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Evaluation of the effects of three European forest types on slope stability by field and probabilistic analyses and their implications for forest management

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ABSTRACT

It is well known that forests play a crucial role in preventing soil erosion and landslides; however, forests are also subjected to dynamic evolution driven by natural processes and anthropogenic factors. This dynamic evolution affects spruce and chestnut forests in some European regions (e.g., Italian Alps, central and northern Europe), where these species have been forced by management practice to establish over long periods where other species, such as European beech, would be expected to occur as a result of natural processes.

Using a large dataset of field and laboratory measurements of root density and root mechanical properties, the performances of Norway spruce, Sweet chestnut and European beech are analyzed from a slope stability perspective by using a model based on the limit equilibrium principle within a probabilistic framework.

The results showed differences and similarities between the root systems of the analyzed species, both in terms of root distribution and mechanical properties. However, the probabilistic distribution that better fits the root reinforcement values obtained by the experimental work is, in all cases, a lognormal function.

The developed method can be used to estimate the factor of safety for several combinations of geotechnical and hydrological parameters and different root reinforcement probability distributions using Monte Carlo techniques. The obtained values have been evaluated in terms of probability to have a factor of safety of less than 1 for increasing values of slope steepness.

Although each single hillslope should be studied individually to account for local stand conditions that strongly affect root system performance, European beech is generally more efficient than Sweet chestnut and Norway spruce in terms of enhancing slope stability.

Based on our results, in all cases where the stability of slopes represents a concern and spruce and chestnut communities are perishing, the natural colonization by European beech should be evaluated positively and possibly promoted by forest managers. Moreover, the developed method provides a general framework that could be applied to other species and conditions to define the consequences of different forest management scenarios in terms of slope stability.

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1. Introduction

Vegetation can affect slope stability in different ways. According to Gray and Sotir (1996), the beneficial and adverse effects of vegetation on slope stability can be separated. Greenway (1987) reported an exhaustive list of both types of effects. For example, positive effects include the reduction in the amount of rain that reaches the soil (due to interception, evaporative losses and absorption), the reduction in the soil water content due to root uptake (i.e., transpiration processes), and the increase in the mechanical resistance of the soil against mass movement and erosion.

The potential negative effects include increases in the soil infiltration capacity due to the formation of macropores by roots or desiccation cracks due to water uptake (Ghestem et al., 2011),

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which leads to the formation of a saturation layer under the rooted soil, the transfer of atmospheric stresses (e.g., wind force, snow accumulation) to the soil and the partial surcharge of the biomass (depending on the slope angle).

Most scientific literature agrees that the most important positive effect of plants on slope stability is root reinforcement (e.g., Wu et al., 1979; Sidle and Terry, 1992; Sidle et al., 2013; Hubble et al., 2013). Root reinforcement is generally expressed in terms of an additional root reinforcement factor, c_r, which is directly related to the number of roots that cross the margins of a sliding volume of soil and to the force mobilized by each root element subjected to tension during the sliding phenomenon.

Including the effects of root reinforcement in the analysis of the stability of a vegetated slope is nowadays considered a difficult task and argument of discussion. When the largely diffused and extremely simplified method of the infinite slope was used, some authors considered null the root reinforcement at the base of the sliding surface (e.g., Zaitchik et al., 2003; Meisina and Scarabelli, 2007; Santini et al., 2009).

When the root reinforcement was considered, in some cases, a unique value, although different between homogenous areas, was introduced in the analysis (e.g. Dietrich et al., 2007; Ray et al., 2010) but it didn't represent the natural spatial variability of the root density distribution over the space. To overcome this aspect, some authors used a uniform distribution of root reinforcement values (Pack et al., 1998; Duan and Grant, 2000; Huang et al., 2007; Deb and El-Kadi, 2009; Terhorst and Kreja, 2009) without any evidence about the effective strength of this hypothesis. Also the contribution of the root systems acting on the lateral surface of the landslide (tension crack; Schwarz et al., 2010b) was questioned. As previously reported, the effect of lateral root reinforcement was considered negligible while recent studies stressed on its relevance in the stabilization process (e.g. Schwarz et al., 2010a).

A further aspect to take into account is the occurrence of critical conditions where the contribution of the root system is locally negligible. It is largely recognized that only sophisticated 3D models can represent the variability of the root system distribution in the space and its effect on slope stability (e.g. Dupuy et al., 2007; Danjon et al., 2008; Jia et al., 2012; Mao et al., 2014).

Accurate model framework are useful to understand site specific conditions but a huge quantity of supplementary data are necessary (e.g. the position of the plants and the architecture of the root system). For other purposes, such land stability mapping on large areas or comparison studies, the simplicity of the method of stability analysis is a key point and an appropriate and simple method that correctly includes the effect of the root reinforcement is still desirable.

When evaluating root reinforcement, an important aspect to consider is the variability between different vegetation types and their effects on slope stabilization.

In the last decades, different studies were conducted regarding the effects of land use modifications on additional root reinforcement. Most of these studies investigated the effects of substantial modifications that occurred, e.g., by harvesting wood (Ziemer and Swanston, 1977; Sidle and Terry, 1992; Steinacher et al., 2009; Vergani et al., 2014), grazing (Glade, 2003), expanding cultivated land area (Chen and Huang, 2013), building infrastructures (Larsen and Torres-Sã¡nchez, 1998) or planting artificial forests in place of natural forests (Genet et al., 2008). In many other studies, the reinforcement properties of different species (e.g., Ekanayake et al., 1997; Abernethy and Rutherfurd, 2001; Bischetti et al., 2005, 2009; Norris, 2005; Docker and Hubble, 2008; Comino and Marengo, 2010; Burylo et al., 2011; Vergani et al., 2012) and the effects of different land uses with (Cammeraat et al., 2005) or without a specific succession chain (Schmidt et al., 2001; Rickli et al., 2009) were investigated.

Few studies have explicitly considered the plant succession (e.g., Osman and Barakbah, 2011) and none investigated the effects of the forest evolution after the abandonment of forest activities, the occurrence of diseases or climate change disturbances, particularly in spruce and chestnut forests where instability phenomena are frequently observed and appropriate management strategies could reduce the damage.

This problem occurs in large portions of the mountainous region between Italy and Switzerland, where sweet chestnut forest is an anthropogenic consociation that was generated for the subsistence of human communities over many centuries (Carraro, 2001; Conedera et al., 2001; Gentili et al., 2009) but has been progressively abandoned in the last decades, starting at higher elevations where it has been naturally and progressively replaced by European beech (Carraro, 2001; Conedera et al., 2001).

Similarly, in some European mountain areas, Norway spruce was artificially established outside of its natural development range (Gaston, 2003; Svenning and Skov, 2004) for economic reasons (e.g., Battipaglia et al., 2009). In these areas, spruce trees are often affected by pests such as black bug (see the review by Wermelinger, 2004) and frequently age rapidly or are subjected to stand collapse due to wind storms (Goisser et al., 2013). In some cases, dead plant communities have been artificially substituted by other species, such as European beech (Goisser et al., 2013). In others, beech is established gradually and naturally (Jonášová and Prach, 2004) or spruce stands are converted to heterogeneous stands to reduce the risk of pests diffusion (Wermelinger, 2004).

Foresters are called to drive the future of these anthropogenic communities by gradually substituting dying subjects with others of other species that have a greater chance of survival. However, when considering sloping areas, the risk of landslides can increase during the transition and dead forests are proven to induce instability (Ziemer and Swanston, 1977; Sidle and Terry, 1992; Steinacher et al., 2009). Thus, foresters must consider the performances of each species that affect slope stability and answer the underlying question: which species should be promoted?

To answer such a question, this paper aims to analyze the processes involved in slope stability by exploring the following research objectives:

- To analyze the root distribution, root resistance and additional root reinforcement of three widespread forest types where the dominant species were respectively European beech (*Fagus sylvatica L.*), Norway spruce (*Picea abies* [L.] H. Karst.) and Sweet chestnut (*Castanea sativa* Mill.), considering different growing stages in the study area using experimental data from 2007 to 2013.
- To provide a simplified framework for evaluating the effects of vegetation in terms of additional root reinforcement and slope stabilization and for managing the natural variability of conditions using a probabilistic approach.
- To supply information to managers that must make decisions regarding the future development of sweet chestnut and spruce forests in regions susceptible to landslides.

2. Materials and methods

2.1. Modeling the stability of forested hillslopes

Shallow landslides in forested hillslopes usually involve the colluvial layer of the earth's mantle (Milledge et al., 2014) and can be modeled as a rigid volume of thin soil (Fig. 1) sliding on a planar shear surface (Casadei et al., 2003; Dietrich et al., 2007).

Hillslope stability can be evaluated schematically by applying limit equilibrium theory and can be expressed by using the Factor Of Safety, FOS, as follows:

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