only three years after felling, does not allow the development of a new deterioration model of additional root cohesion but, providing new, more complete and more rigorous data concerning the temporal dynamics of the contribution of forests to slope stability respect the past, gives a contribution to advancements into the fields of slope stability evaluation and the forest management, with particular reference to protective forests in the alpine environment.

More research will be needed in prolonging the time span after felling, in extending investigation to other species and environments (which are driving factors in root decomposition), and in including coarser roots which better resist to decomposition and which affect heavily root cohesion values.

3.1.6 References

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3.2 Temporal and spatial dynamic of root reinforcement in spruce protection forests as consequence of forest disturbances: a case study in Canton Schwyz, Switzerland

3.2.1 Introduction

Root reinforcement has been recognized as one of the key factor when dealing with slope stability problems and protection against shallow landslides and has therefore become one of the criteria in the guidelines for the active management of alpine protection forests against this type of natural hazards in Switzerland (Frehner et al., 2005). A reliable quantification of root reinforcement still remains the main problem to solve to allow a useful consideration of this component in the forests' management practices and in the definition of a comprehensive risk mitigation strategy in which forests can have a key role. Nowadays, one of the main challenge is to effectively take into account the dynamics of root reinforcement, considering both the spatial and temporal variability (Schwarz et al., 2012, Vergani et al., 2013). Up to now, most of the works implements in the stability analysis a single and constant value of root reinforcement (root cohesion value) for a species or a vegetation community. It is difficult to predict the variation of root reinforcement at the different scales because roots morphology and their distribution reflect both biological mechanisms and the influence of environmental factors. The adoption of constant root cohesion values, however, may be inappropriate where root distribution varies spatially and temporally, and it has been proved that this variability can be huge depending on forest structure and patterns (Schmidt et al., 2001; Hales et al., 2009; Schwarz et al., 2010b, Genet et al.,2010; Mao et al., 2012). Forest landslides are likely to occur within gaps of low root reinforcement or in areas where the root-thread strength declined due to decay (Burroughs and Thomas, 1977). After timber harvest, the interconnected network of a living root system decreases in both density and strength, leaving unreinforced areas around the lateral edges of individual tree root systems. As underlined by different authors, quantifying root reinforcement variability can be the key to understand landslides triggering mechanisms, improving the understanding of why certain portions of the landscape generate landslide in a storm while others remain stable (Hales et al., 2013; Schwarz et al., 2012, Schmidt et al., 2001). To address this challenge, it is crucial to upscale root reinforcement models from the single trees to large spatial scales (Schwarz et al., 2010b).

Although the temporal effects of timber harvesting have been considered in many studies yet, the temporal dynamic of root reinforcement is often assumed to be spatially uniform (Sakals and Sidle, 2004). Previous studies focused mainly on root strength decay (Preti et al., 2012, Amman et al., 2009; Johnson and Wilcock, 2002; Watson et al., 1999; Ziemer and Swanston, 1977) without considering the variation in root frequency and distribution, with few exception (Burroughs and

Thomas 1977, Vergani et al. 2013). In both these works there is an effort to consider variation of root distribution after felling, but the lack of information regarding the spatial variability of root distribution does not allow the upscaling of results at the hillslope level. Sakals and Sidle (2004) proposed a model for the spatial and temporal variability of root reinforcement, based on literature data and field data on *Pseudotsuga menziesii*. No works dealing with spatial and temporal variability in root distribution are available for the alpine species in the literature so far.

This aim of this part of the work is to extend the understanding of the spatial and temporal dynamics of root reinforcement in alpine spruce forests, supplying new experimental data and applying state of the art numerical models to compute root reinforcement. The root reinforcement decay has been estimated in a 15 year time span after timber harvesting and particular attention was given to the horizontal root distribution in the forest stand as suggested by recent studies (Schwarz et al., 2010b; 2011; 2012). Root distribution was sampled systematically at different distance from the trees in order to characterize its spatial variability and to permit a more reliable estimation of the decay of root reinforcement at the hillslope scale. To estimate root mechanical properties, field root pull out were carried out instead of the more common laboratory tensile tests, to provide a more realistic estimation of root strength taking into account also root soil interactions and the effect of interlocking roots. Moreover, roots bigger than 5 mm in diameter were tested in the field, to fill up the current lack of data regarding field pull out of roots of these dimensions. A further contribution presented here is an estimate of the root reinforcement contribution of shrub species and some natural regeneration species after 15 years from felling, when the spruce roots are completely degraded. The role of natural regeneration is a key factor for the management strategies in protection forests, to maintain the continuity in the protection function (Frehner et al., 2005). Finally, a model for the estimation of root reinforcement decay is proposed, based on the two different processes of root number decay and root force decay.

The final aim of the work was to draw up a map of root reinforcement spatial and temporal dynamics in a managed spruce forest stand. This is the basis for the further implementation of a slope stability model in which the variability of root cohesion is taken into account as a critical factor in landslide triggering. Results are discussed in the perspective of future research needed to give a base for forest managers strategies in protection forest against shallow landslides.

3.2.2 Material and Methods

Study area

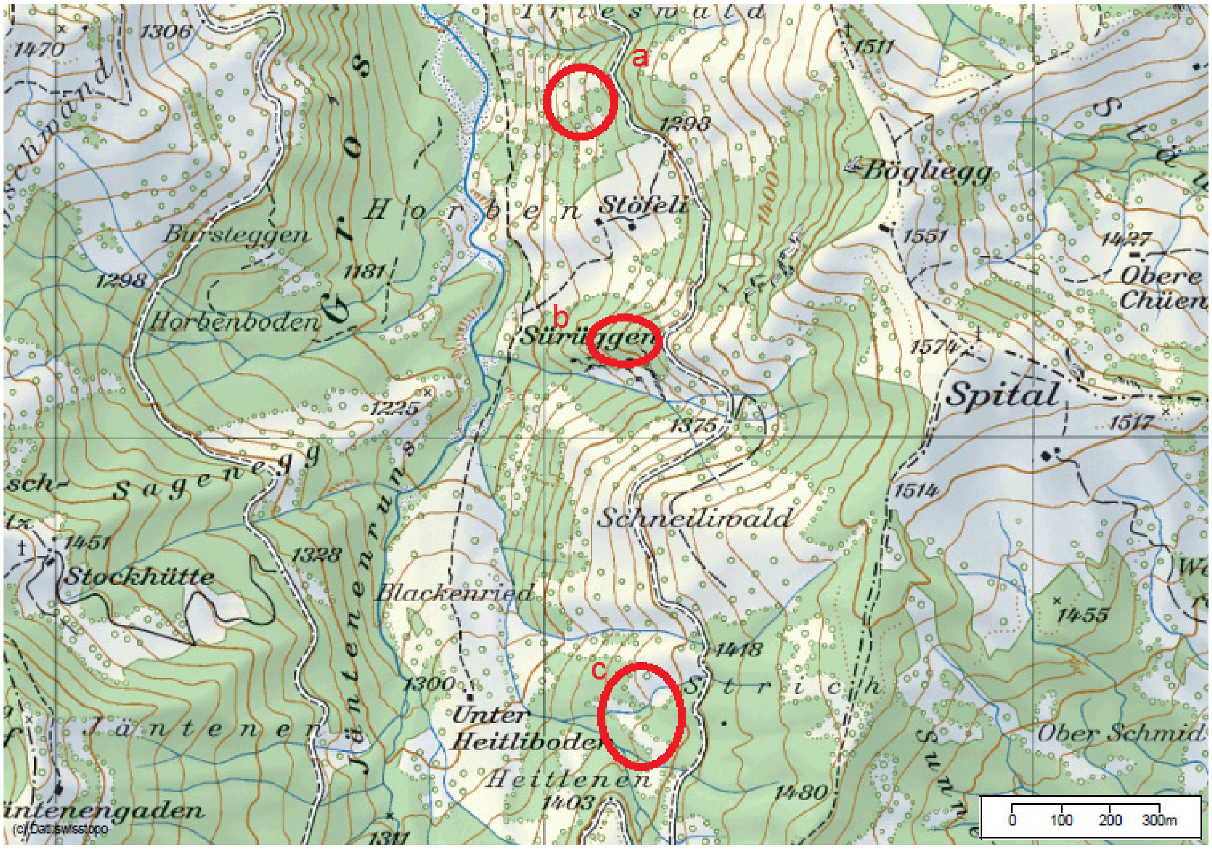

Fig. 3.2.1 Study area with sample sites localization: a – 15 years old cutting; b – undisturbed forest and 5 years old cutting; c- 5 years old cutting.

The study area (Fig. 3.2.1) is located in a small mountain catchment above the village of Obergross, in the Canton of Schwyz (Switzerland), with elevations ranging between 800 and 1400 m asl .The area is characterized by high precipitations rate (about 3000 mm per year) and is subjected to intense rainfall events. In 2007 there was a storm with 300 years return time and 100 mm of water fallen in 24 hours, which caused a flood with a huge amount of wood transport from the streams to the main river of the catchment and then down to the village of Obergross. A lot of cuttings were subsequently carried out on the stream banks to clean them and avoid wood transport into the streams. Additionally, logging activities were carried out intensively on the slopes after the big storms Lothar (1999) and Vivian (1990) which caused the crash of big portions of forest, and after successive bark beetles attacks.

Geologically the basin is located in the flysch area in the northern alpine boundary (Ott et al., 1997) and is characterized by a substratum of sandstone (so called “flysch”), formed by different layers with not permeable clay layers between them. This type of substratum forms soils that are easily eroded and produce big amounts of sediments. Geological patterns, joined with the climatic conditions and the steepness of the slopes determine a frequent occurrence of erosion phenomena, shallow landslides (Fig. 3.2.2) and floods. Active tension cracks are visible on the slopes (Fig. 3.2.3).

Protection forests represent 60% of the total forest cover in canton Schwyz, and the main function of the forests in the considered basin is protection against shallow landslides and floods. Predominant forest cover is a mixed forest of beech, silver fir and spruce, which is substituted by a forest dominated by spruce at the higher elevations (from 1300 m asl). The dominance of spruce is in part due to a selection effect caused by human activities.

The contemporary presence of large cut areas and slopes prone to shallow landslides made the area representative for situations where forest management needs to take into consideration the protective function of forests. Four sample sites were selected in the basin, at an altitude comprised between 1300 and 1400 m asl. Three sample sites (Fig. 3.2.1 and Tab. 3.2.1) are located in spruce forest cut areas where logging activity was conducted respectively in 1998 (15 years old cutting), 2003 (10 years old cutting), 2008 (5 years old cutting). The fourth sample site is located in a mature spruce fir high forest, with the sporadic presence of silver fir, which can be classified as *peccetum-abietum*. The forest has a one layer vertical structure and an homogeneous horizontal structure, with a gap where there is a well-established natural regeneration. The mean diameter is 0.47 m (DBH). Cover height is between 24 and 34 meters. The undergrowth vegetation is scarce and characterized by *Oxalis acetosella, Luzula nivea, Vaccinium myrtillus, Petasites albus, Plantago lanceolata, Omogina alpina*.

In each sample site the position of 25 trees (or stumps) was surveyd through a high precision GPS tool and the species and diameter at breast height (DBH) were identified. This information were then used to upscale the root distribution model from the sampled plants (or stumps) to the whole stand.

Fig. 3.2.2 Erosion phenomena (A) and shallow landslides (B) are common in the study area.

Fig. 3.2.3 Tension cracks in the 5 years old cutting area.

Tab. 3.2.1 Sample sites characterization.

site	**altitude (m asl)**	**mean slope (°)**	**aspect**	**underwood species and natural regeneration species (r)**
undisturbed forest	1300	30	s-sw	*Oxalis acetosella, Luzula nivea, Vaccinium myrtillus, Petasites albus, Plantago lanceolata, Omogina alpina, Picea abies (r)*
5 yrs cutting	1400	25	w	*Vaccinium myrtillus, Petasites albus, Rubus spp, Sorbus aucuparia (r), Picea abies (r)*
10 years cutting	1300	33	s-sw	*Luzula nivea, Vaccinium myrtillus, Rubus spp, Sorbus aucuparia (r), Salix caprea (r), Betula pendula (r), Picea abies(r), Acer pseudoplatanus (r)*
15 years cutting	1300	40	sw	*Rubus spp, Alnus viridis, Luzula nivea, Picea abies (r), Sorbus aucuparia (r), Fagus sylvatica (r), Salix caprea (r), Vaccinium myrtillus*

Root distribution and root strength measurement

In each site were selected 5 stumps (or trees in the case of undisturbed forest) of diameter (at breast height in the case of the undisturbed forest, of the stumps at half meter height in the case of the cuttings) comprised between 30 and 40 cm. For each plant, three trenches 50 cm deep and 50 cm width were excavated at increasing distance of 1.5, 2.5 and 4 meters from the stem in the downslope direction. A total number of 15 trenches were excavated in the undisturbed forest and in the 10 years old cutting; in 5 years old cutting just 14 trenches were excavated because of the impossibility of excavating the trench at 4 m in one case. Finally, in the 15 years cutting just a trenches for each stump, at a distance of 1.5 m, were excavated, for a total of 5 trenches. The reason is that already after 10 years there were really few degraded spruce roots, so just five trenches were excavated in the 15 years cutting to confirm this result.

In each trench vertical surface the spruce roots were identified, counted and measured with an electronic caliper at each depth layer of 5 cm. Roots were classified in diameter classes of 1 mm width, starting from 0.5 mm. Roots with a medium diameter size of 1 mm are considered fine roots ($0.5<d<1.5$ mm). In 10 years old gap and 15 years old gap almost no spruce roots were found, but there was a consistent number of roots of different species, both shrub and regeneration of woody species (Tab. 3.2.1). To quantify root density of the shrub species and natural regeneration, roots of the different species were counted in the five trenches of the 15 years old gap, following the same procedure done for the spruce roots. Identifying the roots of so many different species is hard, so no distinction between species was made, classifying roots generically as “regeneration and shrub roots”.

In the undisturbed forest and in 5 years old gap cutting roots comprised between 1 and 13 mm in diameter were chosen in each trench for the pull out tests. This is was not possible in 10 and 15 years old gap cutting due to the scarceness of roots and to their extremely degraded conditions which did not allow to perform pull out test. The priority was given to bigger roots (up to 5 mm) because there are no data available for roots of this size deriving from pull out tests, and also data coming from tensile tests are scarce. Just roots oriented perpendicularly to the trench wall were selected, or at least inclined in a way that allowed the positioning of the pull out machine perpendicularly to the root. The soil was carefully removed to show at least 10 cm of each root (until 30 cm in the case of the bigger roots), then the selected roots were cleaned and the bark removed. Each roots was strongly fixed to an anchor using an elastic wire and wood-metal glue. After this procedure the root is ready for the pull out tests.

Pull out tests were performed through a self-built device (Fig. 3.2.5) equipped with a crank handle. Each root was attached through its anchor and a snap-hook to a load cell with a 2000 N capacity, which was linked through another snap hook to the crank handle. The crank handle was manually turned slowly and constantly pulling out the root until it broke or slipped out. Always the same person was responsible for pulling roots to minimize errors associated with variations in test speed. However, was not possible to measure the test speed in the field. A wired displacement sensor was fixed on a stake at a known distance from the trench wall. The extremity of the wire was fixed to the anchor of the root, in order to measure the displacement of the root subjected to the pull out procedure. The load cell and the displacement sensor were attached to a CR1000 datalogger, which recorded force (N) and displacement (mm) data each second. Diameter of each root was measured with a digital caliper at the breaking point, where it was possible with bark (Schmidt et al., 2001). Since it was not possible to measure each diameter with the bark, some roots were collected both from undisturbed forest (14 roots) and from the 5 years old gap (19 roots) and measured with and without bark to obtain a relationship that links root diameter without bark with diameter with bark (Fig. 3.2.4). In this way the diameter with bark of all the root tested could be estimated.

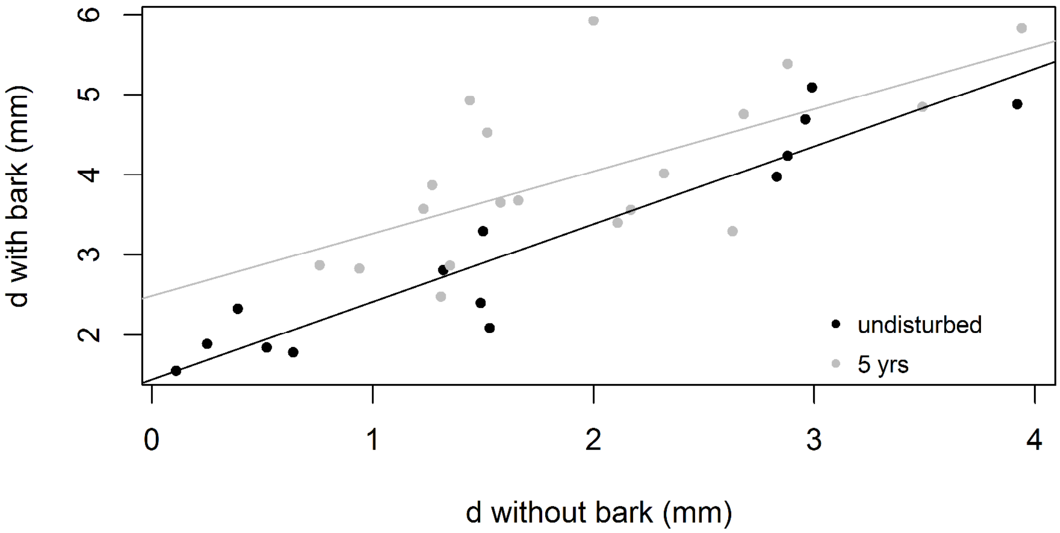

Fig. 3.2.4 Relationship between diameter measurements without bark and with bark for both live and degraded roots.

Tab. 3.2.2 Coefficients and statistical parameters of linear regression between diameter without bark and diameters with bark .

case	**a**	**b**	**p**	**R^2**	**se**
undisturbed	1.44	0.97	< 0.001	0.89	0.44
5 yrs	2.49	0.78	0.003	0.42	0.81

Finally, in the undisturbed forest and in 5 years old gap cutting were collected some additional roots to perform laboratory tensile test in order to compare the results coming from different testing procedures. Laboratory tensile test were performed using a MTS testing machine equipped with a load cell (F.S. 500 N, accuracy 0.1% F.S.) and special clamping devices able to avoid root damage at the clamping points. Only specimens that broke near the middle of the roots between clamps were considered valid. Root size with bark was estimated as the average of three values taken with an electronic caliper at three points near the section of the potential breaking (Abdi et al., 2010; Vergani et al., 2012). The test speed was 10 mm/min and the distance between the clamps was 5 cm.

The mechanical properties of the shrub and natural regeneration species were derived by the laboratory tensile test previously carried out on roots of *Vaccinium myrtillus, Salix caprea and Rubus idaeus* collected in the year 2012 in the Italian Prealps. The procedure of testing was the same described for the spruce roots. Roots found in the 15 years old gap belong to many more species than the one tested, so root mechanical properties cannot be considered complete but can give an idea of the contribution of some shrub and regeneration species.

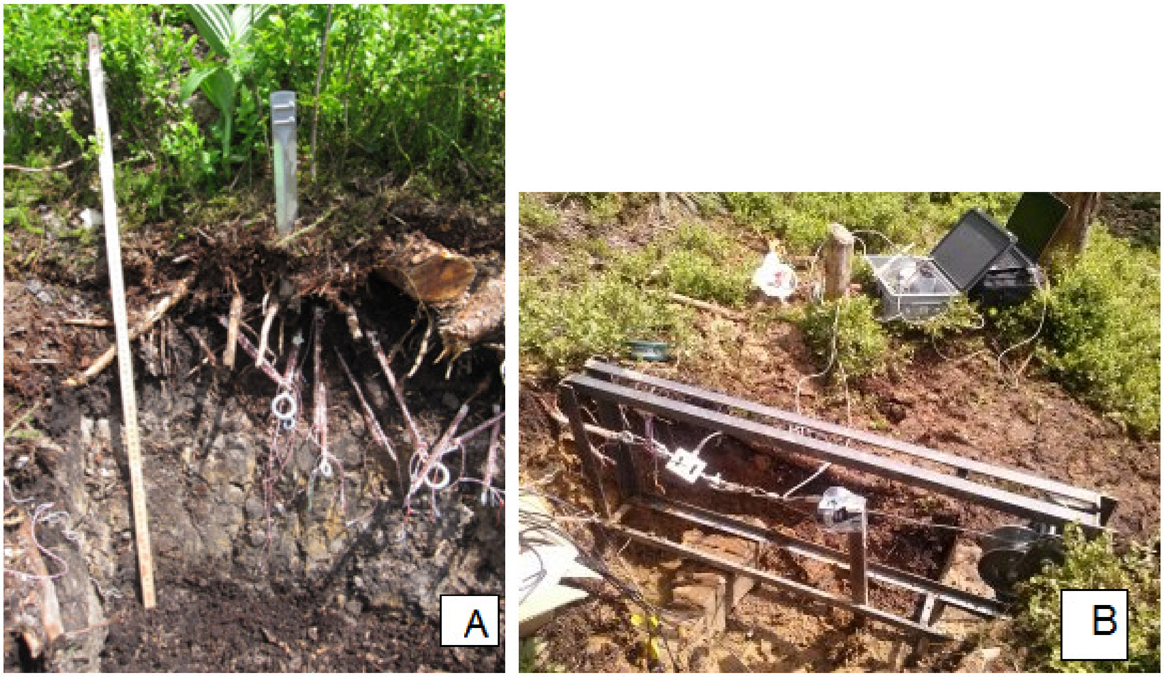

Fig. 3.2.5 Roots fixed to the anchors ready for the pull out test (A) and the pull out device (B).

Root distribution model and Root Bundle Model

Root reinforcement can be distinguished in basal reinforcement, given by the roots that intersect the share surface during the failure, and lateral reinforcement, given by the roots that act on the lateral failure plane. Considering the shallow root system of Norway spruce, only lateral root reinforcement was estimated, which has been proved to significantly affect the onset and size of shallow landslides (Reneau and Dietrich, 1987; Schmidt et al., 2001). Moreover, few roots in temperate forest ecosystems usually cross the shear plane of shallow landslides (Schwarz et al., 2010a). Root reinforcement depends mainly on root density and root diameter distribution, and on root mechanical properties. Given the high variability of root distribution and the time and energy required by the field survey, a model is needed to estimate root diameter distributions at the slope scale. The adopted root distribution model is the one proposed by Schwarz et al. 2010b and 2012, RootMap, which allows to estimate the number of roots of each diameter class at a given distance from the tree stem, allowing the upscale of the estimation of root distribution from a single tree to the forest stand. Only the main steps of the model are reported, for a detailed description see Schwarz et al., 2010b and Schwarz et al. 2012. The distribution of root diameters in a root system is assumed to be strongly correlated to the fine root distribution and to the distance from the tree stem. The total number of fine roots associated to an individual tree *t_frf* is proportional to the stem area (Ammer and Wagner, 2005) and can be estimated as follows :

$$t_{frf} = \mu * \left(\frac{DBH}{2}\right)^2 * \pi \qquad (3.2.1)$$

Where μ (1/mm^2) is a “pipe theory” coefficient and *DBH* (mm) is the diameter measured at breast height.

Fine roots biomass decreases with increasing distance from tree trunk (Ammer and Wagner, 2005). Given the total number of fine roots belonging to a tree of a certain diameter, it is possible to estimate the number of fine roots in a square of 1 m width x 1 m depth as a function of the distance from the stem:

$$frf = \frac{t_{frf}}{d_{stem_{max}} * 0.001}\left[\frac{0.7 + \frac{0.3\, d_{stem}}{5\, DBH}}{2\pi(5 * DBH * 0.001)}\right] \text{ if } d_{stem} < 5 * DBH \qquad (\ 3.2.2)$$

$$frf = \frac{t_{frf}/(d_{stem_{max}} * 0.001)}{2\pi * d_{stem} * 0.001} \text{ if } d_{stem} > 5 * DBH \qquad (3.2.3)$$

Where *d_stem* (mm) is the distance from the stem and *d_stem_max* (mm) is the maximum rooting distance from the stand. The maximum distance from the tree trunk where roots of a subject tree can be found depends on the dimension of the tree (Amman and Wagner, 2005), and can be calculated as a function of *DBH*:

$$d\_stem\_\max = \left(\mathrm{dist}_{\mathrm{coeff}} * \frac{\mathrm{DBH}}{1000}\right) * 1000 \qquad (3.2.4)$$

Where dist_coeff is an empirical coefficient.

To obtain the density of coarse roots (> 1.5 mm) as a function of the distance from the stem, a constant value of branching distance BD (mm) is assumed. For a given *d_stem_max* (maximum root system extent) and for a given fine root density the diameter of coarse roots is defined at each branching point. For each distance from a tree, a maximum root diameter $\mathrm{RD}_{\max}$ is computed as an upper limit for root diameter distribution. The maximum root diameter $\mathrm{RD}_{\max}$ (mm) is calculated in function of the distance from the stem as:

$$RD_{max} = \left[(d_{stem_{max}} - d_{stem})/BD\right] * \frac{1}{red\_coeff} * d_r \qquad (3.2.5)$$

Where *red_coeff* is a reduction coefficient accounting for the reduction of root diameter after a branching point and d_r is the reference diameter of a fine root (equal to1 mm).

The number of coarse roots *crf* at a given distance from the stem for a given diameter value *d* comprised between the reference diameter and the maximum diameter RD_{max} is calculated as:

$$crf\ (d) = frf * \left[\frac{\log(1 + RD_{max}) - \log(1 + d)}{\log(1 + \mathrm{RD}_{\max})}\right] * \left(\frac{d}{d_r}\right)^{exp}. \qquad (3.2.6)$$

Where *exp* is the fitted exponent for the measured data and d_r is the reference diameter.

Once the root distribution is known, root mechanical behavior must be considered to estimate root reinforcement. The root reinforcement wss estimated through the extended Root Bundle Model, RBMw (Schwarz, 2013), which was used to calculate tensile force and displacement of a bundle of roots, according to the roots distribution. Respect to the “simple” RBM, the RBMw implement the Weibull function in order to consider the probability distribution of breakage of roots of the same diameter class. For the detailed explication of the model see Schwarz et al. (2013) and chapter 1.3.

Number of roots decay model and force decay model

Root reinforcement decay after disturbances is due to the reduction in the number of roots and to the reduction in root strength, since degradation affects root mechanical properties. The most used model to simulate root reinforcement decay is the one proposed by Sidle (1991, 1992) which directly estimates the values of root cohesion. This model is simple because it is based just on two parameters, but is calibrated just on North American species and, above all, it does not allow to consider the spatial variation of root reinforcement. For this reason we decide to analyze separately the two processes responsible for root reinforcement decay: the decay in the number of roots and the decay of the force. The number of roots for a certain diameter class d (mm) at the time t (years) is estimated by an exponential function:

$$Nr_d = N_{r0}\, e^{-kt} \qquad (3.2.7)$$

Where N_{r0} is the number of roots of the considered diameter class at the time 0 and k is a decay parameter that is expected to be a function of the diameter class d:

$$k = f(d) \qquad (3.2.8)$$

To allow the calibration of the root number decay model, the root distribution at the time 0 (before disturbances) was back calculated for each stand (5 years cutting, 10 years cutting and 15 years cutting) by means of the root distribution model applied to the tree distribution in each stand. Root distribution was estimated exactly in the position where the pits were excavated. Considering exactly this points, the normalized values Nr/Nr0 were adopted to calibrate the model.

The model proposed for the decay of the root force is an exponential law:

$$F_t = F_0 e^{-ct} \qquad (3.2.9)$$

Where F_0 is given by the force power law of the roots at the time 0, t is the time in years and c is the coefficient of decay. To calibrate this model are used the power law derived from pull out test of the roots coming from the undisturbed forest and the 5 years old cutting.

Statistical analysis

The relationship of root tensile force (N) as a function of root diameter (mm) was interpreted through a power law. The goodness of fit of the regression was estimated through the coefficient of determination R^2 and the coefficient of significance (p-value) obtained from Fisher's Test. Fisher's test was applied to the linear regression obtained from log-transformed values of force and diameter. To compare force values between live and degraded roots (i.e roots coming from the undisturbed forest and roots coming from 5 years old cutting) and take diameter into consideration as covariate (Vergani et al., 2012; Hales et al., 2013) ANCOVA was applied to the linear regressions logF-logd, with a level of confidence of 95%. The normality and homogeneity of variance required for ANCOVA was verified using, respectively, Kolmogorov–Smirnov's test and Levene's test, both of which are suitable for small samples, with a confidence level of 0.05. The normality test was applied to log-transformed values and residuals; Levene's test was applied to log-transformed values.

3.2.3 Results

Root distribution

Firstly root distribution was analyzed without taking into consideration interactions between the root systems of the trees of the stand; this was done in the section of the calibration of the root distribution model. Mean number of roots for each diameter class at each considered distance from the stem is shown in Tab. 3.2.3 for all the case of study and in Fig. 3.2.6 for undisturbed forest, 5 years old and 10 years old cutting areas. Roots considered range between the diameter classes of 1 and 20 mm , which are the one which contribute most to root reinforcement, even if roots up to 40 mm are important for slope stability (Reubens et al., 2007). Roots with diameter less than 0.5 mm are not considered because they do not play a significant role in reinforcement due to their small length and rapid turnover. For each diameter class and distance from the stem a mean number of roots was calculated, as the average of the number of roots found in the 5 trenches considered. The mean number of roots is multiplied for two to scale root distribution to a square of 1 m for 1 m, supposing that about 80-90% of roots is founded in the first 50 cm of soil (Stokes et al., 2009; Burke et al., 2002) and considering the superficial, plate-like distribution of Norway spruce roots. Whatever distance we consider there is an exponential decreasing in the number of roots as the diameter class increases in the undisturbed forest ad in 5 years gap, while this trend is no more visible in 10 years gap cutting (Fig. 3.2.6).

In Fig. 3.2.7, Fig. 3.2.8 and Fig. 3.2.9 mean root distribution with depth is shown for each treatment, joining the original diameter classes in larger ones in order to summarize the data. Root diameter classes are those proposed by Genet et al., 2008 and Ji et al., 2012, 0.5-1 mm (very fine rots), 1-2mm (fine roots), 2-5 mm (thick roots), 5-10 mm (coarse roots), > 10 mm. In undisturbed forest and 5 years gap cutting roots decrease with depth in all case as is well-known, and the majority of roots as well as coarse roots are concentrated in the first soil layers, as is typical of the plate-like root system structure of Norway spruce (Fig. 3.2.7 and Fig. 3.2.8).

In both undisturbed forest and 5 years gap there is a consistent decrease in the number of roots moving from 1.5 meters of distance from the stem to 2.5 m. The total number of roots is about the half at 2.5 m respect to 1.5 m, and this is valid in both the cases. In the undisturbed forest there is a reduction in the maximum diameter of roots at 2.5 m respect to 1.5 m, while this reduction is not appreciable in the gap. Considering a distance of 4 meters, the total number of roots jumps to values similar (in the gap) or even higher (in the undisturbed forests) than the distance of 1.5 m. The maximum root diameter found increases too.

Comparing undisturbed forests and gap cutting, whatever is the distance considered there is a reduction of about 50% in the total number of roots. There is a significant decrease in the number of roots of diameter less than 5 mm, while no significant decrease is appreciable for roots with diameter higher than 5 mm.

If we consider 10 years gap cutting, roots decreasing with depth is less evident. The decrease in the number of roots from 1.5 m to 2.5 m cannot be observed too. Total number of roots falls at about 10% respect to undisturbed forest values at 1.5 m and 4 m, and 24% at 2.5 m. Just roots with diameter higher than 2 mm are found, and the decrease is evident and significant for all the remaining diameter classes.

No spruce roots were found in 15 years old gap, with the exception of two big and severely degraded roots of 56 and 37 mm. Numbers of roots reported in table 3 refer to the regeneration species. Roots belonging to the shrub and regeneration species are all inferior to 5 mm and 83% of the whole roots is under 2 mm.

Fig. 3.2.6 Mean number of roots per diameter class in each treatment and at each distance: blue= 1.5 m, red = 2.5 m, green = 4 m.

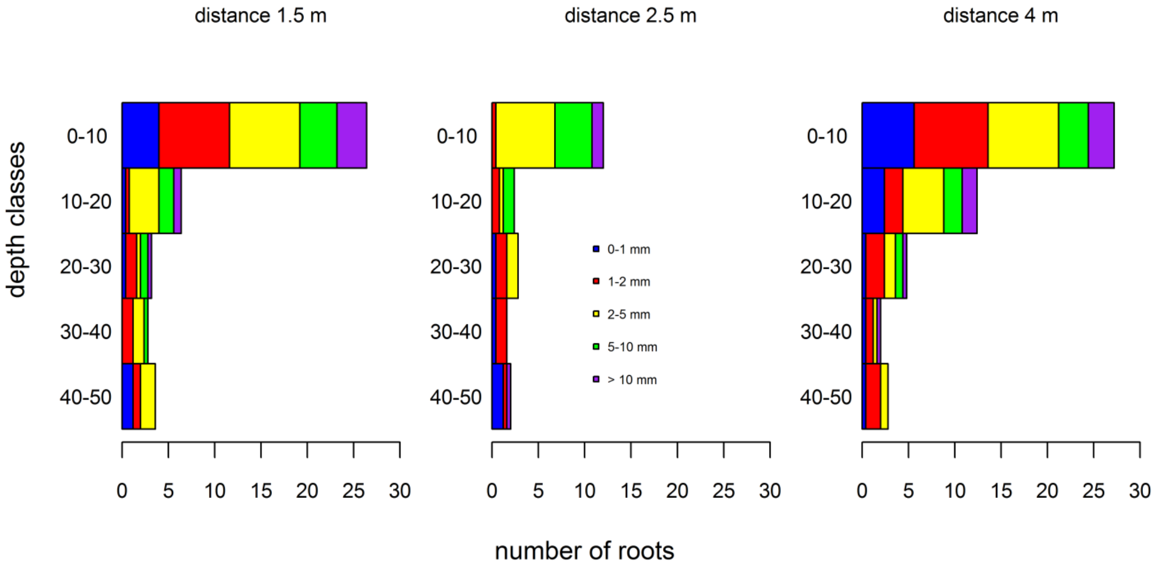

Fig. 3.2.7 Mean root distribution in undisturbed forest, considering a square of soil of 1 meter per 1 meter. Total number of roots are: 42 at 1.5 meters, 21 at 2.5 meters, 49 at 4 meters.

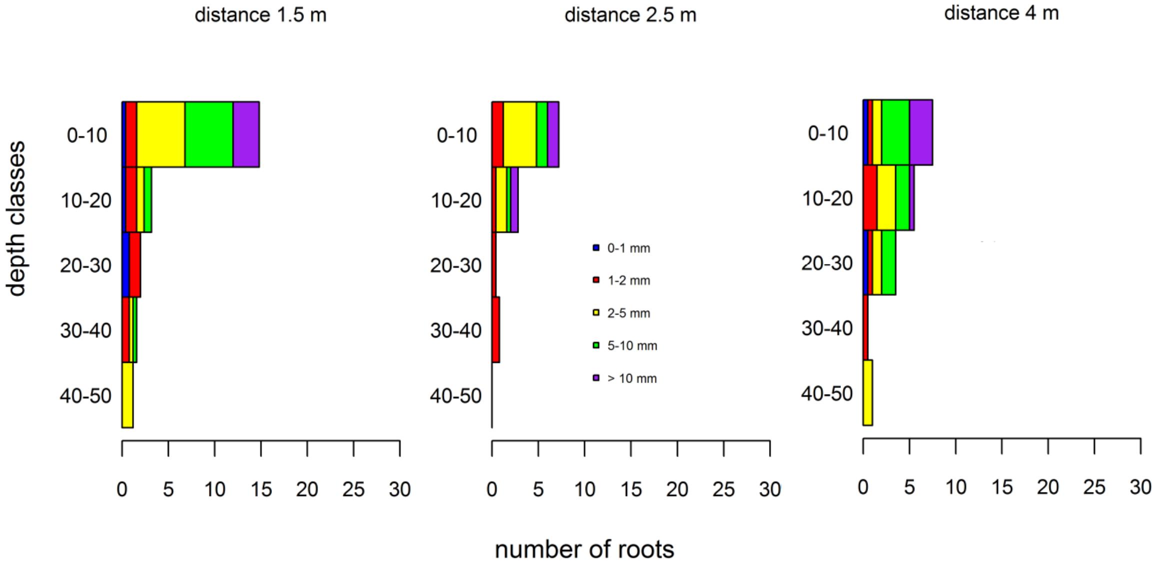

Fig. 3.2.8 Mean root distribution in 5 years gap cutting, considering a square of soil of 1 meter per 1 meter. Total number of roots are: 23 at 1.5 meters, 11 at 2.5 meters, 18 at 4 meters.

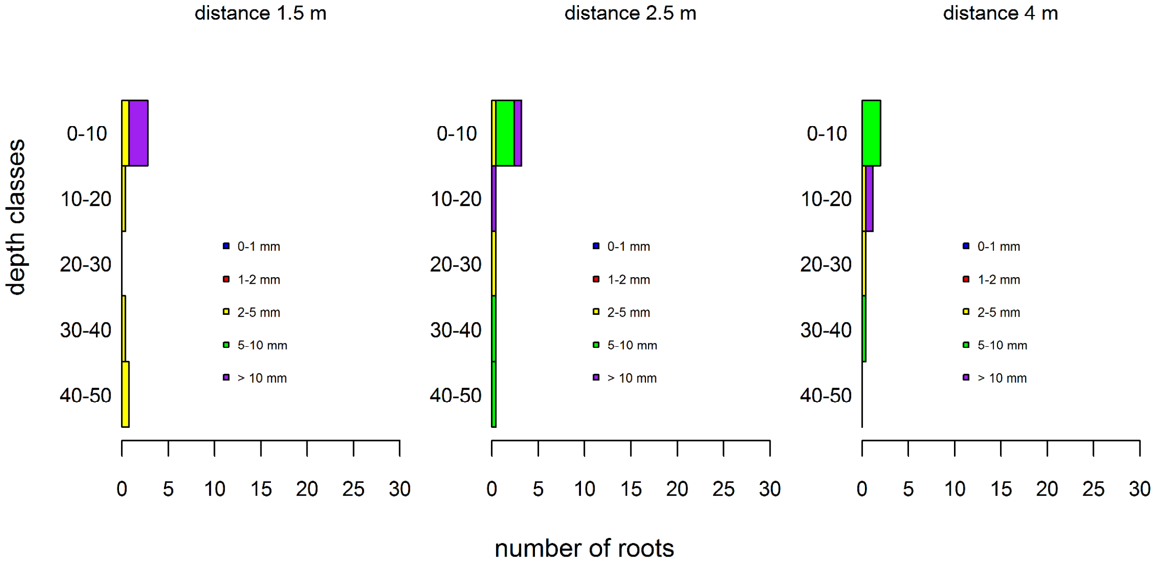

Fig. 3.2.9 Mean root distribution in 10 years gap cutting, considering a square of soil of 1 meter per 1 meter. Total number of roots are: 4 at 1.5 meters, 5 at 2.5 meters, 4 at 4 meters.

Tab. 3.2.3 Number of roots per diameter class in each trench and total number of roots (mean values).

site	distance	total mean number of roots	diameter class	mean n of roots	% on total
undisturbed	1.5	42	0.5-1	12	29
			1-2	7	17
			2-5	14	33
			5-10	5	12
			> 10	4	10
	2.5	21	0.5-1	5	24
			1-2	2	10
			2-5	8	38
			5-10	4	19
			> 10	2	10
	4	49	0.5-1	14	29
			1-2	14	29
			2-5	11	22
			5-10	6	12
			> 10	4	8
5 years old cutting	1.5	23	0.5-1	6	26
			1-2	3	13
			2-5	5	22
			5-10	7	30
			> 10	2	9
	2.5	11	0.5-1	3	27
			1-2	1	9
			2-5	4	36
			5-10	1	9
			> 10	2	18
	4	18	0.5-1	1	6
			1-2	5	28
			2-5	3	17
			5-10	6	33
			> 10	3	17
10 years old cutting	1.5	4	0.5-1	0	0
			1-2	1	25
			2-5	1	25
			5-10	0	0
			> 10	2	50
	2.5	5	0.5-1	0	0
			1-2	0	0

			2-5	1	20
			5-10	3	60
			> 10	1	20
	4	4	0.5-1	0	0
			1-2	0	0
			2-5	1	25
			5-10	2	50
			> 10	1	25
15 years old cutting	1.5	40	0.5-1	23	58
			1-2	10	25
			2-5	7	18
			5-10	0	0
			> 10	0	0

Calibration of root distribution model

Root distribution model was calibrated for the undisturbed forest. The model was not applied to the 5, 10 and 15 years old cutting because the scarce number of roots and the variation in root distribution due to the degradation did not allow its application. Moreover, the model is based on the computing of the fine root biomass (roots of 1 mm diameter) from which the number of the other roots is derived. Applying the model to a situation where the most of the fine roots are degraded makes no sense. Mean branching distance BD was kept constant at 90 mm, as found by Schwarz et al. (2010) in experimental measurements on spruce roots. Then maximum distance coefficient and reduction coefficient were calibrated in order to obtain values of maximum root diameter similar to the maximum root diameter found at the distance of 1.5 m. The distance of 1.5 m was chosen because we have the higher number of sample at this distance (20 trenches) and because it less subjected to the influence of the other plants. To define a realistic value of maximum root diameter all the trenches excavated at 1.5 m were therefore considered, in order to have a consistent number of samples and augment the possibility to find a value close to the reality, considering that bigger roots are not subjected to total degradation in the range of time considered. Maximum root diameter found at 1.5 m was 56.5 mm. Reduction coefficient was imposed to be minor than 1, differently from Schwarz et al., 2012, to give a geometrical meaning to the eq. 3.2.5. Once found a maximum distance coefficient and a reduction coefficient who give back a value of maximum root diameter of 56 mm at 1.5 m, they were kept constant. Maximum distance coefficient was found equal to 16.5 and reduction coefficient is equal to 0.90. Pipe coefficient and the exponent were calibrated on the basis of the position and diameter of the trees in each stand and on the basis of the root distribution sampled, searching the best fitting which minimize the sum of square errors SSE. In the undisturbed forest on a total of 15 roots distribution, 7 were chosen for the calibration and 8 for the validation. Different combination of pits and plants were tested for the calibration (Tab. 3.2.4) and then the validation was carried out on the remaining pits and plants. At the end was chosen the parameters combination which minimize the error in both in the calibration and validation (Tab. 3.2.4). The mean square error obtained in the undisturbed forest is 6 roots in the calibration and 9 roots in the validation. Considering that the mean total number of roots in a pit is 37 roots, the error (root of the mean squared error) is about 6% in the calibration and 12% in the validation. Total mean error is 0.15, showing a medium little overestimation of the number of roots.

Tab. 3.2.4 Values for the model calibration and validation in undisturbed forest and 5 years cutting. The combination of parameters chosen for the undisturbed forest is indicated with *. BD is the distance between two branching points in a roots, red_coeff is the reduction coefficient, µ the pipe coefficient, exp is the exponent for the root diameter distribution; dist_coeff is the maximum distance coefficient; SSE cal and SSE val is the sum of square errors in the calibration and validation set; MSE cal and val is the mean square error in the calibration and validation set.

case	**data set**	**n of data sets**	**BD (m)**	**red_coeff**	**µ**	**exp**	**dist_coeff**	**SSE cal**	**MSE cal**	**SSE val**	**MSE val**
undisturbed forest	combination_pit1	7	0.09	0.9	0.0027	-0.77	16.5	1472	10.51	1422	8.89
	combination_pit2	7	0.09	0.9	0.0027	-0.66	16.5	1175	8.39	1762	11.01
	combination_pit3*	7	0.09	0.9	0.0023	-0.75	16.5	847	6.05	1521	9.51
	combination_plant_1	9	0.09	0.9	0.0023	-0.57	16.5	1776	9.87	1076	8.97
	combination_plant_2	9	0.09	0.9	0.0025	-0.84	16.5	2107	11.71	743	6.19

The parameters of the root distribution model were used for the upscale at the stand level in the undisturbed forest (Fig. 3.2.10 a). The parameters found for the undisturbed forest were then applied also to the stand of the 5, 10 and 15 years cutting to estimate the root distribution of the mature stand before the disturbances (Fig. 3.2.10 a,b,c).

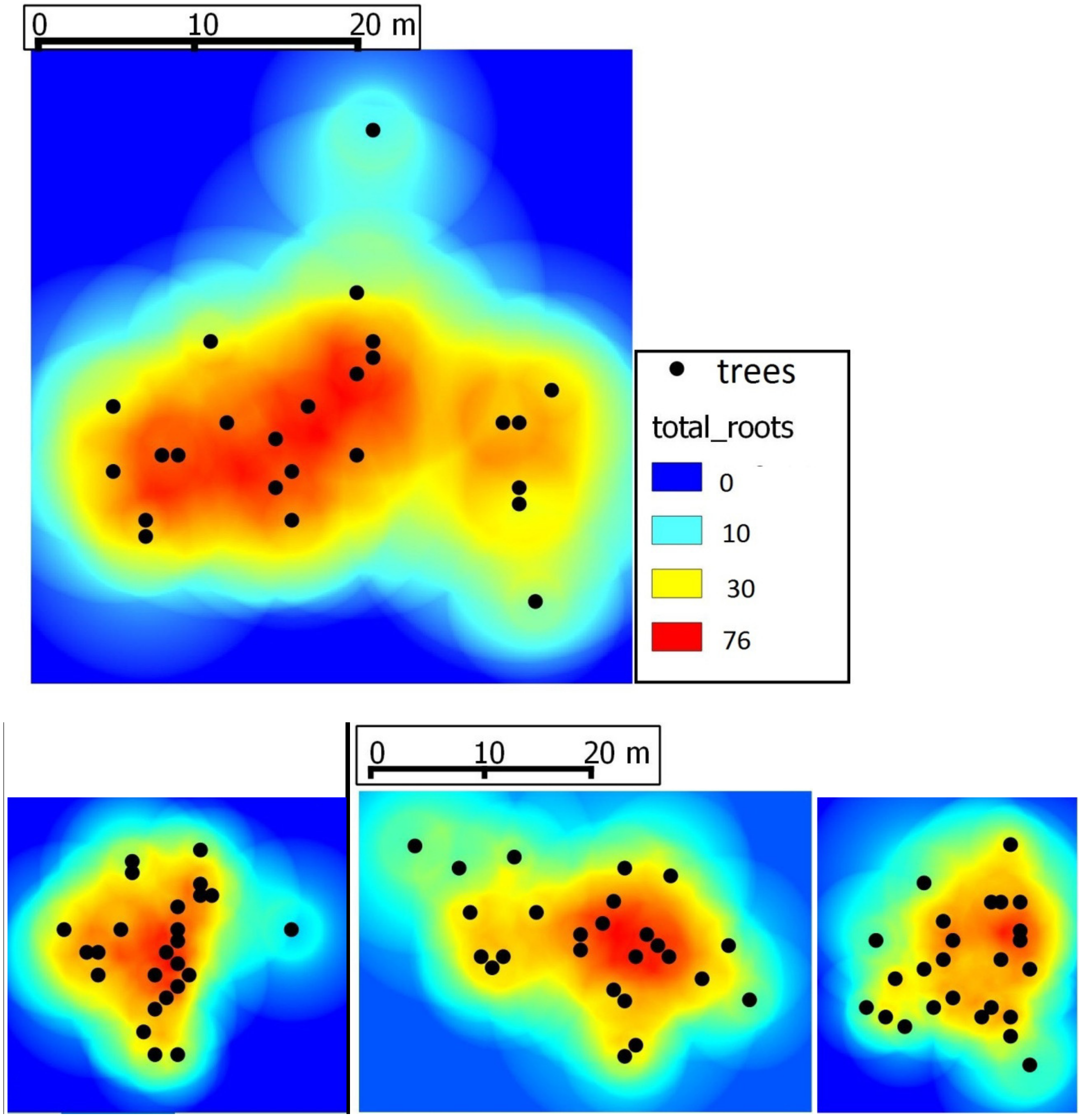

Fig. 3.2.10 Total root distribution (1-20 mm) in the mature forest (A), and simulation of the total root distribution in the 5 , 10 and 15 years old gap before cutting (B, C, D).

Root mechanical properties

A total of 34 valid pull out tests were carried out in the undisturbed forest and 29 in the 5 years old gap cutting. Maximum force-diameter relationships can be approximated to a power law (Fig. 3.2.11 and Tab. 3.2.5) even if the coefficient of determination is low in the case of roots coming from 5 years old cutting. Roots tested range between 2 and 12 mm, roots with diameter higher than 5 mm were privileged in pull out tests because no pull out data are available up to now for roots of this size. Maximum force values range between 63 N and 2540 N for the undisturbed forest, and between 25 N and 1530 N for the five years old gap cutting.

27 tensile tests were carried out with roots coming from the undisturbed forest and 26 with roots coming from the five years old gap cutting. Power law is well confirmed in this case, even if the coefficient of determination for roots coming from 5 years old gap cutting is lower (Fig. 3.2.11 and Tab. 3.2.5). Root tested range between 1 and 6 mm since it was not possible testing bigger roots with the available device due to clamping problems. Maximum root force values range between 11 and 380 N for the undisturbed forest and between 10 and 422 for 5 years old gap cutting.

Power law relationships were transformed in linear relationships through the log transformation of diameter and force, ANCOVA was then applied to compare undisturbed and 5 years cutting conditions and assess if root decay affects root mechanical properties. In both cases, power laws of undisturbed forest and 5 years old cutting result different at the 0.05 level of significance (pull out tests: ANCOVA, $F_{1,60} = 7$, $p = 0.01$; corrected means: 289 N five years rotted roots and 475 N live roots ; tensile tests: ANCOVA, $F_{1,50} = 5.7$, $p = 0.02$; corrected means: 74 N five years rotted roots and 103 N live roots).

Comparing between them tensile test and pull out tests (Fig. 3.2.12) considering just roots under 6 mm in diameters (the maximum diameter that could be tested in laboratory), in the case of undisturbed condition they give different results at the 0.05 level of significance (ANCOVA, $F_{1,42} = 6$, $p = 0.02$) while in the 5 years condition they give not different results (ANCOVA, $F_{1,39} = 1.19$, $p = 0.28$).

Tab. 3.2.5 Coefficients and statistical parameters of the power regressions F-d

case	**technique**	**a**	**b**	**p**	**R^2**	**se**
undisturbed	tensile test	7.38	2.19	< 0.001	0.84	0.38
5 yrs	tensile test	3.34	2.56	< 0.001	0.65	0.64
undisturbed	pull out test	16.91	1.89	< 0.001	0.56	0.63
5 yrs	pull out test	12.80	1.77	< 0.001	0.37	0.86
Regeneration curve	tensile test	15.39	1.78	< 0.001	0.85	0.43

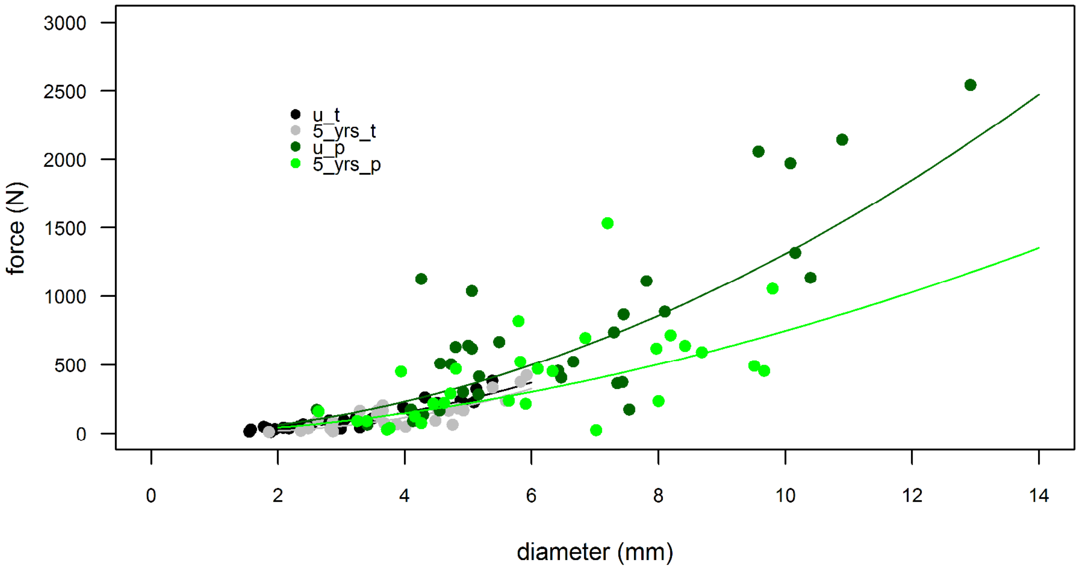

Fig. 3.2.11 Results of tensile tests and pull out tests

Shrub species and natural regeneration mechanical properties were derived from the tensile test carried out in 2012 on the roots of three species sampled in the Lombardy Prealps: *Vaccinium myrtillus, Salix caprea and Rubus aedus*. Single species force diameter power law are shown inFig. 3.2.12. From the three curves we obtained a single general curve that can be considered representative of the shrub and regeneration mechanical properties.

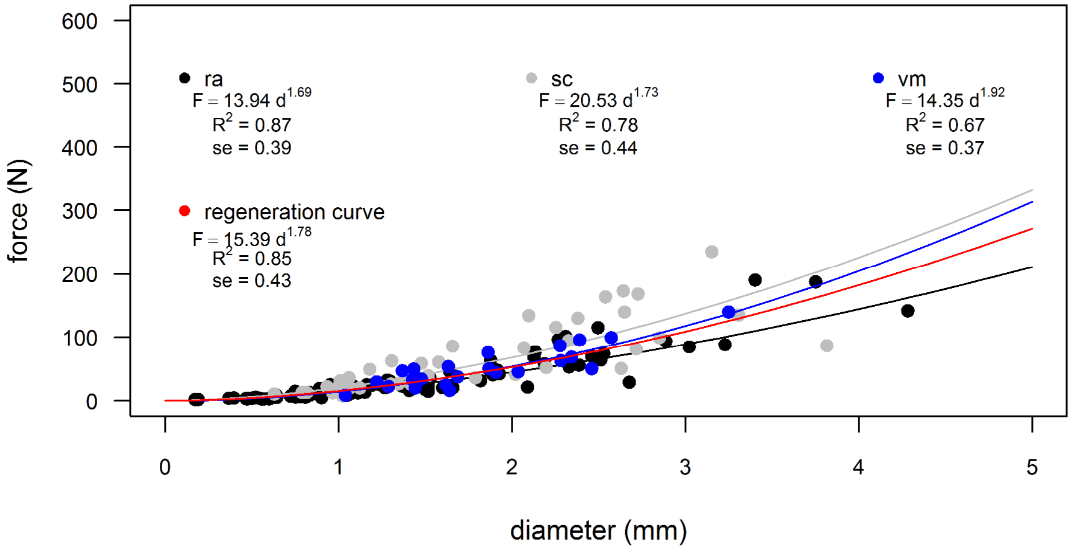

Fig. 3.2.12 Natural re generation power law and general regeneration curve.

Calibration of root decay models

The calibration of root number decay model was carried out for each stand considering just roots comprised between 1 and 10 mm, because the number of bigger roots is too scarce and the randomness in big roots distribution plays a major role, making hard the modeling of root degradation over time. In some cases the number of roots after 5 or 10 years in a certain position is higher than the number of roots at the time zero for the same positions. This happens especially for roots from 5 mm in diameter. In the case of a normalized value N_r/N_{r0} higher than one, the ratio was imposed equal to one because is not realistic an increase in the number of degraded roots during time, but at most we can hypothesize a lack of reduction. The values of the decay coefficient k obtained for each diameter class from the calibration of eq. 3.2.8 are reported in Fig. 3.2.13.

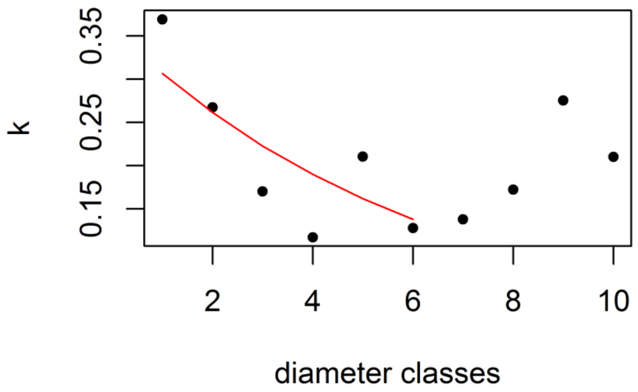

Fig. 3.2.13 Values of the parameter k in function of the diameter classes (mean value, i.e 1=between 0.5 and 1.5)

Values of k are considered reliable just until the class of diameter of 6 mm; in the other classes in fact, the mean number of roots simulated at the time zero is less than one, and as consequence the application of the model is not robust due the randomness in the sampling of big roots. Considering roots until 6 mm in diameter, the trend of the k value in function of the diameter class can be well approximated by an exponential function with a value of R^2 equal to 0.60 (Fig. 3.2.14) :

$$k = z * e^{-w*d} \qquad (3.2.10)$$

Where d is the diameter class, z is equal to 0.37 and w is equal to 0.18. With this function is possible to estimate the values of k of the other diameter classes, and they range between 0.30 for the smaller roots until almost zero for the bigger roots.

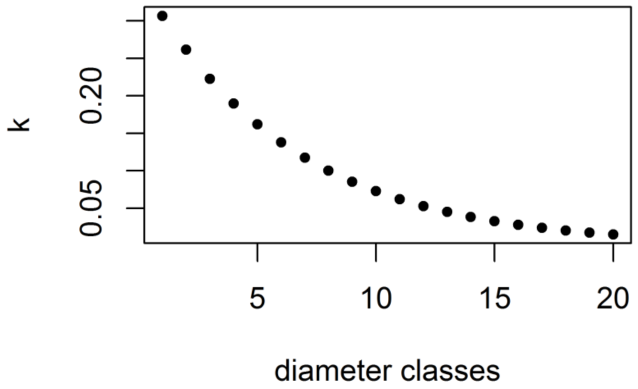

Fig. 3.2.14 Values of the parameter k in function of the diameter class estimated with the exponential law

The estimate of the number of roots for the diameter class between 1 and 10 mm with the equation 3.2.7 has a mean error negative in most cases, showing a slight underestimation of the number of roots at the time t; root mean square error range between 0.55 and 0.08.

Root force decay equation (eq 3.2.9) is calibrated using the power law of the undisturbed forest and the one of the 5 years gap cutting. Coefficient c obtained is equal to 0.11 (Fig. 3.2.5).

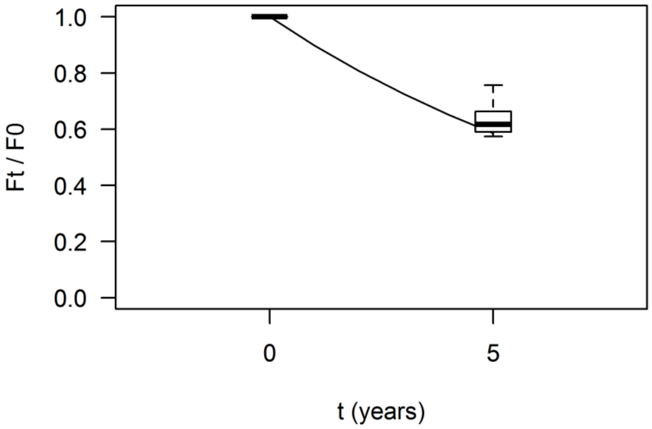

Fig. 3.2.15 Normalized root force values at the time 0 and after 5 years from disturbances and fitted exponential law.

Calibration of RBMw

Power law equations of RBMw were calibrated basing on field or literature data. Force diameter power law adopted for the spruce roots were the ones deriving from pull out tests which give the more realistic results, taking into account root soil interaction; for the roots of the shrub and regeneration species we adopted the general power law curve obtained by tensile test.

Young modulus and root length were estimated using the values proposed by Schwarz et al. (2013). Root length (in meters) for each root diameter class has been estimated through the relationship proposed by Schwarz et al. (2013), based on data of Schwarz et al. (2011), where $\gamma = 0.575$ and $L_0 = 18.5$ (m). Since the quality of field data about the displacement were not reliable due to the difficulty in the correct positioning of the displacement sensors, Young modulus was estimated for both degraded and healthy roots through the relationship proposed by Schwarz et al. (2013), where $E_0=0.248*10^8$ (Pa) and $\beta = -0.3$. Young modulus was proven by Amman et al. (2009) to do not depend on roots state of decay, and this result has been confirmed also by Marcandella (2010). Root tortuosity was set equal to 1 since the equation for the estimation of the secant young modulus was calibrated with data obtained from field experiments that implicitly consider the effect of tortuosity.

The values of the Weibull exponent for each power law curve are calibrated fitting the Weibull Survival function as function of the normalized displacement according to Schwarz et al. (2013). The normalized displacement was calculated as the quotient between the displacement measured by each single tensile test and the corresponding values of displacement obtained using the fitted values of tensile forces fitted by the force-diameter power law function. In each case of study data were ranked according to their normalized displacement Δx_{norm} and the cumulative distribution function of normalized displacement was calculated. Weibull distribution function was then calibrated on data distribution. The obtained exponent values range between 1 and 4 (Tab. 3.2.6).

Tab. 3.2.6 Parameters of the Weibull survival function.

case	exponent	scaling factor
undisturbed pull out test	2.58	1
5 yrs pull out test	1.05	1
Re generation curve	3.96	1

Application of RBMw

RBMw was applied considering roots up to 20 mm in diameter. Figure Fig. 3.2.16 shows RBMw output for undisturbed forest and 5 years old gap cutting considering a mean root distribution for each treatment and distance. In the undisturbed forest the force mobilized by roots ranges between 1685 and 3725 N; in the 5 years gap cutting the force mobilize by roots ranges between 552 and 1797 N. Dead roots reinforcement after five years is lower than the one provided by live roots in a percentage comprised between 40 and 70% depending on the distance considered. Differences are higher (almost 70%) at the distance of 2.5 m from the stem, where the number of roots is lower. Displacement does not differ significantly due to the application of the same Young modulus power law.

RBMw was applied also for the 10 years condition: no force-diameter data were available for this case, so root mechanical properties were derived from the application of the force decay model (eq. 21) and used in combination with root distribution of 10 years old gap. Considering the 15 years condition, no spruce roots were found in the five trenches excavated; the contribution in root reinforement of the natural regeneration was estimated without considering the differences between species and using a general regeneration curve. Fig. 3.2.17 shows RBMw force results for the four analized conditions, considering for each condition all root distributions and all distances (in the case of 15 years old cutting we have just a distance at 1.5 m but it does not matter because only shrub species contribution is considered).. Force median values are 2708 N for undisturbed forest, 1167 N for 5 years old gap cutting, 155 N for 10 years old gap cutting and 726 N for the 15 years old gap cutting. Five years after cutting peak force median values are 43% of the undisturbed forest and ten years after cutting peak force median values are 5% of undisturbed forest. Contribution of shrub species is 27 % of the median peak force value of the undisturbed forest. Variability in root force values in the different position of the stand is higher in undisturbed forest and decreases with time after cutting.

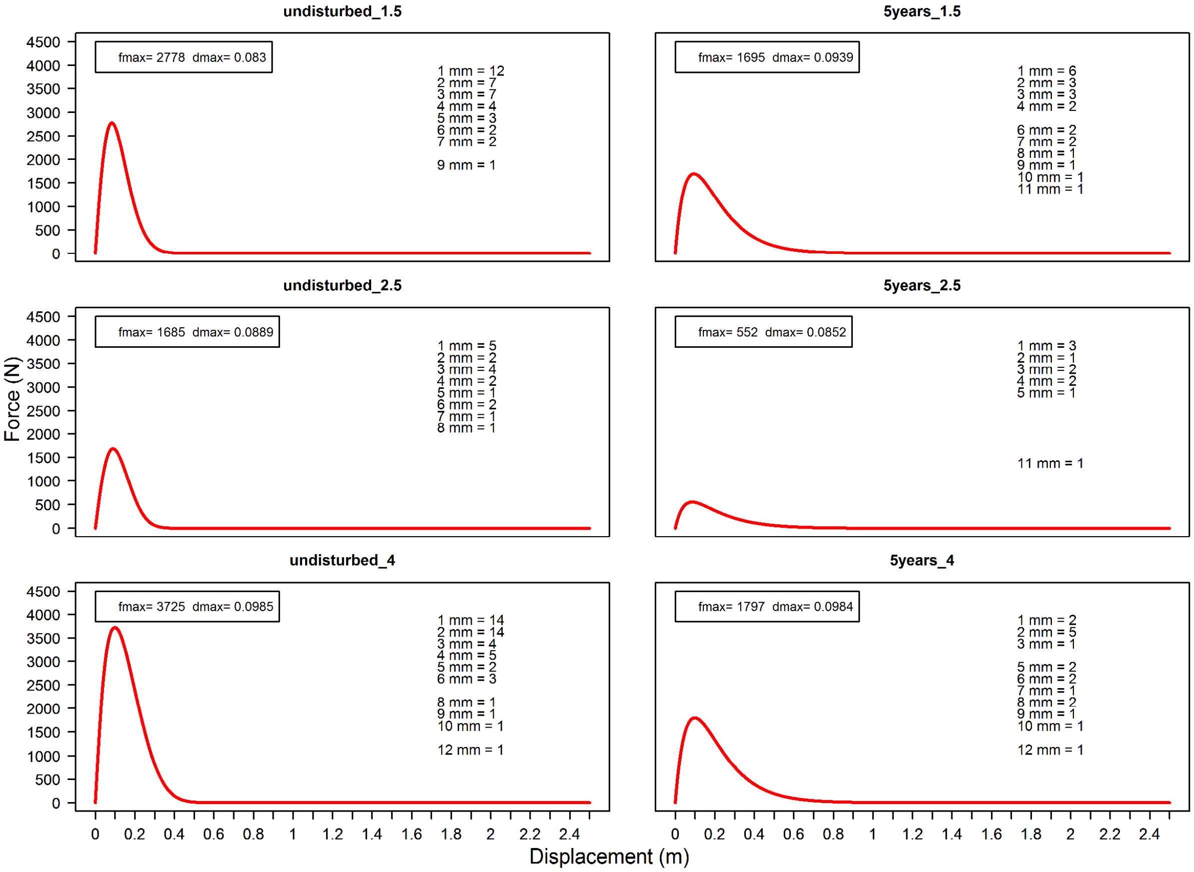

Fig. 3.2.16 output RBMw for undisturbed forest and 5 years old gap cutting, considering a mean root distribution for each distance.

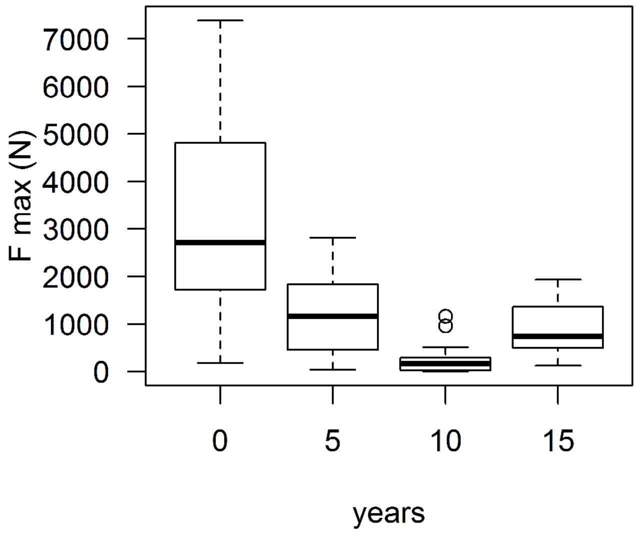

Fig. 3.2.17 Root reinforcement values calculated with RBMw at each time after cutting; all root distributions and all distances are considered for each case.

Further simulations were carried out to assess which component has a major effect on root reinforcement reduction: root number decay or root force decay. Graphics of these simulations are shown in the Appendix D. The first simulation estimated root reinforcement for the undisturbed forest and the 5 years cutting considering in all cases the mean root distribution of undisturbed forests and changing just root force – diameter curve and Weibull coefficient. Five years after cutting root force ranges between 873 and 2031 N. Force values are higher than the ones show in fig 3.2.17 due to the lack of big roots (10,11,12 mm) in root distribution of undisturbed forest. Differences between live roots and rotted roots reinforcement range between 45 and 48%. Similar results are obtained while considering all root distribution of the undisturbed forest with a difference between the median force values of undisturbed forest and 5 years after cutting of 43%. 10 years after cutting (force values in the simulation are estimated with eq. 3.2.9) the median peak force values are about 30% of undisturbed forest. Variability in root force values of 5 and especially 10 years after cutting increases as consequence of the use of root distribution of the undisturbed conditions. Results obtained considering the differences in mean root distribution and keeping constant root mechanical properties (i.e. adopting for all cases undisturbed forest power law and Weibull coefficient) can be so summarized: 5 years after cutting force values increases and in one cases (1.5 meter distance) are higher than undisturbed forest values, due to the use of undisturbed forest power law and to the presence of coarser roots (> 10 mm); they range between 1027 and 3413 N. Differences between live roots and rotted are 40% at 2.5 m of distance, almost 0 at 4 m of distance and rotted roots have higher values of reinforcement (+ 22%) at 1.5 m distance. Considering all root distributions and also the 10 years after cutting case the reduction in median root reinforcement values is 20% 5 years after cutting and 80% 10 years after cutting.

Application of RBMw at the stand scale implementing spatial and temporal variability

Once the decay model and the root distribution model have been calibrated, is it possible to upscale the estimation of root reinforcement at the stand scale showing the variability both in time and space, as shown in Fig. 3.2.18. Maximum pull out force of the bundle of roots in a square of 1mX1m is shown. In figure 3.2.18a is shown the condition of the undisturbed stand at time 0, implementing the model of horizontal root distribution and the force-diameter power law of healthy roots into RBMw. In fig. b,c,d both the root decay model and the root force decay model are applied to evaluate spatial and temporal variability of root reinforcement after 5, 10 and 15 years from cutting.

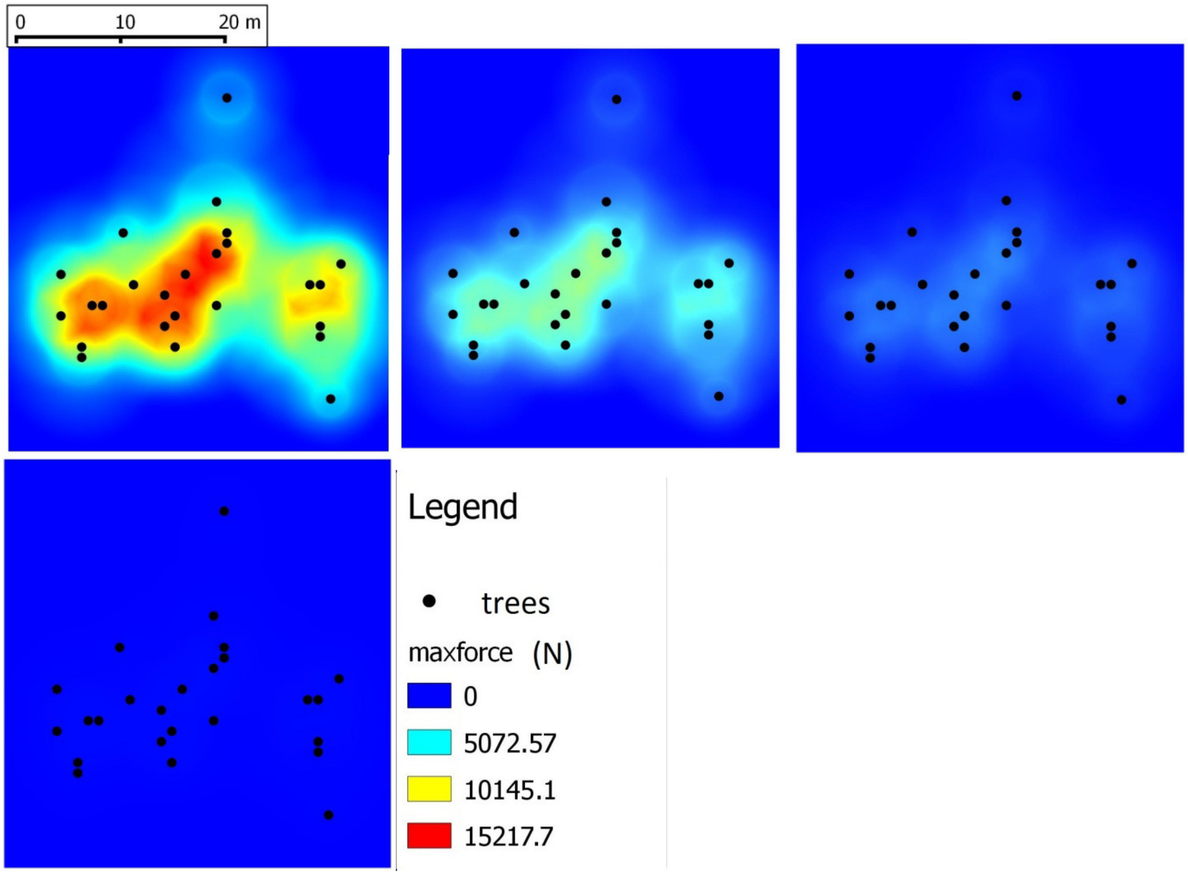

Fig. 3.2.18 Root reinforcement distribution in the undisturbed forest (A), and simulation of the root reinforcement distribution after 5, 10, 15 years from cutting (B,C;D).

3.2.4 Discussion

Root distribution

In undisturbed forest and 5 years gap cutting we observed a superficial root distribution, which is typical for the considered species, and an exponential decrease of the number of roots as the diameter classes increase. A decrease in the number of roots as increasing the distance from the stem can be observed moving from 1.5 m from the stem to 2.5 m from the stem, while at 4 meters from the stem the number of roots increases again. This is due to the overlap with root systems of the neighboring trees, as is typical for forest ecosystems. Five years after cutting there is a reduction of about 50% in the total number of roots, but the decrease concern just roots with diameter less than 5 millimeters. In 10 years after cutting root number decrease becomes severe and doesn't allowed to appreciate the trend with depth and distance from the stem. No roots under 2 mm in diameter were found, and roots remaining are between 24 and 10% of the number of roots in the undisturbed forest.

Few experimental data (Burroughs and Thomas 1977; Schmidt et al., 2001; Vergani et al., 2013) are available in literature concerning the decay of the number of roots and the change in root distribution after tree felling. Schmidt et al. (2001) measured root density in terms of root area ratio in clear cuts until eleven years old and found that total root density was similar to the natural forests; however, considering just live roots found a significant decrease. Basing on our data, we observed a dramatic decrease of spruce fir root after 10 years from cutting (between 80 and 90% of decrease compared with undisturbed forest) and almost no spruce fir roots after 15 years from cutting. In the five pits excavated 15 years from cutting we found just two "old" spruce roots of 57 and 37 mm, in an advanced state of decay. In both 10 years and 15 years gap there was a well-established natural regeneration, constituted mainly of pioneer species. In the five pits in the15 years old cutting the roots of pioneer and brushwood species were counted (without distinguish between species) to have an idea of the contribution of the new-established vegetation to root reinforcement. Mean total number of roots of the regeneration species is equal to the mean number of live spruce roots in the undisturbed forest, in agreement with the observation of Schmidt et al.2001. It is important to note that root diameter distribution radically change: there are no roots higher than 5 mm and almost 60% of the roots is comprised between 0.5 and 1 mm. This is supposed to have an impact on root reinforcement values. Our values of root number of roots in diameter class are comparable with the one reported by Schwarz et al., (2010b) for Norway spruce.

Burroughs and Thomas reported a number of roots (from 0 to 10 mm in diameter) per square meter of soil comprised between 80 and 110 in the undisturbed forest for Coast Douglas Firs and between

70 and 100 for Rocky Mountain Douglas Fir. The obtained results are considerably lower, even if the methodology adopted (manually counting the roots) is the same. Vergani et al., 2013, found for a mixed forest of Norway Spruce-Silver Fir 635 0-10 mm roots per square meter of soil, number that falls to 350 if roots with diameter less than 0.5 mm are not considered. This huge difference can be ascribed at two kind of factors: the methodology adopted (the technique of image analysis instead of the manual counting) and the different root system of Silver fir and Norway spruce combined with the different depth of trenches (1 m instead of 50 cm). Image analysis could lead to an overestimation of the number of roots due to the complexity in clearly identifying fine roots and distinguish them from the ones of the understory vegetation; silver fir has a deeper root system that can determine a higher number of roots in the deeper layers. Anyway, root distribution reflect both biological mechanisms and environmental factors and besides varying between vegetation communities is spatially variable over distances of only meters (Schmidt et al., 2001) so high variability in root distribution patterns between different sites and species is not surprising. Concerning number of roots decay rate, based on extrapolation of their experimental data Burroughs and Thomas found no roots about 16 years after felling in the case of Coast Douglas Fir and 22 years after felling in the case of Rocky Mountains Douglas Fir. Five years after felling roots are slightly more than 10% of undisturbed forest in the first case and 33% in the second case; 10 years after felling are 10% and 20% of undisturbed forest. Our values show a less severe decay in the first 5 years, but similar results at 10 years and 15 years after felling.

Root distribution model

Root distribution model estimates the number of roots in the tree stand with an error comprised between 6 and 12%. Schwarz et al. (2012) found for a spruce stand at Rudlingen, CH, a value of pipe coefficient of 0.09 and an exponent of -1, while for a spruce stand at Uetliberg, CH, values of reduction coefficient of 2.8. Our values of exponent are comparable, while pipe coefficient value is more than one order of magnitude inferior. Maximum distance coefficient is comparable with the one proposed by Schwarz 2012 (18.5). Greatly different is the reduction coefficient, because we imposed a reduction coefficient inferior than one, to give geometrical meaning to the equation 3.2.5.

Root mechanical properties

Maximum root tensile force values obtained by pull out tests in the undisturbed forests range from 63 and 2540 N for roots comprised between 2 and 12 mm. Up to now the only other data available derived by field pull out test are those of Schwarz, (2010), obtained from spruce roots at Uetliberg, CH. In this case the maximum diameter tested was 3.7 millimeters. For a 3 mm roots Uetliberg curve gives a maximum pull out force of 91 N against the 135 N of Einsiedeln. If we consider a 10 mm root, extrapolating values form Uetliberg curve we obtain a force of 1164 N against the 1312 N given by the Einsiedeln curve. Extrapolating the force value for a 10 mm for the Einsiedeln curve limited to 5 mm roots, would lead values of 1600 N, leading to a consistent overestimation of root force. Also considering laboratory tensile test there are few data regarding roots higher than 10 mm. Gallotta (1999) found for different Mediterranean species (*Prunus mahaleb and Pyrus pyraster)* values of force of about 980 N; Ziemer and Swanston (1977) found for 10 mm roots of Sitka spruce values of about 1000 N, comparable with our data. Our data prove that 10 mm roots and higher provide high values of force and are therefore critical for root reinforcement, and are worth of some more experimental measurements.

Pull out tests give values of force significantly higher than tensile tests in the case of the undisturbed forest, while no difference can be detected if we consider degraded roots. The highest values obtained for undisturbed roots in the pull out test can be ascribed to the root-soil friction and the interaction between linked roots which increase the measured strength at rupture; in the case of degraded roots this does not happen because roots interaction are weaker. Hales et al. 2013 found that moisture content affect significantly root strength; laboratory tested roots were conserved in a 15% alcohol solution so their moisture content was surely higher than field tested roots; but this doesn't seem to be the reason for the difference between live roots because is not confirmed in the case of rotted roots.

5 years degraded roots are significantly weaker than alive roots, considering both pull out and tensile tests. Corrected means of force values are about 30% inferior in 5 years degraded roots if we consider tensile test and 40% less if we consider pull out tests. Our values of root force decay fall between the range of values found by similar studies on spruce (Amman et al., 2009; Marcandella, 2010) Marcandella, (2010) found higher rate of root force decrease, with 5 years degraded roots having values of tensile strength about 60% inferior than 3 years degraded roots. On the other hand Amman et al., (2009) found a decrease of about 40% in tensile strength of roots after 8 years from cutting. The fitting of the power law curve significantly gets worse in 5 yrs case, due to an higher dispersion of data: the variability of root force values inside the same diameter class increases, because there are roots at different stages of degradation. This was found also by Vergani et al. for 3 years degraded silver fir roots and by Marcandella, (2010) for degraded spruce fir roots collected in the basin adjacent the study area. Weibull coefficient is an index which take into account this variability, and significantly decrease in the case of 5 years pull out test. The use of this coefficient

is therefore important when modeling the mechanical behavior of rotted roots to take into account variability inside diameter class.

Comparing force values obtained by tensile test with the results obtained by Vergani et al (2013) on silver fir roots, live roots of spruce are significantly stonger than live silver fir roots; 5 years degraded roots are significantly stronger than 3 and 2 years degraded silver fir roots. Live spruce roots force values obtained in this study are in the range of the values obtained by live spruce roots from different sites in the Italian alps (Vergani et al., 2012) .

Root decay model

Due to the huge variability that characterizes the distribution of root systems, it is important to build up models that can be applied also outside of the environment where they have been developed. To address this issue, the interpretation of the meaning of the parameters is essential. Up to now different model have been proposed in literature to estimate root reinforcement decay, from the pioneering one of Burroughs and Thomas on root cohesion (1977) to the one proposed by Preti on root tensile strength (2012). The most used is the one proposed by Sidle (1991,1992) which simulates directly the root cohesion values; this type of model is simple (just two parameters) and extremely efficient for the species and environment where it has been developed, but it is hardly applicable to other situations due to the lack of interpretation of the meaning of the parameters. This is the reason why we simulate separately the two processes involved in root decay, in order to allow a better interpretation of the parameters. The model of the decay of the number of roots is based on one parameters *k* which is a function of root diameter. On the basis of our data, we found that *k* depends on root diameter class following a decreasing exponential law. Different studies observed a slower rate of decay in the bigger roots, due to different factors: the lower leaching of the water soluble components (Fahey et al., 1988), the much time needed to the fungi penetration (Foster and Lang, 1982; Berg, 1984), the presence of a major percentage of structural components and resistant materials in the roots of high diameter (Fitter, 1985). Some authors affirm that the later degradation of fine roots is due to an higher concentration of nutrients, to a lower ratio nitrogen/lignin (Berg, 1984; Camirè et al., 1991) and to a lower lignin content (Silver and Miya, 2001). The root mean square error obtained by the model is always lower than one root in each diameter class, showing a certain reliability of the model itself. The model has to be validated using other data regarding spruce and other tree species to assess his reliability and to seek an interpretation of the parameters that allow its generalization.

Concerning root force decay model, an exponential function have been chosen instead of the linear function proposed by Preti (2012). Our model has been calibrated just on the force at the time of 5 years, but it fits better literature data on spruce (Ammann 2009, Marcandella, 2010) than a linear function. In Fig. 3.2.19 are shown the value of tensile strength derived from the force values calculated with eq. 21 (A) and with the linear model proposed by Preti (2012) (B) in comparison with other literature data on the same species. Applying a linear law would lead to a significant underestimation of force for the higher time of degradation; moreover it would lead to value of force negative from 12.5 years, which has not physical meaning and it is contrast with the findings of Marcandella 2010 who observed a slowing down of the degradation process after 10 years from disturbances, founding not significant differences between degraded and severely degraded roots. Moreover, applying an exponential function satisfy the condition: $\lim_{t\to+\infty} F_t(t) = 0$, while the linear function is conceptually less convincing, with force tending to minus infinite for high values of time.

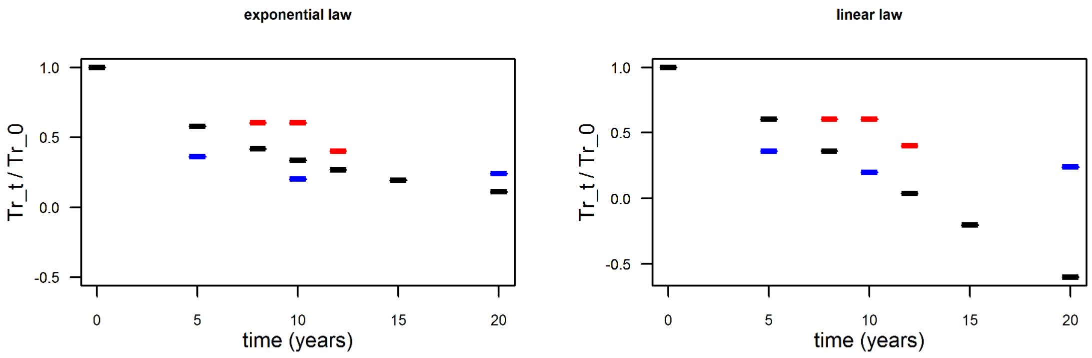

Fig. 3.2.19 A normalized value of Tr estimated on the basis of the proposed exponential law (black) in comparison with the value observed by Ammann, 2009 (red) and Marcandella 2010 (blue); B same comparison, this time with values of Tr estimated with a linear law as suggested by Preti, 2012.

Applying the same model of root force decay to the data of silver fir sampled in the southern part of the Alps (Lombardy, Vergani et al., 2013) for two different sample site with similar altitude, aspect and pedological conditions we obtain a coefficient of decay of 0.20 and 0.35, showing an higher degradation in root mechanical properties, probably due to the climatic factor, even if further research is needed to address this issue.

Application of RBMw

Using the previously discussed data to compute root reinforcement, we obtained that after 5 years from cutting we have a reduction of reinforcement comprised between 40 and 70 % (median values). After 10 years from cutting we have a reduction in the reinforcement of about 90%, while we have no reinforcement at all provided by spruce fir roots 15 years after cutting.

We carried out a sort of sensitivity analysis to evaluate which component has the major role in root reinforcement reduction, if the root strength decay or root number decay. The results suggest that 5 years after cutting the decay in root reinforcement can be mainly attributed to root force decay, while root distribution doesn't play a critical role. We don't have data regarding root mechanical properties after 10 years of cutting and we estimated it through the root force decay model. Basing on Marcandella (2010) findings, who did not find any difference between degraded and severely degraded roots, and basing on our data regarding root distribution, we can say that after 10 years from cutting the reduction in the number of roots has a predominant role in root reinforcement decay. The reduction in the number of roots is therefore critical in estimating the root reinforcement after cutting. For instance, Marcandella, (2010) found that after 20 years of cutting degraded roots can still have 54% of the strength of live roots; after 15 years however we almost did not find roots of Norway spruce, so root number decay has to be taken into consideration for a reliable estimation of root reinforcement. If no roots of cut Norway spruce have been found, on the other hand a big amount of natural renovation and shrub species have been observed, especially in 10 and 15 years gaps. The contribution of natural regeneration 15 years after cutting is 27% of the contribution of the undisturbed forest: the role of renovation and shrub species is worth to be taken into consideration in root reinforcement estimation.

3.2.5 Conclusive remarks

Considering mean values of reinforcement in the stand, the protection effect against shallow landslides of a spruce forest in the the study area is about 40% of the undisturbed condition after 5 years from cutting, and completely vanish after 15 years. The role of shrub species and natural regeneration is important because it can guarantee almost 30% of the root reinforcement of an undisturbed forest after 15 years from cutting. The reinforcement provided by natural regeneration is therefore worth of further research considering in particular woody regeneration species like *Picea abies* itself, pioneer and ecologically interesting species as *Betula pendula*, *Sorbus aucuparia, Acer pseudoplatanus*.

Root reinforcement is not homogeneous along the stand, but there are weaker point. The use of a root distribution model is mandatory to correctly understand root reinforcement spatial dynamics, and its use coupled with a decay model for both the number and the force of roots allows to upscale root reinforcement temporal and spatial dynamics at the stand scale, which is important for stability analisys.

3.2.6 References

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4 Conclusions, limitations of the study and outlook for future research

The present work focuses on the quantification of the variability of root reinforcement both at the spatial and temporal scale.

After a review of the role of forests against shallow landslides and the methods for root reinforcement estimation, the second part of the work deals with the spatial variability of root reinforcement as consequence of the variability of root force and root distributions measured in several sites of Alps.

Investigation on root tensile force of six different alpine species, both broadleaves and conifers (chapter 2.1), have shown that root tensile resistance differs significantly among species, but also within the same species, with a great variability. No single environmental factors have been found to explain significantly such variability, whereas it can be interpreted through the Forest District approach, which includes in a holistic and ecological perspective the driving factors for trees' growth and development. This approach may represent the appropriate balance between a macro- and a micro interpretation of the environmental factors that affect root resistance variability. If it will be confirmed by further studies, such an approach will lead to consider averaged force (or stress)–diameter relationships valid for larger areas and facilitate the use of additional cohesion into hillslope stability models. It will be important to test this hypothesis in a wider geographical range, involving all the Alpine chain and not only the Lombardy side of the Alps, as was done in this study.

The effect of both tensile force variability and root distribution variability on root reinforcement, which requires a huge quantity of data, has been quantified for a single species, *Picea abies*. Such species was selected because is very common in the Alpine region. The study based on a wide dataset of measured root distribution and root mechanical properties (chapter 2.2). To estimate root reinforcement the Root Bundle Model was adopted, as it seems to overcome some criticism involved in the previously proposed models. Results show that root reinforcement estimation varies hugely also in the same site as consequence of root distribution variability. Such variability results in some cases higher within the same stand than between different stands, indicating the relevance of forest structure and small scale topography, in comparison to regional factors at larger spatial scales. Small scale variability of root distribution and its effects on root reinforcement estimation underlines the importance of modeling horizontal root distribution at the forest stand scale. Although the aim of this study was not to investigat the differences in root distribution and as consequence in root reinforcement between different sites, it is important to underline that the considered data were obtained by different sampling methods. Future researches should consider this issue, especially to allow a more reliable comparison between different literature data.

The obtained results show the dominant role of root diameter distribution in influencing root reinforcement model's output, but, in contrast with other works, differences in root diameter-force functions are still important and can't be ignored. A site-specific characterization of mechanical properties and of roots distribution are fundamental for the quantification of root reinforcement at the stand scale. An error of the order of 30% in the estimation of peak pullout forces of a bundle of roots could derive from the application of a not site-specific root diameter-force function, and up to 60% due to the variability of root distribution within the same forest stand. Forest district force-diameter curves, proposed in chapter 2.1, could be a good compromise between the need of a reliable estimation of root force values and the need of a razionalization of the data collecting activity, which is demanding and time consuming. Further studies on the variability of root mechanical properties and root distribution must be considered fundamental for the characterisation of root reinforcement in different sites and for different tree species. Moreover, the study emphatizes the lack of data of the pullout forces of roots with diameter larger than 5 mm, which results to play a major role in root bundle where coarse roots are present.

In the third part of the work the effect of forest management strategies on root reinforcement is addressed, considering two cases of study in the alpine area.

In chapter 3.1 new and comprehensive data concerning the deterioration of roots and its consequence in terms of additional cohesion are presented for a three-year period after felling in two Silver Fir-Norway Spruce stands in the Italian Alps. Tensile strength of roots sampled after tree cutting, in terms of rupture force, was proven to be related to root diameter by a power law relationship as in the case of live roots. The force values, however, showed an increasing spread with time from cutting as consequence of the contemporary presence of decomposed and healthy roots. In the considered cases root deterioration did not affect root strength for the first two years, whereas the reduction became statistically significant at the third year in one case and after two years in the other case. Root density reduction, becomes important three years after cutting, even if interest only fine roots. The root degradation process due to bacteria and fungi is not uniform, and root degradation has been showed to decrease more rapidly in the shallower layer and for thinner roots, again accordingly to literature on decay studies. Root reinforcement, being a combination of root strength and root diameter distribution, starts to reduce as consequence of root degradation between two and three years after cutting. Variability in root distribution inside the same stand is high and hides the effect of the degradation especially in the first years after cutting. In the studies concerning root degradation it is important to consider the spatial root distribution as function of the distance from the stem and the diameter of the stem, using a model to assess root distribution. The use of a model it is also important because it allows to upscale root distribution and root reinforcement from the tree to the stand and eventually to the slope scale.

This problem is faced in chapter 3.2, in a case of study in Swiss Alps, by adopting a spatial model of root distribution. The larger time span analyzed, in comparison with Italian cases, allows the calibration of a root number and root force decay model. The results show that the protection effect against shallow landslides of a spruce forest in the climatic conditions of the study area is about 50% of a mature forest after 5 years from cutting, and completely vanishes after 15 years. The role of shrub and natural regeneration is important because it can guarantee almost 30% of the root reinforcement of a mature forest after 15 years from cutting. In this study just a rough estimate of natural regeneration contribution is furnished; new and comprehensive studies will be important to better quantify the role of the different regeneration species and to give practical indications to forest managers regarding the best practice to improve slope stability. Root reinforcement is not homogeneous along the stand, but there are weaker points: the use of a root distribution model is therefore mandatory to understand root reinforcement spatial dynamics in the study on root degradation. The adopted model need to be tested and validate on other data which involve also other species, to allow some consideration on the parameters meaning and range of variations. In the same way both the proposed root force and root number decay model need a validation procedure on the basis of new data to assess their validity and analyze the variability of the parameters in order to better understand the factors which driven root reinforcement decay.

Appendix A: Root distributions of section 2.2

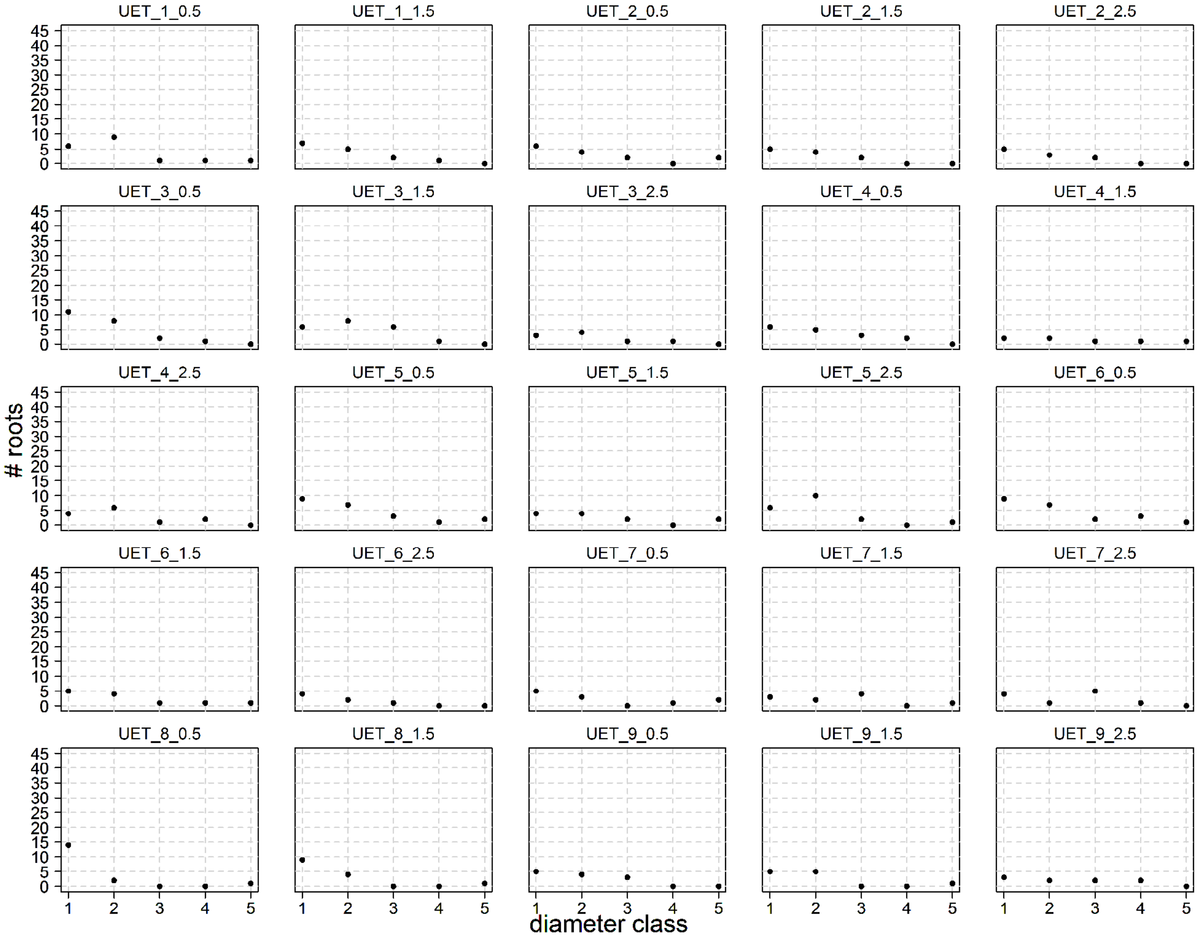

Fig. A 1 Root distribution in Uetliberg sample site.

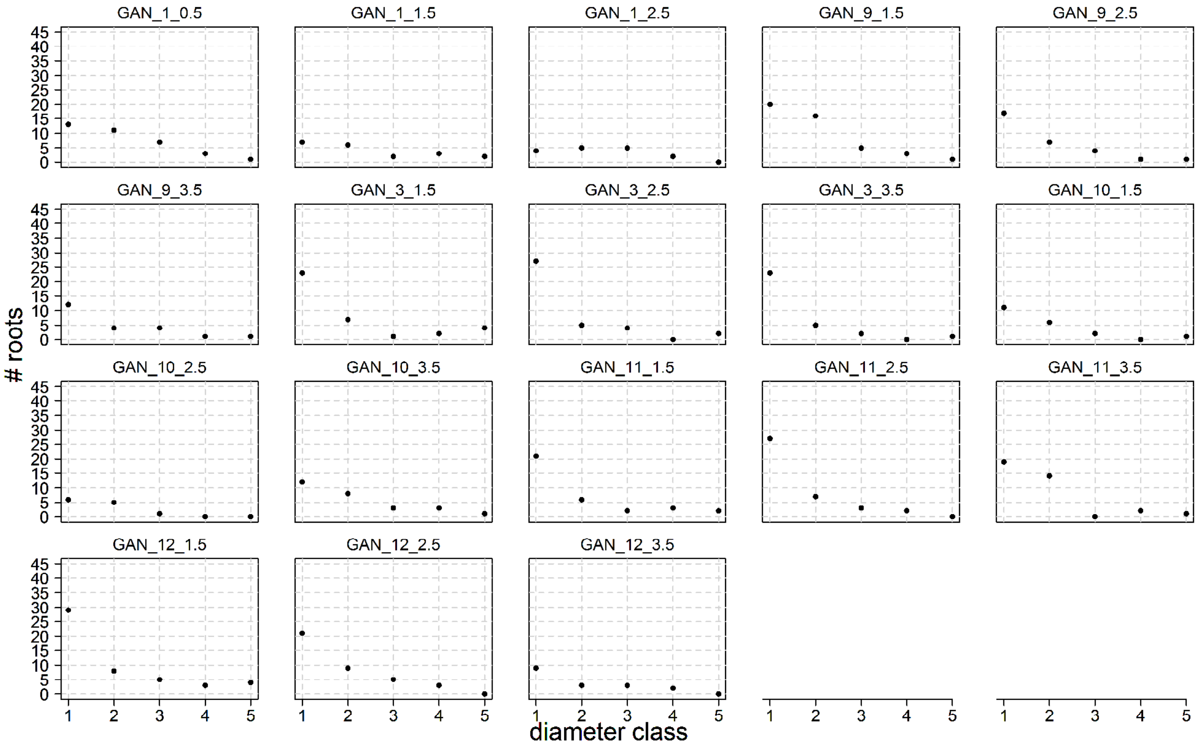

Fig. A 2 Root distrubution in Gantrisch sample site.

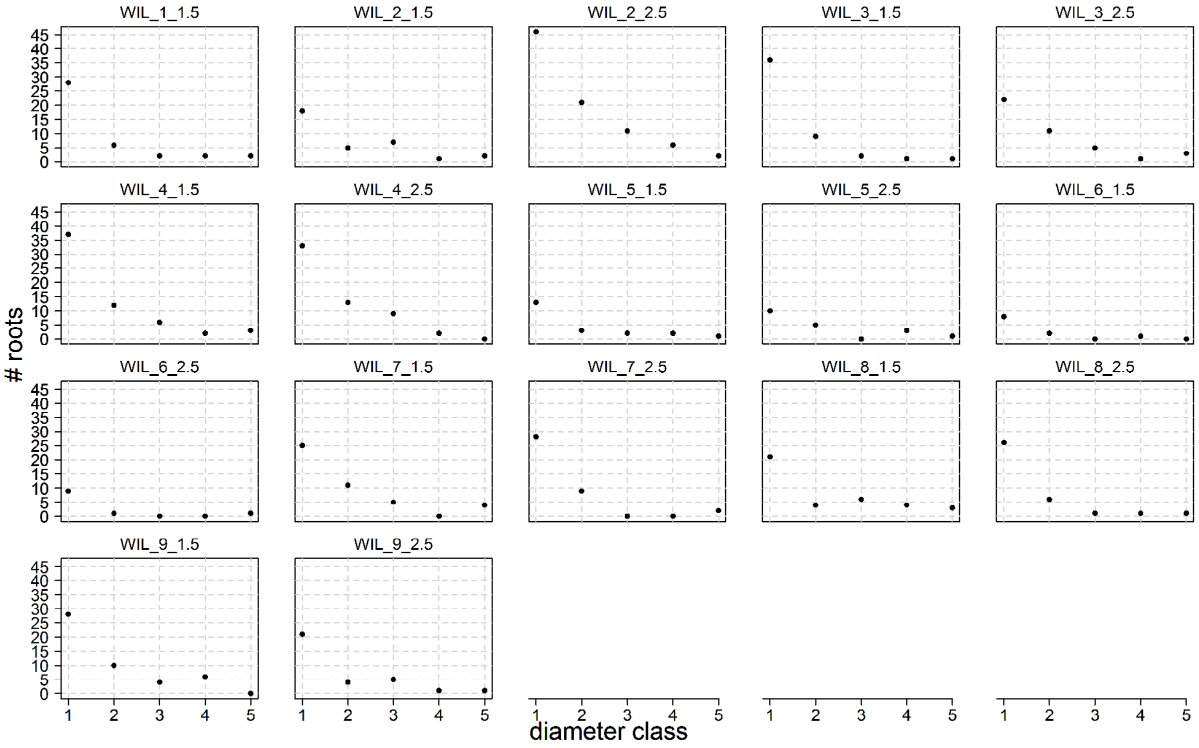

Fig. A 3 Root distribution in Wiler sample site.

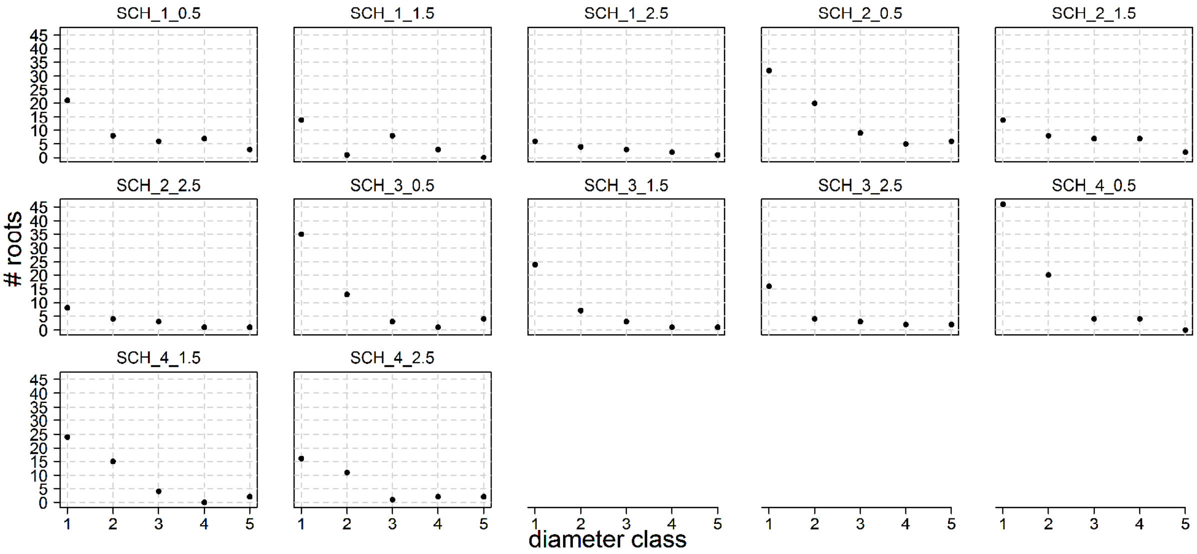

Fig. A 4 Root distributions in Schangnau sample site.

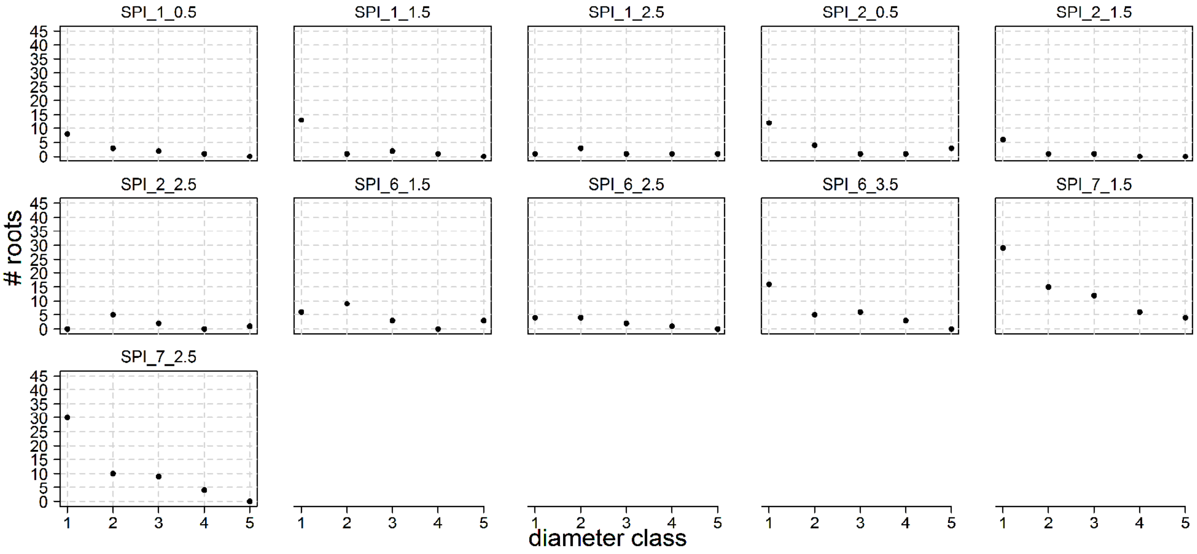

Fig. A 5 Root distributions in Spisibach sample site.

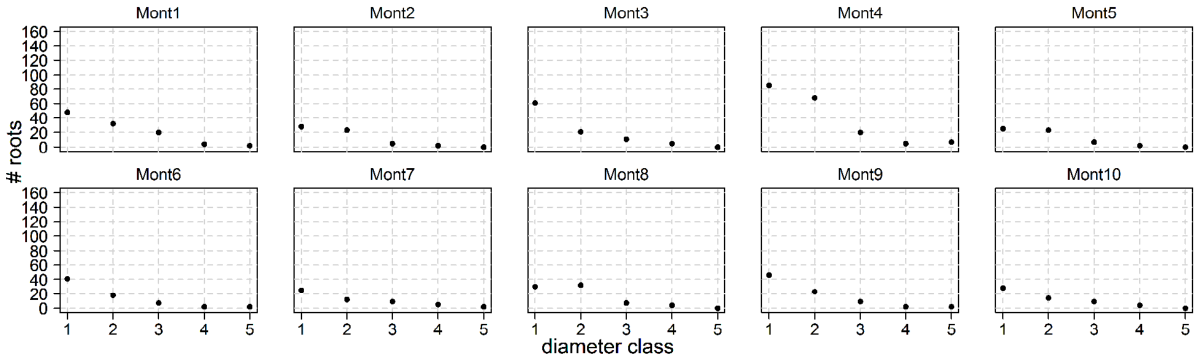

Fig. A 6 Root distribution in Monte Pora sample site.

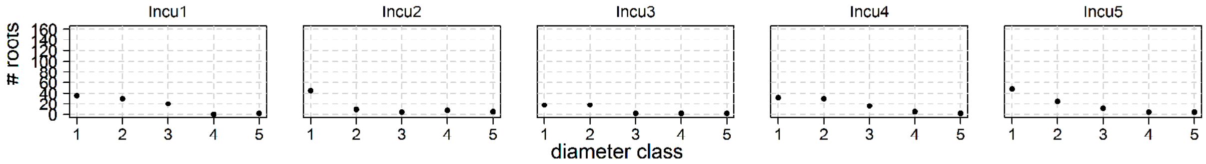

Fig. A 7 Root distribution in Incudine sample site.

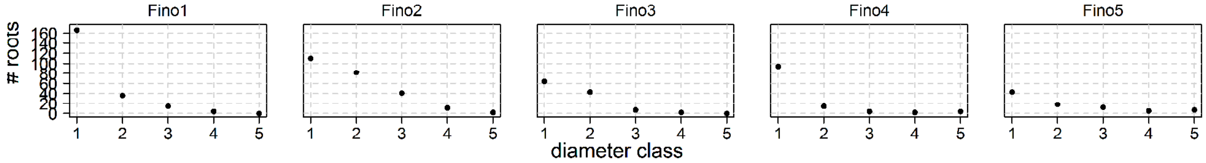

Fig. A 8 Root distribution in Fino sample site.

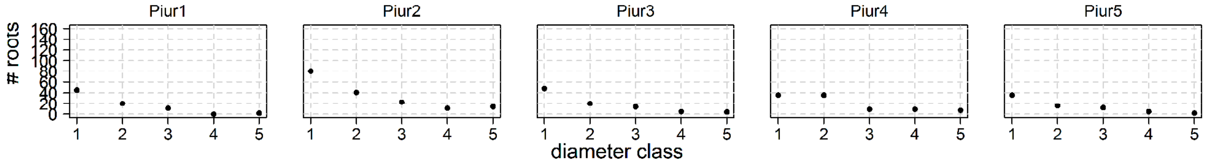

Fig. A 9 Root distribution in Piuro sample site.

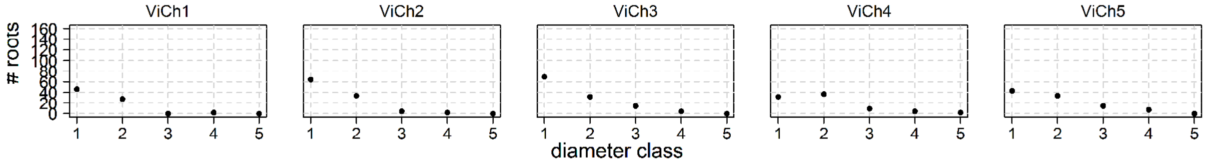

Fig. A 10 Root distribution in Villadichiavenna sample site.

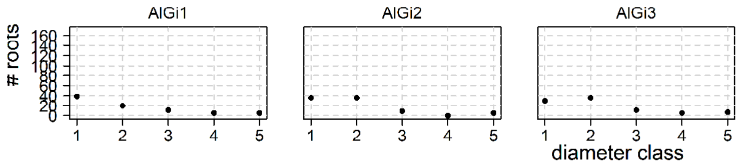

Fig. A 11 Root distribution in Alpe Gigiai sample site.

Tab. 3.2.1 Number and diameter of trees considered in Swiss sample sites.

site	tree	diameter (cm)
Uet	1	22
	2	30
	3	31
	4	21
	5	29
	6	25
	7	39
	8	27
	9	26
Wil	1	22
	2	32
	3	15
	4	21
	5	29
	6	25
	7	39
	8	27
	9	26
Sch	1	37
	2	22
	3	20

	4	37
Spi	1	27
	2	18
	3	45
	4	50
Gan	1	14
	2	19
	3	40
	4	49
	5	34
	6	45

Appendix B: Study sites of section 3.1

Fig. B 12 Undisturbed forest in Averara study site and excavated trench .

Fig. B 13 Example of applied frame and corresponding rectified picture, trench in undisturbed forest, Averara.

Fig. B 14 gap cutting in Averara study site 6 months after cutting

Fig. B 15 excavated trench in Averara gap 6 months after cutting

Fig. B 16 Averara gap 1 year after cutting and excavated trench.

Fig. B 17 Averara gap 2 years after cutting and excavated trench.

Fig. B 18 Partially degraded roots in Averara gap 2 years after cutting.

Fig. B 19 Undisturbed forest in Cusio study site and excavated trench

Fig. B 20 Gap cutting in Cusio study site one year after cutting

Fig. B 21 Excavated trench in the gap in Cusio 1 year after cutting and example of frame applied to the soil profile.

Fig. B 22 Gap in Cusio 2 years after cutting and excavated trench.

Fig. B 23 Gap in Cusio 3 years after cutting and excavated trench.

Fig. B 24 Partially degraded roots in Cusio gap after 3 years from cutting.

Appendix C: study sites of section 3.2

Fig. C 1 Slopes in the Obergross catchment

Fig. C 2 10 years old cutting and the adjacent undisturbed stand

Fig. C 3 excavated trenches in 10 years old gap and in the undisturbed forest

Fig. C 4 10 years old cutting and an excavated trench

Appendix D: RBMw Simulations of section 3.2

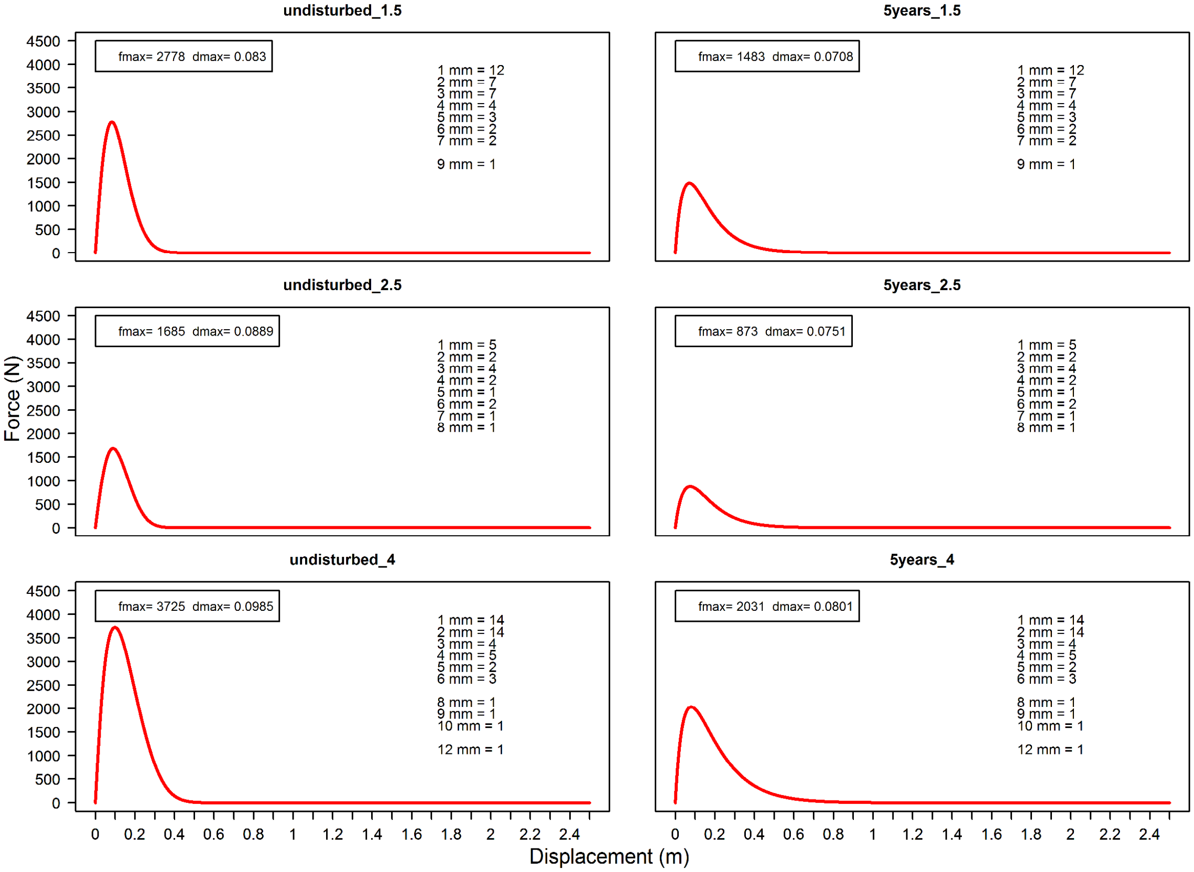

Fig. D 1 Output RBMw for undisturbed forest and 5 years old gap cutting, considering in all cases the mean root distribution of the undisturbed forest and changing just root mechanical properties (i.e weibull coefficient and root force power law).

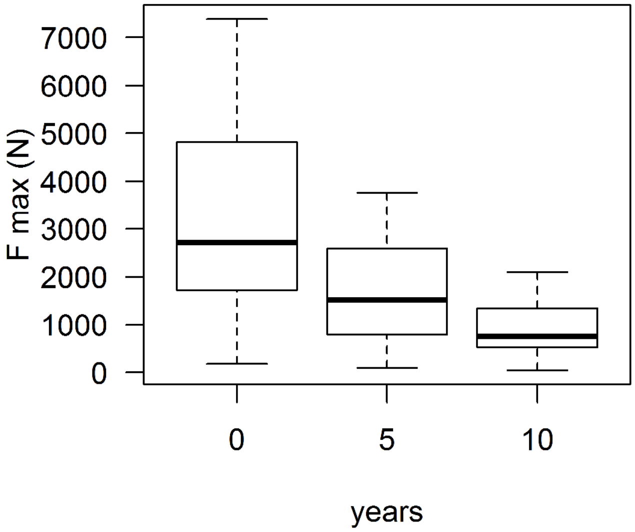

Fig. D 2 Root reinforcement values calculated with RBMw at each time after cutting considering in any case all root distributions of the undisturbed forest and changing just mechanical properties.

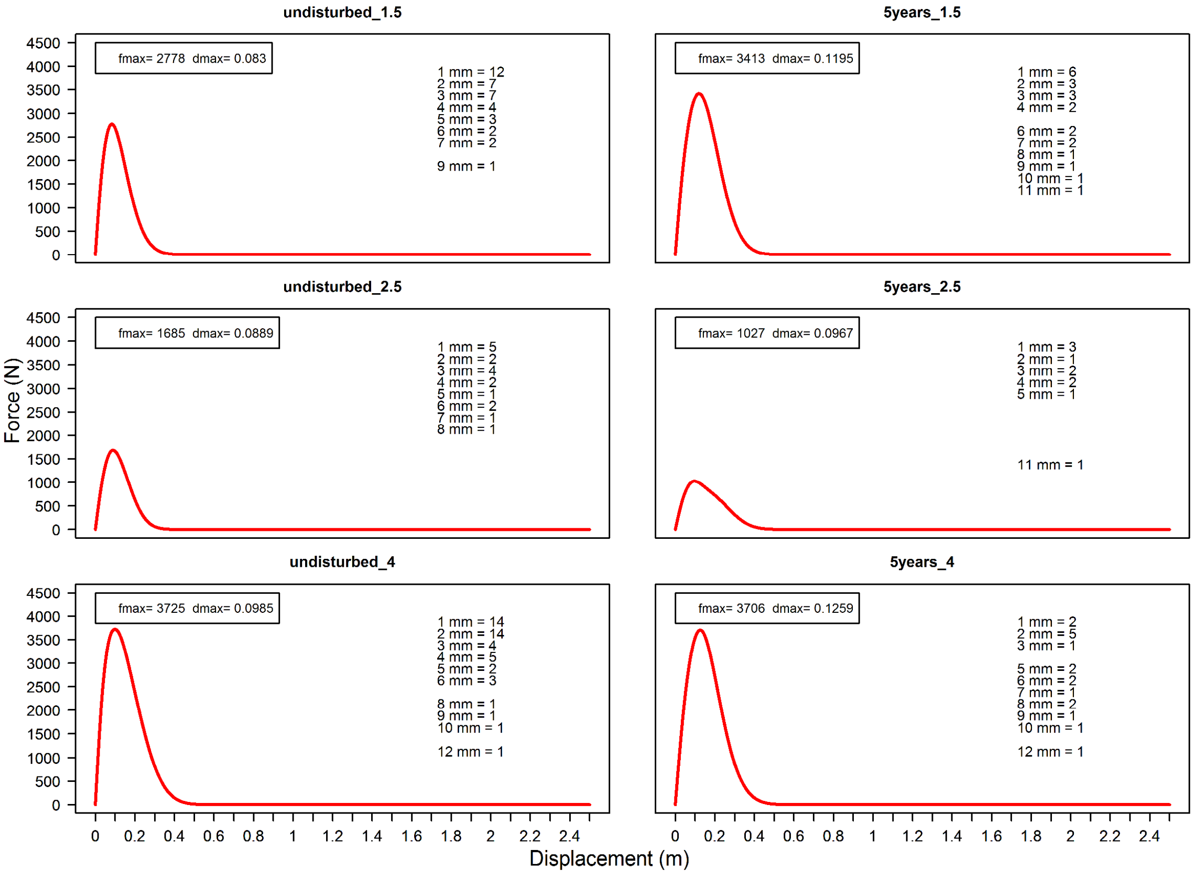

Fig. D 3 output of RBMw for undisturbed forest and 5 years old gap cutting, considering in all cases the root mechanical properties (i.e. Weibull coefficient and root force power law) of the undisturbed forest and changing just root distribution.

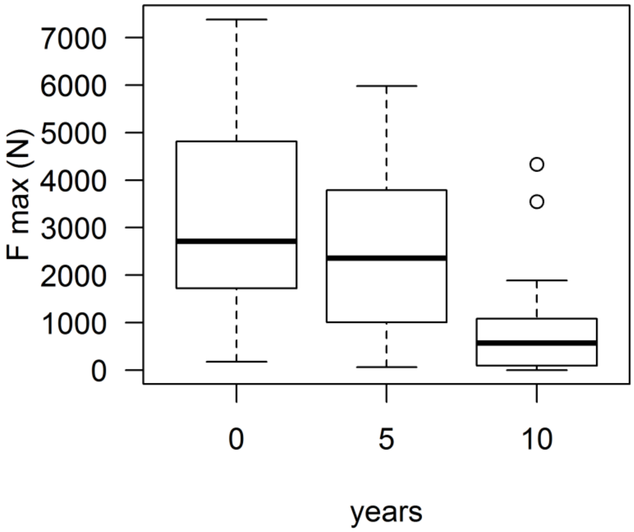

Fig. D 4 Reinforcement values calculated with RBMw at each time after cutting considering in any root mechanical properties of undisturbed forest and considering for each case all the root distributions sampled.

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List of Publications

Peer reviewed

Vergani C, Chiaradia EA, Bassanelli C, Bischetti GB (2013) *Root strength and density decay after felling in a Silver fir – Norway spruce stand in the Italian Alps.* Plant and Soil, DOI 10.1007/s11104-013-1860-4

Vergani C, Chiaradia EA, Bischetti GB (2012) *Variability in root tensile resistance of roots in Alpine forest tree species.* Ecological Engineering, 46, 43-56

Proceedings and Reports

Bassanelli C, Bischetti GB,. Chiaradia EA , Rossi L, Vergani C (2013) *The contribution of chestnut coppice forests on slope stability in abandoned territory : a case study* .Proceedings of the 10th conference AIIA : Horizons in agricultural, forestry and biosystems engineering , Viterbo, Italy, September 8-12

Vergani C, Bassanelli C, Rossi L, Chiaradia EA, Bischetti GB (2013) *The effect of chestnut coppice forest abandon on slope stability: a case study.* Geophysical Research Abstracts Vol. 15, EGU2013-10151, 2013. EGU General Assembly 2013

Vergani C, Chiaradia EA, Bassanelli C, Minotta G, Bischetti GB (2011) *Indagine sulle caratteristiche degli apparati radicali di una abetina sottoposta a taglio a buche in alta Val Brembana (BG).* Convegno di medio termine AIIA, Belgirate, 22-24 Settembre.

Chiaradia EA, Vergani C, Bassanelli C, Minotta G, Bischetti GB (2011) *Prime considerazioni sull'effetto del taglio a buche sulla coesione radicale in boschi alpini di conifere.* Convegno di medio termine AIIA, Belgirate, 22-24 Settembre.

Vergani C, Bischetti GB, Chiaradia EA (2011) *Valutazione a scala locale e regionale del contributo della vegetazione alla stabilità dei versanti.* Quaderni di idronomia montana, 29/2.