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Invited review

Root reinforcement dynamics of European coppice woodlands and their effect on shallow landslides: A review



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ABSTRACT

In European mountain regions, forests play an important role in the mitigation of risk due to natural hazards such as landslides, rockfalls, floods and avalanches.

Conifer species usually provide a protective effect at higher altitude, while at lower altitudes broadleaf species are dominant. These forests are or were often managed as coppice systems.

The high stem density of coppice stands, their rapid growth and the permanence of root systems in the soil can be considered as assets in terms of protective function. However, these considerations are poorly researched and there is generally a lack of studies investigating the suitability of coppice as protection forests. The issue is relevant, considering that many coppice stands in mountain regions have become uneconomic and are now abandoned and overaged. Whether and how to manage these forests stands is a key question for practitioners.

In this contribution we analyze the implications of coppice management for slope stability and in particular to mitigate shallow landslides, focusing on root reinforcement, the main mechanism by which vegetation can reinforce slopes.

We review available studies concerning root distribution and dynamics in coppice stands to formulate hypotheses about their contribution in terms of root reinforcement. Finally we highlight the lacks of knowledge and the further steps needed to properly evaluate the effectiveness of the coppices in protecting against shallow landslides.

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1. Introduction

More than 20% of European forests directly protect soil, improve water quality or provide other ecosystem services, while 2% (7% including the Russian Federation) are specifically designated to protect infrastructure (MCPFE, Ministerial Conference on the Protection of Forests in Europe, 2015). The importance of these functions is reflected in European forest policies, where most countries focus on further maintaining and enhancing the role of forests to prevent soil erosion and protect water quality.

In mountain regions, forests play an important role in mitigating the risks of natural hazards such as landslides, rockfalls, floods and avalanches. In these areas, this specific ecosystem service is well known and integrated into risk management, and the percentage of protection forest cover reaches values up to 50% of the total forested area, as for instance in Switzerland (Losey and Wehrli, 2013). In Europe, about 3.3 million hectares of forest provide a direct protection against natural hazards (MCPFE, 2015).

The continuity and sustainability of forest protective functions strongly depends on the type of management and the dynamics of forest regeneration. Natural disturbances such as fires, storms, insect pests and diseases (Schelhaas et al., 2003), besides timber harvesting, can cause temporal reductions or even total elimination of the protective effect, exacerbating the magnitude and intensity of natural hazards (Conedera et al., 2003; Feistl et al., 2015; Maringer et al., 2016). Similarly, soil erosion risk may increase. Soil loss, resulting from forest harvesting, can become an issue at slope gradients above 8–9° and increases significantly above 20°, when major landslides and debris flows are likely to occur (Borrellia et al., 2016). Construction of forest roads may exacerbate the occurrence of shallow landslides and surface erosion (Sidle and Ochiai, 2006). These processes directly influence water quality increasing the sediment transported in suspension and the intensity of related natural hazards at the catchment scale such as floods and debris flows.

By adopting an appropriate silviculture (e.g. Frehner et al., 2005; Berretti et al., 2006), protection forests can permanently reduce natural hazards' damage to human life and property, although in cases of extreme risk trees may have to be supplemented or replaced by civil engineering solutions (Dorren et al., 2005; Dorren et al., 2007). As a general rule, in European mountains, coniferous forest species such as Norway spruce (*Picea abies* (L.) H. Karst), silver fir (*Abies alba* Mill.) and European larch (*Larix decidua* Mill.) provide a protective effect at higher altitudes, whereas broadleaved species are dominant at lower altitudes, even if in many European forests the lower forests belt were replaced by Norway spruce monocultures (Lässig and Močálov, 2000).

In different European areas these broadleaved forests were often managed as coppice systems. Coppice forests are located mainly in the central-southern parts of Europe (Fig. 1). Coppice woodlands cover about

6.8 million ha in France, 5.7 million ha in Turkey, 3.3 million ha in Italy, over 3 million ha in Spain, 1.6 million ha in Greece, 1.8 million ha in Bulgaria,

1.4 million ha in Serbia and Montenegro, 0.84 million ha in Bosnia and Herzegovina, 0.56 million ha in Republic of Macedonia, 0.5 million ha in Hungary, 0.54 million ha in Croatia, 0.4 million ha in Albania, and 0.25 million ha in Romania (Nicolescu et al., 2014).

Coppice management has a long tradition and was developed in numerous forms (Piussi, 1994; Nyland, 2007; Smith et al., 1997). The most common coppice species in Europe are European beech (*Fagus sylvatica* L.), oaks (*Quercus* spp.), sweet chestnut (*Castanea sativa* Mill.), limes (*Tilia* spp.), maples (*Acer* spp.), ash (*Fraxinus* spp.), hazel (*Corylus avellana* L.), whitebeam and wild service tree (*Sorbus* spp.), hornbeam (*Carpinus betulus* L.), hop hornbeam (*Ostrya carpinifolia* Scop.), and black locust (*Robinia pseudoacacia* L.) (Jancke et al., 2009). Additionally, species that form Mediterranean scrub, such as *Quercus ilex* L., are often managed as a coppice.

In terms of their protective function, the high stem densities of coppice stands can be considered advantageous (Gerber and Elsener, 1998). Additionally, their rapid re-growth from stools results in the formation of a complete cover within a few years. Moreover, part of the root system remains alive or regenerates itself rapidly after cutting. However, these considerations are poorly researched and there is a lack of studies investigating the suitability of coppices as protection forests.

The issue is particularly relevant because nowadays in mountain areas many coppice stands are uneconomic and are now abandoned and overaged. This problem is particularly relevant in mountainous areas in the southern side of the Alps. Overaged coppice stools have oversized aerial biomass and limited root systems (Conedera et al., 2010), which in time may lead to instability and uprooting (Vogt et al., 2006). Fallen and uprooted trees may then be transported into erosion gullies, torrents and rivers by landslides and windthrow events, intensifying the debris flows hazard. In some cases it is even argued that the weight of the vegetation may trigger shallow landslides (Motta, 2016); however, it has been demonstrated that this effect is rarely relevant for slope stability. Trees have the effect of increasing the surcharge, and hence the shearing stresses, on a slope, but at the same time they also increase the normal stresses, with a stabilizing effect. The overall positive or negative effect on the stability depends on the slope steepness: on very steep slopes this can be a problem; however root strength can often offset any increase in shearing stress (Selby, 1993). It must be also considered that a whole forest on a slope represents a relatively small surcharge when compared to the soil mantle and other weight factors: for this reason it is not seen as having a significant effect on slope stability (Stokes et al., 2008).

Whether and how to manage overaged coppice stands on slopes is a key question for practitioners: many different strategies have been

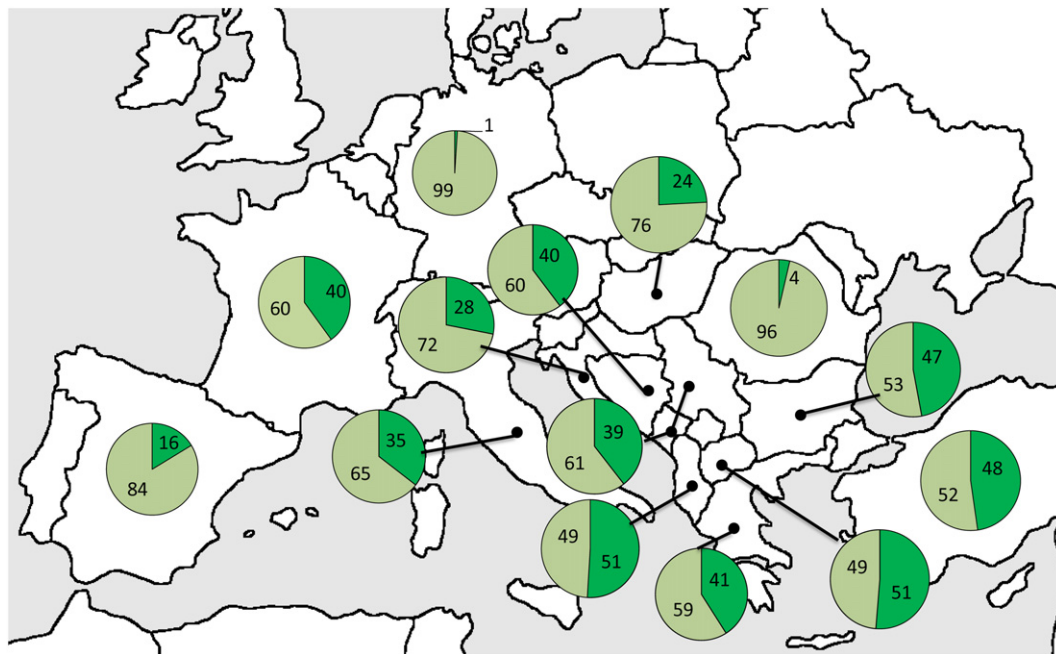


Fig. 1. Coppice woodlands (Nicolescu et al., 2014) as ratio of total forested area per country, in percentage. Dark green, coppice; light green other forests.

proposed, which sometimes contradict each other. For instance, Ciancio et al. (2006) suggested converting the stands to high forest, whereas others have suggested maintaining traditional coppicing (Bassanelli et al., 2013; Conedera et al., 2010), justifying the management costs by the maintenance of slope protection.

In this review we analyze the implications of coppice management for slope stability, in particular the role of root reinforcement in preventing shallow landslides. The work inserts itself in the context of how the land use, and in particular the vegetation, affects the process of shallow landslides, which has a key role in the shaping of the landscape through the sediment transport and delivery (Istanbulloughlu and Bras, 2005). Our focus is in particular how forest management determines different types of vegetation which in turns have different effect on the slope stability. Based on available information concerning root distribution and development in coppice stands, we formulate hypotheses concerning the dynamics of root reinforcement and discuss its effect on shallow landslides and therefore on the protection function of coppice woodlands. Finally we highlight gaps in knowledge and the need for further research in order to help foresters with making management decisions.

The focus of this work is on European tree species which grow in mountainous areas and on slopes, both in the Alpine and Mediterranean range. However, as information on root systems is often scarce, data concerning other species (e.g. hybrid poplars and mallee) are also presented, where relevant in reconstructing general root dynamics in coppice stands.

2. Background

2.1. Overview on gravitational mass movements

According to the Encyclopedia of Geomorphology (Goudie, 2004), a mass movement is the downward and outward movement of slope-forming material under the influence of gravity and does not require a transporting medium such as water, air or ice.

In Europe, the major risks caused by gravitational mass movements are related to processes such as landslides, rockfalls and avalanches. Even if the term landslide is often used as a synonymus for mass movement phenomena (Goudie, 2004), it can be more precisely defined as a downslope movement of soil, rock and organic material under the effect

of gravity, occurring on a recognizable surface of rupture (Highland and Bobrowsky, 2008; Goudie, 2004). The term 'landslide' usually covers a wide range of processes from very large landslides to hillslope debris flows. Landslides are classified on the basis of the type of movement and shear surface (fall, topples, rotational slide, translational slide, lateral spread, flow, or a combination of those), the type of material (rock, debris, and earth), the depth of failure plane (shallow, middle, and deep), or the velocity of movement (from extremely rapid (m/s) to extremely slow ($\mu\text{m/s}$)). Table 1 shows a landslide classification after Varnes (1978). A recent revision of the classification of landslides may be found in Hungr et al., 2014.

While large and deep-seated landslides are driven by fluvial or glacial processes (causing channel and valley incisions) or tectonic movements, shallow landslides usually occur at the hillslope scale (Korup and Montgomery, 2008). We define shallow landslides here as hillslope material (earth, mud, clay, or debris) <2 m deep moving downslope by sliding, flowing or by other complex movements, (Rickli and Graf, 2009; Sidle and Bogaard, 2016). Typical shallow landslides consist of volumes of up to 1000 m³ of material and a mean depth of 1.5 m (Rickli and Graf, 2009). These are usually local, episodic processes triggered by individual rainfall events or earthquakes. In geomorphology, shallow landslides are considered to be the dominant process shaping the landscape of forested mountain catchments, responsible for a

Table 1

Landslide classification modified after Varnes (1978). *In falls, material moves by free fall, bouncing and rolling. In topples the movements pivot around the base of the slopes (van Beek et al., 2008).

Type of movement	Type of material		
	Bedrock	Coarse soil	Fine soil
Falls	rock	debris	Earth
Topples*	rock	debris	Earth
Slides (rotational and translational)	rock	landslides (coarse)	landslides (fine)
Lateral spreads	rock	debris	earth
Flows (rapid)	rock	debris	earth
Flows (slow), creeping	rock	debris	earth
Complex (combination of two or more principal types of movements)			

substantial part of the total sediment delivery (Dikau et al., 1996; Marden, 2011; Sidle and Bogaard, 2016).

The hazard due to this type of slope instability can be considerable, both directly and indirectly. In some cases infrastructure and people are directly endangered by the sliding mass; in other cases shallow landslides recharge channels developing channelized debris flow or bed-load transport during floods, increasing the intensity of those processes.

2.2. Shallow landslides and surface erosion

At the catchment scale, shallow landslides are considered important mass wasting processes, strongly associated with surface runoff erosion (Dietrich et al., 2008). The combination of both processes leads to soil loss, enhanced sediment transport, and decrease of water quality.

It is, however, important to stress that surface erosion and shallow landslides are two different processes (Sidle et al., 2006), and that the effects of the vegetation and in particular of plant roots on them have to be analyzed separately, because they act in different ways.

Surface erosion is considered as one form of hydro-geological instability, and can be defined as the detachment and transport of soil particles due to the action of water or wind. Plant roots are effective in reducing soil surface erosion, due to complex interactions with the soil matrix, which cause a change in the mechanical and hydrological properties of the soil (Vannoppen et al., 2015). The presence of roots increases the soil aggregate stability, the ability of the soil to retain its structure when exposed to different stresses (Frei et al., 2003). Soil aggregate stability is enhanced through multiple processes such as the presence of fibers (fine roots and hyphae of mycorrhizal fungi) and exudates from roots or microorganisms (Bronick and Lal, 2005).

In contrast, in shallow landslides the main effect of plants is root reinforcement (Sidle and Bogaard, 2016), which contributes to increase the soil shear strength (see below).

Even if soil aggregate stability has been shown to be directly related to soil shear strength (Graf and Frei, 2013), it is confined in the first few centimeters of the soil, and generally does not contribute to the shear strength along the failure plane of shallow landslides at 1–2 m soil depth. Soil shear strength and soil erodibility are therefore negatively correlated, so that some authors (e.g. Vannoppen et al., 2015), consider the increase in soil strength provided by roots as a proxy variable to characterize the effect of vegetation on erosion.

However, from the physical point of view, root reinforcement or root tensile strength are not directly related to the intensity of erosive processes. Instead, surface roughness and energy dissipation due to the presence of roots exposed on the hillslope surface clearly may contribute to mitigate erosion (Gyssels et al., 2005).

2.3. Effects of forests on slope stability

The effects of forests on shallow landslides can be distinguished as two main types: mechanical and hydrological. At the catchment scale, hydrological effects influence the quantity and velocity of runoff processes, whereas at the local scale mechanical effects, and especially root reinforcement, are the most important factors for slope stability. In the long term, forests may also have an indirect effect through development of the soil under the influence of different tree species (Graham and Wood, 1991). This long-term physical-chemical effect has never been quantified and discussed in the literature with respect to shallow landslide predisposition.

The hydrological effect of vegetation is to reduce the moisture content of the soil and thereby delay the onset of soil saturation levels at which landslides are triggered (Forbes and Broadhead, 2011). The most important processes involved are:

- Interception and evaporation: both processes reduce the amount of effective rainfall reaching the ground. Light rainfall may be mostly intercepted, and even during high intensity storms trees intercept

up to 0–5 mm of rainfall (Keim and Skaugset, 2003), or in rare cases up to 20 mm. Different species have different interception capacity; annual canopy interception loss in percentage of precipitation can be between 6% and 45%, depending on species, ages and density of the stands, as reported in the review by Carlyle-Moses and Gash (2011) on the basis of recently published studies. Coppicing periodically removes canopy cover and therefore any rainfall interception; this will vary, however, depending on the rotation period and other management options such as the amount of litter and branches left on the ground (Piussi and Puglisi, 2012). No scientific data are available to our knowledge on this topic.

- Suction and transpiration. Trees are able to extract moisture from the soil at considerable depth and to reduce moisture levels from distances 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 subalpine regions, the reduction in soil moisture through transpiration and evaporation is negligible, and is almost zero during intense rainfall. Nevertheless, evapotranspiration may reduce soil moisture prior to a rainfall event and thus increase the amount of water that can be stored in the soil, although this may be effective only during dry periods. A study in British Columbia showed that reduced evapotranspiration after logging could 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. Forests usually have high infiltration rates, but they may reduce soil moisture through subsurface flows 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 no channels were present (Vergani and Graf, 2015). Root channels also raise infiltration rates and soil moisture content, which can increase landslide hazards. Studies that quantify these effects are missing from the literature.

Mechanical effects can be summarized as follows (Sidle and Ochiai, 2006; Forbes and Broadhead, 2011):

- Soil reinforcement by roots: individual strong woody roots anchor the soil mantle into a more stable substrate; strong roots tie across planes of weakness and potential slip surfaces, thereby anchoring the soil, while small roots provide a membrane of reinforcement to the soil mantle, increasing soil shear strength. Soil reinforcement by roots is recognized as the main contribution of forests to slope stability and can act on the basal failure plane of a landslide or on lateral failure (tension cracks). The loss of root reinforcement is one of the major causes of landslides after logging: the window of susceptibility begins when roots start to decay. The loss of protective function persists until woody vegetation is re-established and sufficient root density is achieved.
- Buttressing and arching: roots and stems of woody vegetation can act as buttress piles or arch abutments to counteract downslope shear forces (Gray and Sotir, 1996).
- Surcharge: tree weight increases the normal force components as well as the tangential force components, but in general plays a minimal role on the overall stability of a slope (Selby, 1993; Stokes et al., 2008). The local effects of loading due to wind and snow are not well known. However, it may be assumed that in general these effects have no influence on the overall stability of a landslide; only in extreme conditions can they contribute to shallow landslide triggering.

3. Root system dynamics in coppice stands

3.1. Regeneration strategy of coppice

Coppicing is based on the vegetative regeneration of trees through the formation of sprouts and suckers arising from buds activated from

the living stumps (stools). These resulting shoots have the same genetic makeup of the parent trees. A large variety of broadleaves species are managed in this way in order to obtain small poles and fuelwood, using rotations ranging from only a few years (e.g. short rotation forestry) up to several decades. The rotation period varies depending on the species and the desired assortment of wood production.

Coppice stands can be: i) even-aged (all trees being harvested at the end of the rotation period), ii) selective or uneven-aged (where sprouts of different ages, usually three age classes, grow on each stool), iii) coppice-with-standards (some trees, the standards, are left to grow for two, three or more rotations over the young coppice), or iv) high coppice by pollarding (in which branches are cut at 1–3 m above ground).

In coppiced trees there are different types of sprouts originated by different types of buds (Fig. 2) (Piusi and Alberti, 2016).

Proventitious sprouts (or stump sprouts) derive from the so-called dormant buds, which originate from periclinal cell division of the cambium and are connected to the vascular system. This type of bud is present on the trunk, branches and roots, and remains dormant growing outward with the cambium just beneath the bark (Fig. 3). Shoots originating from buds on the roots are called root suckers. Among the species that easily regenerate from suckers (root-shoots) are aspen (*Populus tremula* L.), black locust, field elm (*Ulmus minor* Mill.) and cherry (*Prunus avium* L.). Proventitious sprouts can also develop independent roots which in time are able to “free” themselves from the original stool.

Adventitious sprouts (or stool sprouts) derive from adventitious buds forming after coppicing along the stem, the branches or callus tissue on the stool. These sprouts are often vulnerable to breakage during the first phase of growth because of their weak connections with the stool. The capacity to produce adventitious buds or to activate dormant buds typically decreases during the life of the plant for oak, beech, birch, lime and ash. Chestnut, black locust, black alder (*Alnus glutinosa* L.) and hop hornbeam tend to maintain their ability to generate sprouts after coppicing.

Sprouts developing in close contact with the soil are more likely to form an independent root system. This can be facilitated by cutting near ground level, or by removing stumps to promote the regeneration of root suckers. Cutting near ground level is not always feasible for some species, such as beech, where the cut should be at the base of the younger sprouts (not the stool), to avoid the premature death of the tree.

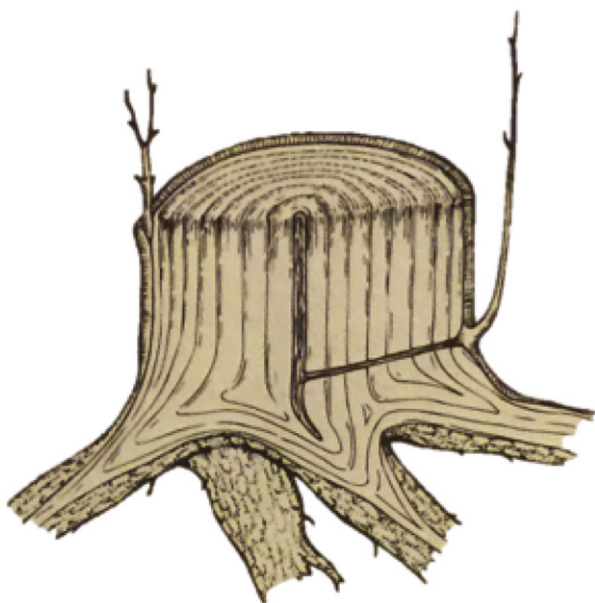


Fig. 2. Vertical section of a stool showing a proventitious (on the right) and an adventitious (on the left) sprouts. Piusi (1994).

3.2. Root system characteristics in coppice stands

Literature concerned with coppice root systems is very diverse, e.g. dealing with carbon pools and biomass allocation, the performance of different clones under different rotations and management, and fine root dynamics (Table 2). We are not aware of any specific study dealing quantitatively with root reinforcement of coppice, except that of Bassanelli et al. (2013). The species most investigated are chestnut, beech, birch, oak, poplar, and eucalyptus. (Table 2). Different sampling strategies have produced different types of data, usually presented as biomass (dry weight of roots), while fewer studies report root numbers in different diameter classes and their distribution in the soil profile.

Root sampling strategies vary greatly among the different studies, involving soil corers, minirhizotrons, trenches and whole or partial root excavation (Table 2):

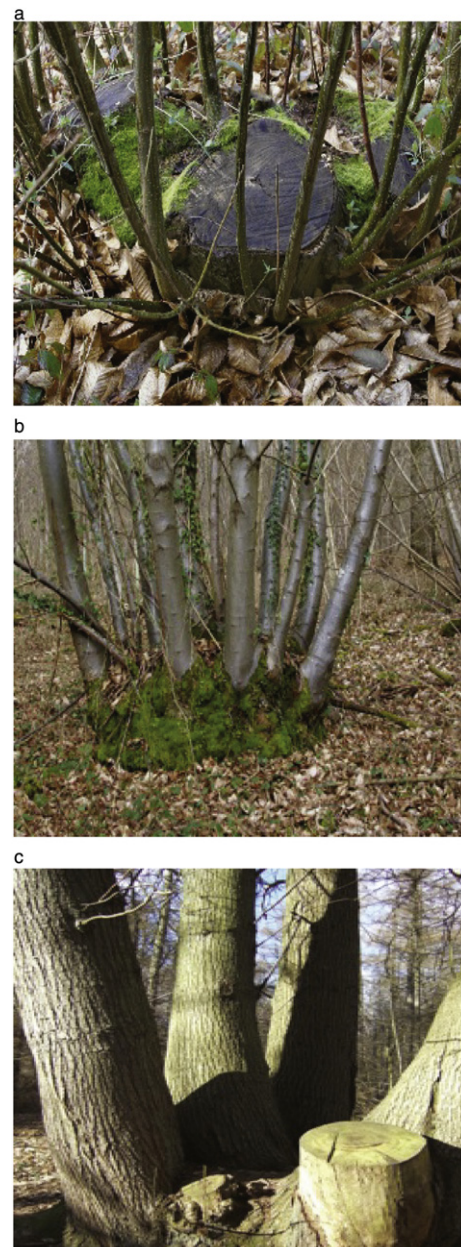


Fig. 3. Chestnut stumps with shoots arising from dormant buds at three growth stages (a) 1 year old resprouts, (b) 10 year old resprouts, and (c) an overaged resprouts.

Table 2
Overview of the analyzed studies on coppice root system.

Sampling strategy	Type of data	Species	Authors
Soil cores	Root total length; root area; root volume; root dry mass	Populus spp.	Al Afas et al., 2008
Soil cores	Dry root mass	Populus spp.; <i>Quercus petraea</i>	Bédènaud and Auclair, 1989a, 1989b, 1989c; Bruckman et al., 2011; Fortier et al., 2013
Soil cores	Dry root mass; production; mortality	Populus spp.	Berhongaray et al., 2015
Soil cores	Live and dead root dry mass; root mass seasonal patterns; annual production; turnover rate; distribution with depth	<i>Fagus sylvatica</i>	Montagnoli et al., 2012
Minirhizotrons	Root growth	Populus spp.	Dickmann et al., 1996
Minirhizotrons	Root area; root dry mass; annual root production; annual mortality	<i>Quercus ilex</i>	Lopez et al., 2003
Minirhizotrons	Root length; root diameter distribution; annual production and mortality	<i>Liquidambar styracifolia</i>	Price and Hendrick, 1998
Soil trench	Number of roots per diameter class; position; vertical distribution	<i>Castanea sativa</i> ; <i>Fagus sylvatica</i>	Bassanelli et al., 2013; Di Iorio et al., 2013
Soil trench	Dry root weight; root elongation rate; root position	Oak-birch coppice	Bédènaud and Auclair, 1989b
Soil trench	Vertical distribution; root dry mass	Populus spp.	Fortier et al., 2013
Soil trench	Root dry mass	<i>Eucalyptus globulus</i>	Vega-Nieva et al., 2015
Whole root system excavation	Root system architecture: diameter, position, age	<i>Fagus sylvatica</i>	Bagnara and Salbitano, 1998
Whole root system excavation	Age of the roots	<i>Castanea sativa</i> ; <i>Betula</i> spp.	Bédènaud and Pag'es, 1984
Whole root system excavation	Morphological measurements; maximum rooting depth; root dry mass	Populus spp.	Friend et al., 1991
Soil block excavation	Root number; root length; root surface area; root dry mass	<i>Quercus variabilis</i>	Ma et al., 2013

- Soil coring samples: a cylinder of soil is extracted with metal augers of varying length (ranging from 10 to 30 cm) and diameter (ranging from 4 to 10 cm), separating the roots from the soil and then determining their dry weight. Soil cores are typically used in studies aimed at determining fine root biomass and carbon stocks.
- Minirhizotrons are plexiglass or plastic tubes inserted in the soil; an optical device is then introduced into the tube and images of the soil around it are obtained, allowing fine root growth to be monitored over time. Both rigid minirhizotrons (Dickmann et al., 1996) or inflatable minirhizotrons (Lopez et al., 2003); have been used, up to 2 m length.
- Whole root excavation can determine root system architecture, and is usually done using water pressure, air fluxes, or diggers (Böhm, 1979). This method gives the most comprehensive picture of root system structure and distribution, but it demands much time and effort, and portions of the fine roots may be lost during excavation.
- The trench wall method consists in excavating one or more soil profiles to record the position and diameter of roots intersecting the wall face. The dimensions of these trenches varies between studies (widths of 50 cm to 4 m and depths of a few centimeters to 1–2 m).

No information about the distribution of the roots as a function of the distance from the coppiced tree stems is available to our knowledge. Most authors have focused on fine roots (<2 mm), while less information is available concerning coarse roots (Bédènaud and Pag'es, 1984; Di Iorio et al., 2013; Bagnara and Salbitano, 1998; Berhongaray et al., 2015), especially roots >1 cm. Here we review the literature that we consider more meaningful from the point of view of root reinforcement and slope stabilization.

3.3. Root distribution and root system architecture in coppice systems

Some pioneering studies have investigated the organization of whole root systems in multi-stem stools.

Aymard and Freydon (1986) used phytocid applied to the roots of different chestnut stools (coppiced) in order to investigate the connection between roots and shoots. The results showed that each subunit of clumps and shoots had an independent root system. However, transport of nutrients and water across different clumps and different roots was not excluded. The conclusion is that the stool does not merely act as a

support, but it also plays an active role in the diffusion of substances transported by the roots.

Analysing beech stools, Bagnara and Salbitano (1998) found that different root systems belonging to different shoots could be clearly distinguished and had a preferential link with each of the shoots.

The vertical distribution of the root system depends on several factors such as species morphology and the prevailing environmental conditions (soil type and depth, availability of water and nutrients, etc.). Most studies on the below ground biomass in coppices have found that the majority of the roots are concentrated in the upper 30–50 cm of the soil (Al Afas et al., 2008; Berhongaray et al., 2015; Lee, 1978; Friend et al., 1991, for poplar; Bédènaud and Auclair, 1989b for birch-oak coppice stands; Di Iorio et al., 2013 for beech). This is typical in general of most forest soils (Stokes et al., 2009).

Root distribution obviously depends on species morphology. An experiment at Gisborne, New Zealand, using two clones each of poplar and willow, found that after one growing season the willows outperformed the poplars in terms of their radial root spread. Willow roots were more numerous and fibrous than poplar, but it was thought that on hill slopes the thicker roots of poplar would allow better penetration into compact soils (Phillips et al., 2014).

Slopes also appear to influence root distribution, with the larger roots orientated uphill, assisting soil anchorage, as observed in downy oak (*Quercus pubescens* Willd.) and manna ash (*Fraxinus ornus* L.) by Chiatante et al. (2003). Di Iorio et al. (2005) found the same tendency in maiden trees of downy oak, growing on slopes between 14 and 34°, where the first-order lateral roots clustered asymmetrically in the upslope direction; moreover these larger roots were stiffer. This adaptive root architecture emphasizes upslope root resistance to pullout, counteracting the turning moment to which tree stems, and particularly tall, abandoned coppice stools, are constantly subject. The fact that mechanical stress induces an adaptation of the root system in terms of asymmetry of the root system and development of larger root diameters is confirmed by few field observations and studies (Crow and Houston, 2004).

3.4. Effect of coppicing on root system development

Root systems of different species seem to react differently to coppicing. Table 3 illustrates the main strategies and root system development for some important coppice species (Bernetti, 1995). Studies on this

Table 3
Sprouting strategies and root system behaviour after coppicing for some important European species.

Species	Sprouting	Effect of coppice on the root system
oak	Vigorous sprouting behaviour; survival of the stool decreases with increasing age; sprouts are mainly in the upper part of the stool	Mainly regenerates a new root system
chestnut	Vigorous sprouting behaviour; maintains ability to regenerate sprouts after coppicing; sprouts are mainly in the basal part of the stool	Mainly regenerates a new root system
beech	Weak sprouting behaviour; survival of the stool decreases with increasing age; sprouts are mainly in the upper part of the stool, (few) root suckers	Mainly regenerates a new root system
birch	Weak sprouting behaviour; survival of the stool decreases rapidly after a few coppice cycles; sprouts from adventitious buds and root suckers	Mainly keeps the old root system

topic are few and quite pioneering, but provide insights in to the behaviour of the root system after coppicing and the age of the root system in relation to the age of the (coppiced) stool. In an investigation of coarse roots (>5 cm) in chestnut and birch coppice stands, Bédèna and Pagès (1984) found that the age of birch roots corresponded to the age of the stool; chestnut roots, on the contrary, were always younger than the stool. They inferred that chestnut completely renews its root system at each rotation, while birch keeps the old root system. As these results concerned relatively young coppice systems, which were subjected to one or two cuttings, caution is necessary when interpreting these results. Bagnara and Salbitano (1998) conducted a similar study on beech stools, where the age of the roots was always inferior to that of shoots in a coppiced stump, suggesting that the root system was totally regenerated after each cutting. Another detailed investigation by Amorini et al. (1990) analyzed the root systems of two released shoots (dominant and codominant) in a 42 year old coppice transitory stand, where two thinnings were carried out to convert it to high forest. They found that root systems were almost entirely new and the structural roots developed after the last coppicing. Furthermore, the root systems of the released shoots showed similar morphological structure to maiden trees and developed an autonomous root system whose growth was enhanced by thinning. These are, to our knowledge, the only studies available that have systematically compared stool root and shoot age.

In a study on *Eucalyptus kochii* based on fine root biomass analysis, Wildy and Pate (2002), showed that this tree behaved similarly to birch, by shedding fine root biomass after cutting, but retaining the superstructure of the root system, confirming the results of Riedacker (1973), who also found that *Eucalyptus camaldulensis* and *Eucalyptus gomphocephala* kept their original root systems over further rotations. Soon after the re-development of the tree canopy, Wildy and Pate (2002) observed that fine roots started being produced again, but further investments in structural roots remained slow until the functional shoot/root ratio was restored. The removal of shoots at coppicing therefore reduced root biomass production and secondary thickening during the first two and a half years of shoot generation, while there was a continued unimpeded increase in root biomass of uncut trees. Similar results were found in both poplar and willow short rotation plantations, where regular cuttings slowed root development and removed the need for larger roots (Crow and Houston, 2004): in particular when short rotations were applied, the plant used carbohydrates stored in the roots for the new stem growth, which could inhibit root size and growth (Lee, 1978).

Because most data on the effect of coppicing concerns mainly fine root biomass, it is difficult to form a comprehensive picture of the behaviour and organization of the whole root system. At the same time, the different management techniques, rotation periods, times of cutting, and the species behaviour strongly influence root system development.

3.5. Fine root dynamics in coppice

Most authors refer to fine roots as those smaller than 2 mm, but some extend the category to 2.5 mm (Lopez et al., 2003) or 5 mm in diameter (Al Afas et al., 2008). In some cases, the upper threshold is not clearly defined (Bédèna and Auclair, 1989a, 1989b). In this review we will refer to fine roots as roots smaller than 2 mm, unless differently specified. According to Claus and George (2005), fine root biomass in forest stands generally develops in three phases: i) rapid increase after a clear cut harvest, reaching a maximum of fine root biomass; ii) a decrease during the maturation of the stand; and iii) a steady state in mature stands.

Most of the data available on fine root biomass dynamics in coppice concern poplar. In a hybrid poplar stand in 3 year rotation, the first year after coppicing seemed to enhance the growth of fine roots, presumably by preferentially mobilizing carbohydrate reserves (Bédèna and Auclair, 1989a). Shorter rotations caused a decrease in root regeneration, probably due to smaller available reserves.

The peak of fine root growth activity occurs in spring and summer (Bédèna and Auclair, 1989b), so cutting during the vegetation period may prevent the root system from expanding and the new roots from growing. Berhongaray et al. (2015) observed, again in poplar, a large mortality of fine roots after coppicing on a two-year rotation, but also an increase in fine root production compared to pre-coppice. The overall balance was a slight decrease in the fine root biomass in the first season after coppicing. Similarly, Ma et al. (2014) found a decreasing trend in the number of fine roots after cutting, particularly of the first order roots. On the other hand, Dickmann et al. (1996) stated for poplar clones that when cuts were done during the dormant season no dieback of fine roots was observed after cutting, and the root system remained fully functional afterwards.

3.6. Comparisons between coppice and other silvicultural systems: case studies

It is hard to generalize about root system patterns of managed coppice compared with those produced by other silvicultural systems. Several factors cause root system variability: site conditions, tree species, rotation length and the silvicultural types that are to be compared, such as high forest, conversion to high forest or over-aged coppice stands. For this reason we focused on case studies of systematic comparisons between coppice and other forest management types.

In a traditional oak coppice-with-standards system, Bédèna and Auclair (1989c) compared the root system of a maiden tree with a coppice stool. The maiden tree had twice as many roots as the coppice stool, while the root density declined rapidly beyond 50 cm of the stool. Whereas the maiden tree displayed powerful rooting with many coarse roots, the coppice stool had more fine than structural roots.

Fine root (<2.5 mm) biomass, production, mortality and longevity were studied in a thinned Mediterranean oak (*Quercus ilex* L.) coppice (coppiced until the 1960s), with an unthinned control using minirhizotrons (Lopez et al., 2003). Observations of fine roots started 1 year after thinning and continued for almost 3 years. Higher root biomass was found in thinned plots compared with controls, together with a general movement of fine roots into shallower soil layers, probably due to a thinning-induced increase in water and nutrients in the upper soil layer. Thinning also significantly affected the seasonal pattern of fine root production from the second year after felling, with higher maximum values in thinned plots than in control plots, whereas minimum production was the same for all treatments.

Using the trench method, Montagnoli et al. (2012) and Di Iorio et al. (2013) compared the root systems of 40-year-old coppice stands and two conversion cuttings. They found a general decrease in fine root biomass in the converted stands compared with the old coppice, but higher fine root turnover and annual production. The management of the forest stand seemed therefore to stimulate the production of fine roots, in

agreement with Lopez et al. (2003). The number and total cross sectional area of coarse roots (>5 mm) in the converted stands increased with increasing stand basal area, with the older stand showing the highest number of large roots (10–20 mm diameter) while in the younger one no large roots were found in the trenches. The radial growth increase of coarse roots in response to reduced tree density therefore became evident only several years after felling.

Bassanelli et al. (2013) compared the root distributions of a regularly managed chestnut coppice stand (25 years rotation) and two overaged chestnut stands. The managed stand had a generally shallower root distribution and a higher root density, which may have been influenced by renewal of the root systems after each coppicing event, although the abandoned coppice sites grew on deeper soils.

4. Modeling of root reinforcement: from single root to forest stand

Several methods have been developed over the last 40 years to quantify root reinforcement. Most are aimed at soils under shear stress and are mainly based on the tensile properties of roots. In this review we refer to the most recent Root Bundle Model (RBM) (Schwarz et al., 2013; Giadrossich et al., 2016), in order to highlight the most important parameters needed to estimate root reinforcement. Other methods for calculating root reinforcement can be found in Mao et al. (2012).

The RBM was explicitly developed for the calculation of root reinforcement stress-strain behaviour under tension (Schwarz et al., 2010a) and compression (Schwarz et al., 2015). The RBM is a module of a more general framework developed to upscale root reinforcement from the single root to the hillslope scale and is used in calculating slope stability in relation to shallow landslides (Schwarz et al., 2010a).

4.1. Mechanical properties of roots

Most information on root mechanical properties refers to the tensile strength of roots obtained by laboratory tests (Bischetti et al., 2005) and to the tensile force of root bundles obtained by laboratory pullout tests (Giadrossich et al., 2013) or field pullout (Vergani et al., 2016). Only a few studies have investigated the mechanical behaviour of roots under compression (Wu et al., 1988; Schwarz et al., 2015) or bending (Fan and Tsai, 2016). The relationship between root diameter and tensile force is usually fitted by a power law, in the best case using

numerical methods (see Schwarz et al., 2013; Giadrossich et al., 2016). Fig. 4 shows an example of laboratory tensile test data from two different chestnut coppice stands reported in Bassanelli et al. (2013). In this particular study no difference in root tensile force was found between the overaged coppice stand and the managed coppice stand.

Recent studies (Vergani et al., 2014; Werlen, 2015; Hildebrand, 2016) have emphasized the importance of field pullout tests on a large range of root diameters (up to a few centimeters) in order to better characterize root reinforcement. In particular, field pullout tests best demonstrate the variability of root mechanics due to variation in root diameter along long lengths of the root (not just along a small segment as in the laboratory tests), local variation in root direction, and local geometrical anomalies of the roots (Fig. 5). The mechanical variability of root material can be described using a Weibull survival function as discussed in Schwarz et al., 2013. Moreover, field pullout tests make allowance for the macroscopic elongation behaviour of roots during tensile loading, described in terms of the secant spring constant, which is influenced by the tortuosity of the roots, the soil-root frictional behaviour (which depends on many factors such as soil type, soil moisture, soil confining pressure, root grafting, etc.), and other factors that are not possible to consider in laboratory tests.

The decrease of root tensile force after tree death due to timber harvesting or natural disturbances has been documented and modelled by several authors (Vergani et al., 2016; Preti, 2012; Ammann et al., 2009; Watson et al., 1999) as it is a key factor in root reinforcement reduction.

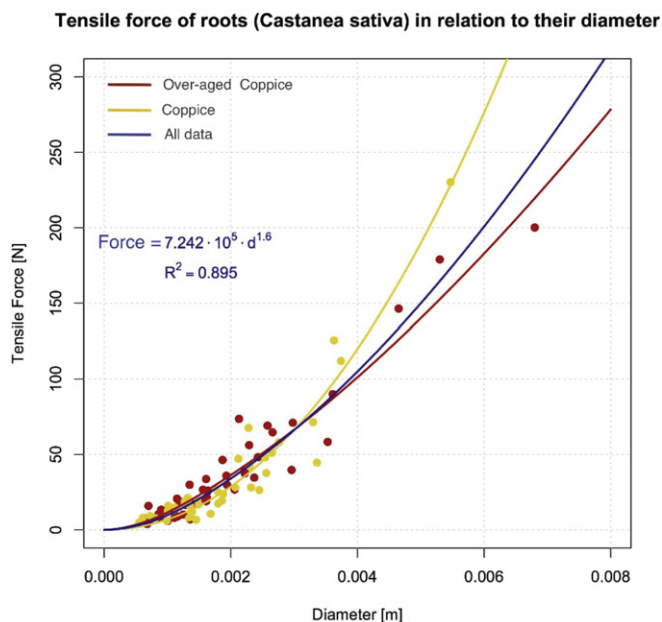


Fig. 4. Example of laboratory tensile test data of chestnut (*Castanea sativa*) plotted as function of root diameter. Data fitting follows Schwarz et al. (2013).

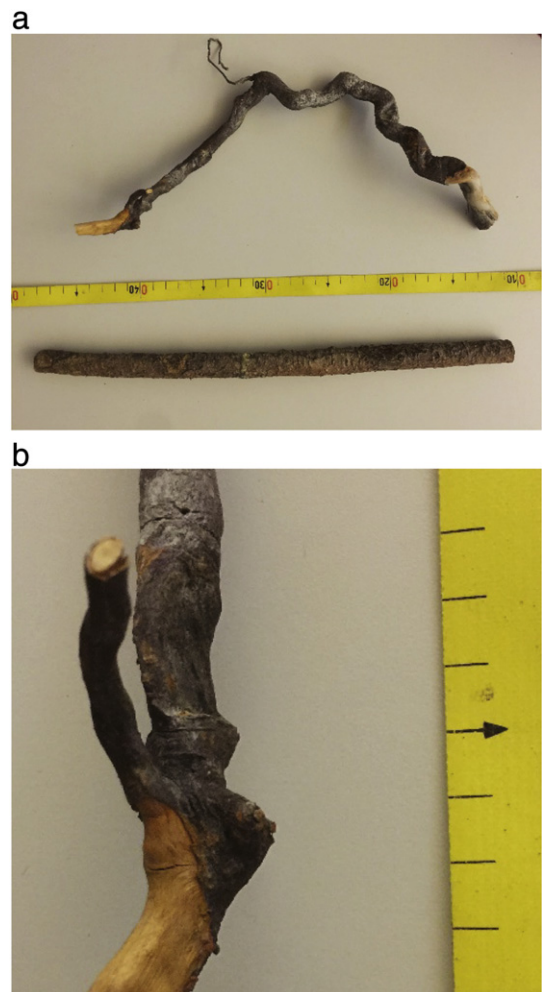


Fig. 5. Example of two roots with different tortuosity. (a) Root of gray alder (*Alnus incana*) growing in a gravel soil (top) and of spruce (*Picea abies*) growing in the soil organic layer (bottom). (b) A detail of the alder root showing the variability of root diameter of a root growing in gravel soil. Scale is in centimeters.

Studies in both Alpine and Appennine areas have shown that 10 years after tree death there is a decrease in root tensile force between 40% and 90%, and the contribution of roots is completely gone after 15–20 years. The rate of decay depends on the species (Sidle and Terry, 1992) and on environmental conditions such as altitude and climate.

4.2. Mechanical behaviour of a root bundle

A root bundle fails progressively during loading. This is principally due to three factors: 1) roots have different diameters and thus different maximum tensile forces (Fig. 4), 2) roots have variable stiffness, and 3) maximum tensile force of roots can vary in the same diameter class.

In the RBM these factors are partially considered assuming a diameter-tensile force function, a linear relation between root diameter, the measured secant spring constant, and a Weibull survival function in order to take account of mechanical variability. Fig. 6 shows the application of the RBM to the data of Fig. 3, considering the different contributions of fine and coarse roots classes to the overall root reinforcement. In fact, a single 50 mm root is equivalent to >500, 1 mm fine roots in terms of maximum tensile force of the bundle in the Bassanelli et al. (2013) example. It is important to notice that maximum tensile force of different bundles takes place at different displacements (bundle elongations). Analogous results were obtained for bundles of roots under compression (Schwarz et al., 2015). These results demonstrate the importance of the role of root diameters (coarse versus fine roots) and root distributions on root reinforcement at the stand scale.

The RBM assumes that each single root acts independently of the others. In reality, for a high density of roots, bundles of roots tend to detach the surrounding soil in blocks (as in wind-thrown trees), due to the fact that the overall root-soil friction is higher than the resistance of soil to shearing or tension. Giadrossich et al., 2013 have shown experimentally and numerically that such conditions are likely to be present close to tree stems, but that a few decimeters away the roots do not interact mechanically with each other. This aspect is important when considering whether roots break or just slip out of the soil. Previous studies (Schwarz et al., 2011) have shown that in general, small roots (<3 mm diameter) tend to slip out of the soil during tension or shearing, whereas bigger roots tend to break, as is commonly observed in the field. This implies that far beyond the tree stem, where only small roots are present, roots do not interact mechanically with each other

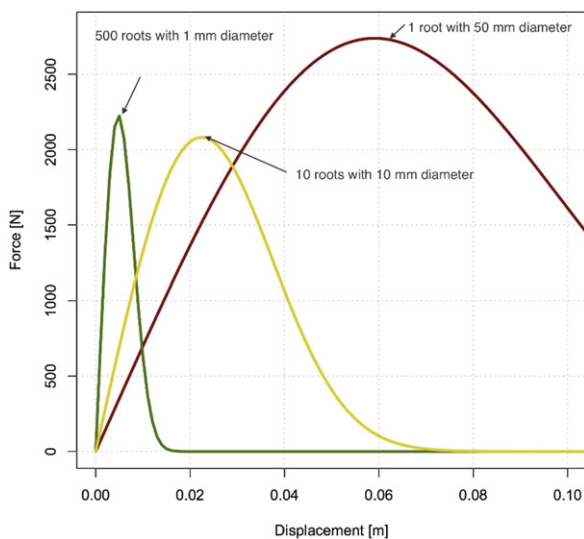


Fig. 6. Results of the Root Bundle Model (RBM), considering a bundle of fine roots (green line), one of 10 mm diameter roots (yellow line), and one 50 mm diameter root (red line).

and tend to slip out of the soil, whereas coarse roots dominate root reinforcement near to the tree stem, mobilizing their whole tensile strength as they break. All these aspects may be incorporated within the RBM using field pullout tests on a wide range of root diameters.

The contribution of each root to reinforcement under different factors (tension, compression, shearing) also depends on root orientation with respect to the loading stress. While in tension and compression, the heterogeneity of root orientation may result in a quasi-isotropic behaviour, so that under shearing conditions a correction factor considering the effects of perpendicular and parallel components of root tensile forces should be introduced. However, no studies have systematically shown the effect of root orientation on the shearing mechanism.

4.3. Modeling of root distribution

In order to apply model approaches for root reinforcement to the hillslope scale, it is necessary to consider the heterogeneity of root distributions, both in terms of number of roots per diameter class, and also, if possible, root orientation. Few models of root distribution are designed to consider this, but those proposed by Schwarz et al. (2012) and Mao et al. (2015) estimate the distribution of roots based on tree stem size and the distance from the stem. Due to the time-consuming nature of data collection, their validity has only been partially tested, with variable results at a small scale (Schwarz et al., 2016). However, a clear relationship between number of roots and maximum root diameter as a function of distance from a tree stem has been shown. These models are based on allometric functions similar to those used for the estimation of the above ground biomass of trees (Gehring et al., 2015).

5. Discussion

5.1. Implications of coppicing for root reinforcement

Schwarz et al. (2010a, 2015) distinguished between 3 main mechanisms by which roots mechanically stabilize the soil (Fig. 7). The first, and most efficient, is the basal reinforcement that roots provide when they cross the slip surfaces of a shallow landslide, reaching the underlying stable layer (the strata below the shear plane). When roots do not reach the failure plane, their contribution to stability is reduced, depending on the dimensions of the potential shallow landslide (Schwarz et al., 2010b). In this case roots stabilize the soil through so-called lateral reinforcement, i. e. the mobilization of root tensile strength and compression force at the lateral surface of the landslide (tension crack, Fig. 8). The third stabilizing mechanism is the stiffening of the soil material due to the roots in the sliding mass: this is relevant when there is a strong interaction between neighboring root systems.

5.1.1. Root mechanical properties

Root tensile strength varies considerably between species: for diameters <2 mm, Burroughs and Thomas (1977) reported values of 578, 464, and 102 kg cm⁻² for Douglas fir (*Pseudotsuga menziesii*), birch and spruce/hemlock, respectively. More recent work in the Italian Alps by Vergani et al. (2012) tested the root tensile strengths of seven common tree species, including five broadleaves (mostly in coppice stands) and two conifers. Root diameters up to 6.6 mm confirmed the power law relationship between root diameter and both the breaking force and breaking stress for all species. However, the mean corrected breaking forces were twice as great in beech compared with the conifers. Environmental factors were only weakly correlated with root force variability, and only weak relationships were found for some species between breaking force and increasing elevation and distance from the stem. When evaluating root reinforcement, root mechanical properties should take each species into account, as their mechanical characteristics can considerably influence the model's output (Vergani et al., 2014).

Concerning the mechanical properties in coppice root systems, the only available information is reported for chestnut in Bassanelli et al.

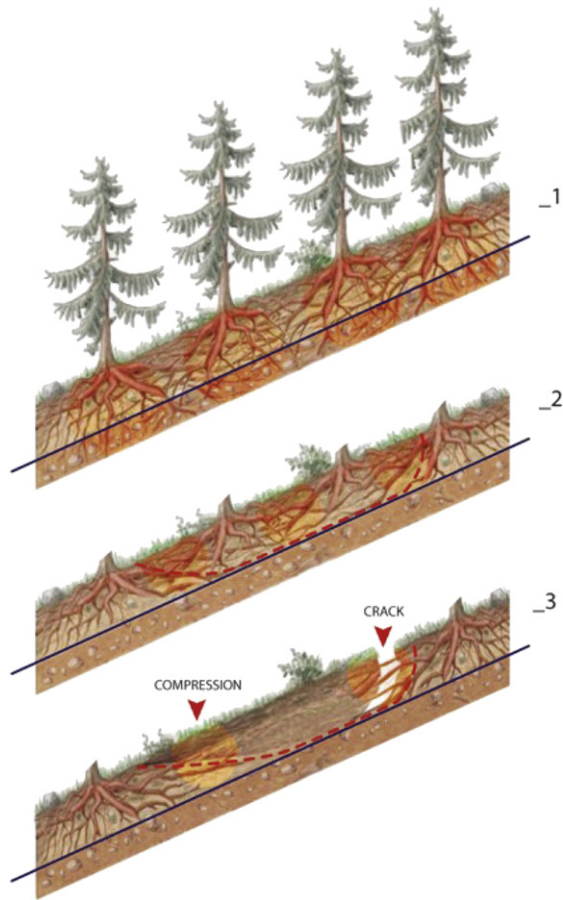


Fig. 7. Illustration of the three possible mechanisms through which root reinforcement contributes to slope stability. 1) Basal root reinforcement, 2) stiffening and buttressing of sliding mass under compression, and 3) lateral root reinforcement (tension, compression, and shearing).

(2013), who performed laboratory tensile tests: these authors did not find any significant difference in root mechanical properties between overaged coppice stand roots and the roots of regularly managed coppice stands. It therefore seems that coppicing does not affect root mechanical properties, although more data would be important to confirm these findings and to evaluate other factors, such as difference between species, different testing techniques such as pull out field tests, as well as different types of forest management, such as coppice and high forest systems, which have not been studied so far.

5.1.2. Vertical root distribution

In vertical root distribution, which is relevant to basal reinforcement, coppice systems follow the pattern already observed for different forest ecosystems (Stokes et al., 2009), where most of the roots are concentrated in the top layers of the soil (30–50 cm depth). We can therefore expect that the contribution to basal reinforcement is low or null. From the literature we can also surmise that thinning, as in conversion of coppice to high forest, seems to cause a shift of the root system into shallower soil layers in the very first years after the cut (Lopez et al., 2003). Trees with relatively deep rooting, such as European ash, oaks, aspen and alder may give better soil anchorage, especially when species with different root forms are mixed together (Rayner and Nicoll, 2012).

5.1.3. Root decay versus root regrowth of fine and coarse roots

Considering root distribution in different diameter classes, the evidence with regard to fine root biomass is quite variable. However, most studies report an increase in fine root production after coppicing, with no catastrophic dieback if coppicing is done in the dormant season.

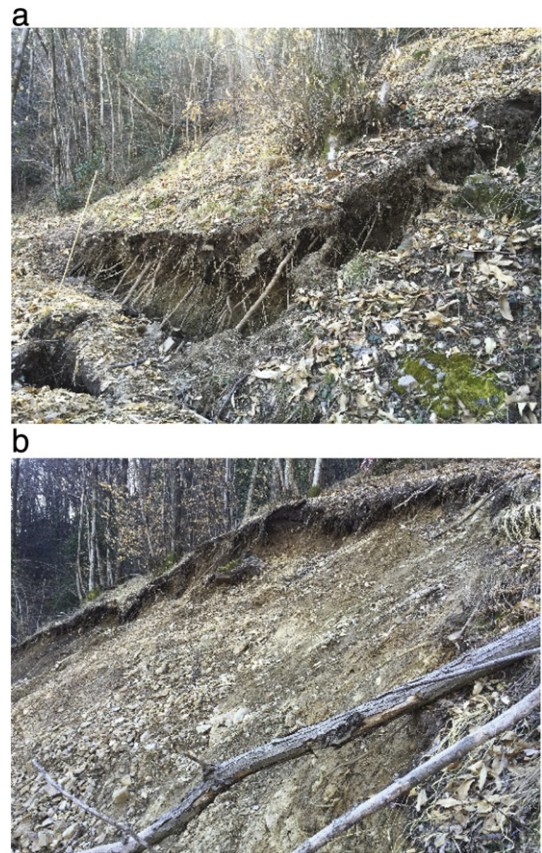


Fig. 8. Root reinforcement along tension cracks.

There is also some agreement that coppicing prevents the thickening of the roots because the plant reacts by restoring its shoot/root ratio and in producing sprouts which can compete for light. Coppicing seems, therefore, to shift the root diameter distribution of live roots towards finer dimensions, at least for those species which renew the root system at each rotation.

This has important implications for lateral reinforcement, as it has been demonstrated that the contribution of coarse roots (> 1 cm) can be significantly greater than finer roots (Vergani et al., 2014 and Fig. 6). Fig. 9 shows an example of the root system of a coppiced chestnut stool exposed by surface erosion. This illustrates the exposed coarse roots that were probably developed during the last rotation period before erosion took place (Fayle, 1968). In the absence of erosion, these coarse roots would be expected to decay and new roots to develop from the new sprouts, leading to a temporal decrease in root reinforcement, especially in the middle distance between stools. In contrast, we could expect that the root system of a maiden tree would be more developed, with coarser roots able to reach greater distances from the stem and in deeper soil layers. This suggests that conversion to high forest, even while increasing the production of fine roots immediately after thinning, could produce a higher root reinforcement in the long term. However, data are still needed to confirm this hypothesis and to quantify the differences in root reinforcement.

Several studies have demonstrated that after cutting the roots degrade, leading to a reduction in root reinforcement. After tree death, the dense network of living roots decreases both in density and strength, leaving unreinforced areas around the lateral edges of individual tree root systems (Schmidt et al., 2001). Root decay affects not only root mechanical properties (Ammann et al., 2009; Johnson and Wilcock, 2002; Preti, 2012; Watson et al., 1999; Ziemer and Swanston, 1977), but also living root frequencies and their distribution in diameter classes (Werlen, 2015; Burroughs and Thomas, 1977; Schmidt et al., 2001;

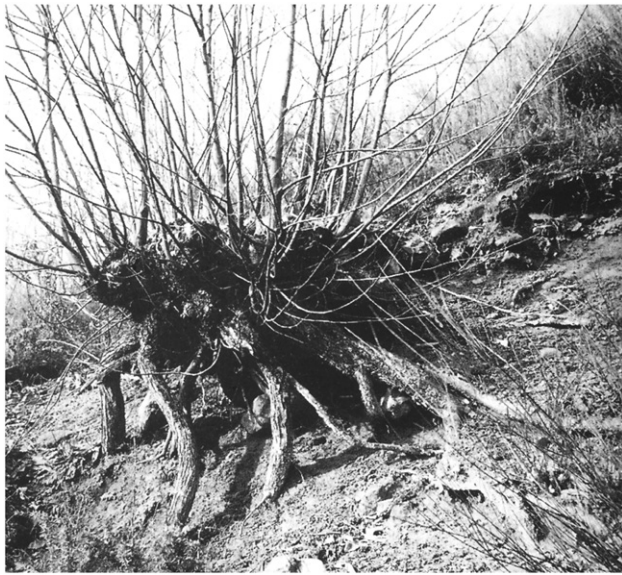


Fig. 9. Stool of chestnut tree with coarse roots remaining from the last rotation exposed by active erosion processes. Piussi (1994).

Vergani et al., 2014). A study about subalpine spruce forests (Vergani et al., 2016) showed that 80% of the roots were totally decayed 10 years after cutting, and almost no old spruce roots were still present after 15 years. In general, root reinforcement decreases 60% from the initial value 5 years after cutting, and can be considered null after 15 years. Fine roots turnover rapidly in a few months, whereas coarse roots need several years to decay (Vergani et al., 2016; Werlen, 2015). These same studies also demonstrated that the recovery of natural regeneration 15 years and 4 years respectively after the disturbance (cutting or fire) is not sufficient to counterbalance the reinforcement provided by a live mature forest. This was mainly due to root diameter distribution: for instance no roots bigger than 5 mm were found within natural regeneration 15 years after cutting.

Root decay and regeneration, therefore, have a major influence on the development of root reinforcement after coppicing depending on the species and length of the rotation. For those species which tend to renew the root system after coppicing, the growth of the new roots may not counterbalance the decay of the old root system, causing reductions in the root reinforcement over time, compared to a high forest (Fig. 10). Based on the theory that aboveground and belowground biomass must achieve an equilibrium in the development of each forest stand (Clauser, 1981) we can speculate that root development, and therefore increasing root reinforcement, increases during the growth

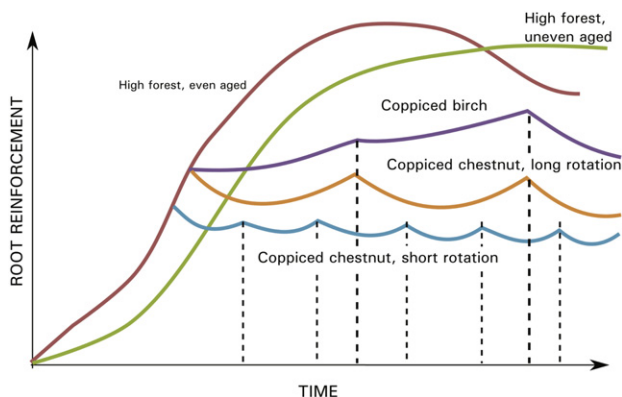


Fig. 10. Conceptual illustration of the long term development of root reinforcement at the stand scale as function of the silvicultural system and the species.

of high forest to a point where the stand reaches maturity (Fig. 10). In the case of even-aged stands, senescence could eventually lead to a decrease in root development and therefore root reinforcement, while this would not occur in an uneven-aged stand, where the decrease in root reinforcement due to the senescence does not occur because of the presence of trees at different stage of development. In the case of coppice systems, harvesting leads to the death and subsequent decay of some roots, so that the overall root reinforcement is a balance between the rate of decay and the regrowth of the new roots. We could therefore expect that species which tend to keep the old root system will increase their root reinforcement over time, even if this is less than in high forest, while those species which have to renew their root systems will provide lower reinforcement. In the case of short rotation coppice, the distribution of live roots in the different diameter classes would be expected to significantly shift towards fine rooting, lowering their root reinforcement contribution compared with longer coppice rotations or high forest. Species which are supposed to keep their “old” root system after cutting should retain a more constant and increasing reinforcement over time because the majority of coarse roots remain alive and functional over several rotations. In some cases, an extension of the rotation period might increase the average level of root reinforcement and encourage the full recovery of soil resources and productivity (Rubio and Escudero, 2003). This conceptual hypothesis needs to be verified with field data for different species, environmental conditions and management techniques, which are highly variable in coppice systems. In particular different form of coppice management, for example uneven aged coppicing or coppice with standards, would be expected to produce a different root system distributions and dynamics compared with conventional low coppice systems.

One aspect that is worth taking into account, even if it is beyond the scope of the present review, is the resilience of coppice forests after disturbances. Coppice systems can guarantee rapid regrowth after disturbances, reestablishing a protective function earlier than a high forest. Further studies are needed to investigate this aspect.

5.2. The problem of instability in overaged chestnut coppice stands

Studies on overaged chestnut coppices on steep slopes in Italy and southern Switzerland have shown an instability situation due to the collapse of the stools (Vogt et al., 2006; Pividori, 2009; Conedera et al., 2010). This occurred especially in hollows and on the steepest slopes, where the plants developed a comparatively larger above-ground biomass. The authors attributed this phenomenon to an imbalance between above-ground and below-ground biomass (Gehring, 2010). One explanation is that overaged coppice stands invest most reserves in the development of sprouts in order to compete for light in the first years after cutting. In conditions where soil resources are abundant (as in moist hollows), the trees invest in shoots rather than in root growth, leading to the development of unstable stools. In contrast, stools on poor soils need to invest more resources in root development during the early stages after coppicing, and can only commit resources to shoot growth when the system has developed.

The collapse of stools has been considered as a proxy for generally unstable conditions (Pozzi, 2005) and the weight of overaged stools has been implicated as a possible factor promoting shallow landslides. For this reason some authors have suggested that maintaining a continuous coppice management regime is necessary on steep slopes in order to prevent instability and to guarantee sufficient forest regeneration. However, the collapse of stools cannot be considered as a trigger of shallow landslides, whereas it can cause problems of erosion. In the same way, the surcharge of the slope rarely promotes shallow landslides (Stokes et al., 2008). This review suggests that for species which renew their root system at each rotation (such as chestnut and beech), regular coppice management can be less effective than their conversion to high forest where the presence of coarse roots associated with large stems contributes considerably to slope stability.

It is interesting to note that uprooted trees lying on the surface could lead to a form of slope stabilization (Pawlik, 2013). Layers such as gravel armours or rock fragment veneers limit erosion and thus stabilize hillslopes (Schaetzl and Follmer, 1990; Osterkamp et al., 2006). Similarly, coarse woody debris inhibits downslope sediment transport and erosion below tree trunks. However, some authors have documented a very interesting dualistic effect, through which tree uprooting also contributes substantially to hillslope sediment flux in the long term (e.g. Hughes et al., 2009; Constantine et al., 2012).

Roering et al. (2010) argued that root systems can disaggregate large volumes of bedrock and that timber harvesting at short (<50 years) intervals may compromise the ability of root networks to physically disturb bedrock and initiate soil formation. The balance between soil formation and soil wasting in the long term (>1000 years) is an important characteristic of mountain catchments that influences the frequency-magnitude of processes such as shallow landslides, sediment transport, and debris flow.

Recent field root excavations of chestnut trees suggest that in over-aged stools, the death of some of the sprouts due to intra-stool competition leads to the decay of part of the root system, which in turn causes the formation of an asymmetrical root system that can less contrast wind-snow stresses.

Single sprouts, selected for conversion to high forest, may invest more resources in the development of the root system in the early stages after thinning (Amorini et al., 1990), and have less need for light. Moreover, these selected sprouts would develop more symmetrical root system, probably promoting the development of larger root systems and more stable trees/stools in the long term. Management decisions must in any case consider many factors, such as local conditions, financial resources and the main function that the forest is expected to fulfill: conversion to high forest may be extremely expensive and demanding, while cutting coppice on a short rotation may be more easily achieved and practicable.

From a silvicultural point of view, the progressive formation of gaps in the canopy through windthrow may trigger episodes of forest regeneration that within decades (20–30 years) have the potential to re-establish a good protective cover against shallow soil movements (Fig. 11). As far as this process remains both progressive and local, (Conedera et al., 2010), losses of overaged coppice stools do not represent an issue for slope stability in the long term. However, overaged coppice stands near roads or mountain torrents may require special treatment.

5.3. Riparian vegetation, channel processes and riverbank stability

Coppice systems on riverbanks require special attention. Rudolf-Miklau and Hübl (2010) suggested maintaining managed coppice forest within the active erosion zone along riverbanks and gullies. In order to avoid overturning of tall stems through windthrow in this zone, the authors suggested placing mixed and managed forest, allowing tall stems only on shallower gradients.

In this case, a multi-aged coppice system could be a means of increasing the magnitude and continuity of root reinforcement. Fortier et al. (2013) found that establishing an agroforestry system, for example by buffering hybrid poplars in the riparian zones, led to an increase in both coarse and fine roots compared to herbaceous cover and a root biomass comparable or greater than would occur by natural secondary succession. Furthermore, the system ensured a deeper root penetration compared to mid-successional or climax species due to the root distribution pattern typical of early successional species which are generally more deeply rooted than mid successional and climax species.

Although along riverbanks coppice woodlands would be the best compromise between stability and risk due to large wood debris, the cost of maintaining this practice would make it difficult to sustain. In many cases, managing coppice woodlands along rivers is too onerous for local communities. Moreover, it has been shown that the



Fig. 11. Example of beech regeneration in a ca. 15 years old canopy gap due to the progressive collapse of over-aged coppice stands (Monti di Gerra, Ticino, Switzerland).

development of root systems on river banks may be hindered by phreatic water levels and periodic floods (Pasquale et al., 2014). There is currently a lack of knowledge about the characteristics of root systems and root reinforcement by European riparian tree species and only a few studies are available (e.g. Bischetti et al., 2010).

6. Conclusions and outlook

This review provides a detailed examination of the knowledge available on rooting characteristics of coppice woodlands, and considers the role of root dynamics and root distribution in reinforcing slopes against shallow soil movements. It is clear that the effect of coppicing in areas prone to shallow landslides must be differentiated according to several factors, including slope disposition, tree species, ecological conditions, the type of coppice management and the individual locations (e.g. steep slopes or riverbanks).

In general we suggest that on vulnerable hillslopes, the management of coppice woodlands should aim to increase the extension of root systems and especially,

the presence of coarse roots. This aim may be fulfilled using different strategies depending on the species, the environmental conditions, the local multi-functional role of the forest (e.g. production, biodiversity, protection against other natural hazards and recreation), and the resources of the community (financial reimbursement and man power). It is important to stress that an overall comparison between species is not possible, but the slope and management conditions should always be carefully evaluated.

The review information collected here suggests the following general indications:

- geomorphological characteristics (hollows, angle of slope) should be considered in order to optimize the stability of trees, allow the conversion of coppice to high forests, and increase the stability of the slope through coarse root production
- overaged coppice on steep slopes can raise problems as discussed by Conedera et al. (2010), but a good planned conversion to high forest might be a better alternative to continued coppicing, at least for the species that renew the root systems at each rotation.

There are several omissions in the literature which could improve our understanding of root reinforcement and the ability of coppice systems to control slope stability; in particular:

- Measures of root distribution (comparing regular coppice before and after cutting (5–10 years), overaged coppice and high forest); particularly lateral root distribution and its relation to tree position and tree dimensions. This would help to characterize the spatial heterogeneity of root distribution (and hence reinforcement) at the stand scale. Most of the works analyzed in this review do not consider tree position and dimensions in relation to root system distribution.
- Monitoring of the effects of different coppice management systems (e.g. low coppice, uneven aged coppice, coppice with standards) on root reinforcement, in order to discuss the possible different kind of management.
- Measures of pullout tests in the field, including coarse roots, in order to characterize root mechanical properties of the different species.
- A study of hydrological conditions in coppice stands in relation to slope stability: no studies are yet available on this topic.
- Surface erosion is another important process which is heavily affected by land use: a review of the long term effects of forest management and in particular of different coppice management techniques on the erosion process, beyond the scope of this review, is needed.

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Appendix A

A.1. Glossary

adventitious roots: roots that develop from buds formed spontaneously after cutting the tree stem, often producing root suckers

adventitious shoots: shoots arising from buds formed spontaneously on the callus tissue produced after cutting, not originally part of the vascular system

conversion cutting: the process of converting multi-stemmed coppice stand into a high forest by thinning the stems and extending the original rotation period

coppice: the cutting of the stems of young trees or shrubs close to the ground, causing them to resprout and to re-establish the canopy; or an area so treated

coppice with standards: forest or stand consisting of coppice among which a number of trees (standards), that are generally of seedling origin, are retained on a long rotation to provide large material and seeds to regenerate the forests.

high forest: a forest management system which allows the trees to grow to at least two-thirds of their ultimate height, as opposed to earlier cutting or coppicing where a much lower canopy is formed

maiden tree: a tree which has never been coppiced, and is supported by its own original root system and not from a coppice stool or root sucker

over-aged stand: a coppice stand which has been neglected and allowed to develop beyond its normal rotation period

proventitious shoots: shoots arising from a dormant bud originating from a shoot apical meristem, and therefore connected to the vascular system of the tree

proventitious roots: roots, like shoots, originating from the original vascular system of the tree

rotation period: rotation period (or length): the number of years required to establish and grow even-aged timber crops or stands to a specified condition of maturity when harvesting occurs. In the case of an uneven-aged crop or stand, the average number of years after which a tree is considered mature for felling.

shoot: a shoot arising from an adventitious bud at the base of a woody plant that has been cut near the ground. In the case of a sucker, the shoot arises from the root of the plant.

stump: the base of a tree and its roots left in the ground after felling.

stool: the cut tree base from which new coppice shoots arise

stump: the cut base of a tree after felling, which may or may not re-shoot

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