Efficiency of vegetation roots for protection against surface erosion in mountainous areas: the case of *Mahonia aquifolium*

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Efficiency of vegetation roots for protection against surface erosion in mountainous areas: the case of *Mahonia aquifolium*

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Efficiency of vegetation roots for protection against surface erosion in mountainous areas: the case of *Mahonia aquifolium*

Efficientie van wortelvegetatie tegen oppervlakte-erosie in bergachtige gebieden: de casus *Mahonia aquifolium*

(met een samenvatting in het Nederlands)

PROEFSCHRIFT

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Abstract

Soil erosion is a natural phenomenon which is often exacerbated by human activities (e.g., construction work, agriculture, recreational purposes etc.). Top soil is a valuable resource for agricultural production. Any destructive changes in the quantity and/or quality of topsoil can deteriorate the on-site and off-site environment and be detrimental to agricultural production. Small scale mountain agro-ecosystems are particularly sensitive to soil degradation and their productivity is heavily influenced by soil quality. Farmers have to consider financial and environmental factors in order to make farming sustainable. The appropriate plant selection, cultivation and soil conservation techniques can help provide income in the long term as well as prevent or reduce land degradation.

This research provides information and possible solutions to farmers and soil conservationists on the sustained utilization and maintenance of small-scale mountain agro-ecosystems in Hungary and France with the view to prevent or reduce soil erosion damage for long term sustainability.

Vegetation cover is of major importance for soil protection especially on slopes. The role of vegetation in improving soil stability has already been recognized. And while vegetation is able to improve soil stability through both its aboveground and belowground biomass, few studies have focussed on the significance of the root system. The root system is particularly important when the aboveground vegetation is absent for some time e.g. after harvest, grazing, fire or outside the growing period of the crop.

Therefore, this study investigates root characteristics and how root systems contribute to reducing top soil erosion in mountainous agro-ecosystems. The morphological and functional traits of roots of various plant species (tree, shrub and herbaceous species) and their efficiency in erosion control were first determined. Emphasis is put on the root systems of *Mahonia aquifolium*. The *Mahonia aquifolium* shrub has been cultivated in Hungary for decades. It is used as a decorative garden plant in landscape architecture and its evergreen foliage is used in flower arrangements. Furthermore, it is employed in both human and veterinary treatments. Due to its wide marketability as well as its high adaptability to soil and site conditions it is of interest to determine its potential for soil erosion control. Laboratory, field and modelling studies were carried out to evaluate the suitability of *Mahonia aquifolium* for soil erosion reduction.

Wu's reinforcement model was applied to evaluate and compare the root systems of *Mahonia aquifolium* along with tree, herbaceous and other shrub species for soil reinforcement. The results show that the root of *Mahonia aquifolium* is comparable in terms of slope stabilization with other plant species that are used or could potentially be used for slope stabilization (e.g. *Pinus nigra*, *Thymus serpyllum* etc.).

Plot based field studies on soil loss and runoff with different ages of *Mahonia aquifolium* population were carried out and confirmed the plant's suitability as effective erosion control. Such soil conservation techniques are significant factors in the stabilisation of the soil and for long-term sustainable use of small-scale mountainous agro-ecosystems.

The use of permanent vegetation strips between crops on cultivated slopes is a common effective way to trap runoff and sediment. Therefore the effectiveness of *Mahonia aquifolium* strips on soil erosion control under various bio-physical conditions was investigated by model simulations. The outcome of the empirical soil erosion model simulations indicate that contour strips of *Mahonia aquifolium* on sloping agricultural fields are an effective method of reducing surface runoff and soil loss. The results also suggest that steeper slopes can be used for

agricultural plant production both on small-scale and large-scale if *Mahonia aquifolium* strips are applied.

Chapter 1

1. Introduction

1.1 Water erosion in Europe

"Upon this handful of soil our survival depends. Husband it and it will grow our food, our fuel and our shelter and surround us with beauty. Abuse it and the soil will collapse and die, taking humanity with it." (Sanskrit scriptures Rig Ved, (Heuser, 2010))

Soil has been used for agriculture and engineering purposes for nearly 10,000 years, but soil protection has only recently been studied scientifically as an important element of human activity (Heuser, 2010). Throughout history, population growth has increased the need for agricultural produce which in turn created a need for cultivation of more land and the intensification of farming. With the growth of human population, the stability and sustainability of nature often suffers. Each year, there is approximately 75 billion tons of soil loss worldwide (Eswaran et al., 2001). To put this into a financial context, Lal (1998) estimated this to be equivalent to a worldwide loss of 400 billion US$ per year, which is about 70 US$ per person per year. In densely populated areas such as South Asia and sub-Saharan Africa, land degradation has a particularly severe economic impact. The mean yield reduction caused by erosion has reached 20% in numerous countries like India, China and Pakistan (Eswaran et al., 2001).

At the present time in Europe there are more than 150 million hectares of land affected by erosion and 45% of soil is deemed to have a low organic matter content (Heuser, 2010). The Mediterranean region is especially in danger from erosion as the weather conditions exacerbate erosion processes (Van der Knijff et al., 2000). Unsustainable farming practices, overgrazing, deforestation, construction works (Grimm et al., 2002) and wildfires (Mayor et al., 2007) are the main causes of soil erosion in Europe. The European Union (EU) Common Agricultural Policy (CAP, 1997) recognizes the natural circumstances of mountain areas and their proneness to depopulation and land abandonment. Approximately 56% of the agricultural areas used in the EU are classified as less favoured areas, and of this a substantial amount is classified as mountain areas (McDonald et al., 2000). Over 30% of European land area is mountainous, and mountain farming represents 18% of agricultural holdings, 15% of utilised agricultural areas and 15% of the agricultural workforce (Hopkins, 2011).

In Hungary, 70% of the total area of the country is occupied by agricultural lands (Kertész, 2009) and 55% of all croplands are situated on mountains and hillsides (Thyll, 1992). Soil degradation processes in Hungary often affect agricultural lands and soil erosion has become one of the most significant causes (Kertész, 2009). Over one third of agricultural lands are affected by water erosion, caused mainly by inappropriate land use management. Hungary has currently some 9.3 per cent weakly eroded, 9.6 per cent moderately and 6 per cent strongly eroded areas (Németh et al., 2005). This results in approximately 80–110 million metric tons of topsoil loss every year (Németh et al., 2005).

After the political changes in 1989, when collectivisation was followed by economic restructuring (Bouma et al., 1998), subsequent land restitution resulted in the majority of agricultural farms being drastically reduced in size, becoming small scale holdings (< 1 ha). According to the latest national agricultural census in 2010, 98% of farms were owned by private owners and 73% of privately owned farms were less than 1 hectare (Valkó, 2012). Since the changeover plant production has become the leading aspect of Hungarian agriculture. In 2010 nearly 78% of privately owned farms were occupied with plant production (Valkó, 2012).

1.2 Slope stabilization with vegetation

On the hills of Hungary, land degradation is even more severe and widespread (Kertész, 2004). The vulnerability of hillsides to erosion necessitates finding the best possible land use pattern to reduce soil loss on agricultural fields, minimise any erosion processes and help sustain the environment (McDonald et al., 2000). This would help to rehabilitate not only the physically damaged environment but also the social and cultural traditions which have suffered because of the economic migration from these rural areas. It is a great challenge to find plant species which would not only suit the environmental conditions but also satisfy the economical and market demand and prevent land abandonment in mountainous areas by giving alternative solutions to farmers (Hopkins, 2011).

The importance of vegetation in the role of improving soil stability has been recognized for a long time (Morgan, 2005). Both root system and foliage have significant influence on soil stability. The main influencing properties for erosion control are the plant architecture and its mechanical properties (Morgan, 2005). Aboveground vegetation is of crucial importance in the reduction of splash and inter-rill erosion (Gimeno-Garcia et al., 2007) while the root system is just as significant in slope stabilization and in reducing soil erosion (e.g., Gray and Sotir, 1996; Gyúró, 1974; Reubens et al., 2007). Plant roots improve soil structure and increase the soils organic matter content (Angers and Caron, 1998). They lower pore water pressure and increase soil shear strength (Hamza and Anderson, 2005; Wu, 1995). Vegetation root strength and distribution affect shallow mass stability by increasing the shear strength of the soil through root reinforcement (Gray, 1995; Reubens et al., 2007). In temperate regions, it is believed that root reinforcement contributes much more to shallow soils stability than hydrological factors (Gray and Sotir, 1996; Stokes et al., 2009). Plant roots provide additional cohesion to the soil, and root-permeated soils are therefore much stronger than soil alone in withstanding soil erosion processes (e.g.; Mickovski and van Beek, 2009; Operstein and Frydman, 2000; Ziemer, 1981).
Roots increase the resistance of the soil by modifying its mechanical and hydrological properties (e.g., Gray and Sotir, 1996; Styczen and Morgan, 1995). In cultivations where the canopy is lacking for a large part of the year the root system plays the most significant role in soil protection, particularly in the case of perennial crops. For slope stabilization, a deep and densely distributed root system (small trees and shrubs) would provide the best protective function, whilst for protection against water erosion, a shallow and densely distributed root system (shrubs and grasses) is preferable (Gyssels et al., 2005). However, greater protection is provided by a mixture of species and vegetation types as different root architectures form a more complex root structure which reaches a greater depth than that of monoculture (Reubens et al., 2007).

Resource-poor farmers in the mountainous areas of Hungary are in a particularly difficult position when selecting plants for the establishment of new plantations or to modernize existing ones. Financial considerations have to be combined with environmental considerations, particularly soil conservation, in order to make farming in these areas sustainable. It is important to choose plants which can provide income to small-scale private farm owners in a long term and consequently would help prevent or reduce land abandonment. Wertán, (1962) in his earlier study on Mahonia spp., recommended future research on growing *Mahonia aquifolium* in orchards, specially on slopes as a vegetation strip for soil erosion control.
His recommendation derived from his observations on plants cultivated under semi shade, where *Mahonia aquifolium* can have an enhanced foliage development. However, his recommendation has never been acted on.
Potentially, *Mahonia aquifolium* (Pursh) Nutt. is suited for cultivation on small-scale farms where landowners can rarely factor the costs of soil conservation into their farming budget due to a lack of profit. *Mahonia aquifolium* is a highly adaptable, marketable plant that requires relatively low maintenance and input costs which makes it an interesting option for soil conservation purposes.
The crop value per ha in Hungary varies widely, e.g., almond is approximately 9000 EUR per ha, sour cherry is 3700 EUR per ha (Apáti, 2009) and cereal is about 2000 EUR per ha (Avar, 2013). The value for *Mahonia aquifolium* as a cut green foliage per ha starts from 5700 EUR. Data on plant value as a herbal or medicinal plant was not accessible. However the demand for herbal plants is growing worldwide at an estimated rate of 10-15 per cent per year (IFAD, 2008). Non-traditional horticultural crops generally involve a higher level of risk than traditional crops that already are well known in the market. But they have a higher economic return per unit area compared to traditional crops (IFAD, 2008). Small-scale farms are generally at a disadvantage when compared to larger farms in the wholesale market. Most successful small-scale farms choose to market their product directly to consumers and farmers may have to develop their own customer base. Small-scale farms are more sensitive to extreme price swings however, in the case of *Mahonia aquifolium* this risk is lessened as the plant can be marketed for numerous purposes.

1.3 Objectives

Since soil erosion on the agricultural hillslopes of Hungary is a major issue of concern (Kertész, 2009), there is a need to develop and test solutions that reduce soil losses and prevent environmental damage. Selecting appropriate vegetation species that increase the stability of hillslopes, but at the same time provide income for the farmers, is a major challenge. This study focussed on *Mahonia aquifolium* and determined its potential for soil erosion control. The aim of the study was to assess the effects of the root system on soil strength and soil losses. The following specific objectives were defined for the study:

- To determine the morphological and functional traits of vegetation roots and their efficiency in erosion control on small size mountain agro-ecosystems.
- To assess the difference in root morphology between cultivated and non-cultivated *Mahonia aquifolium* in order to determine its potential in soil conservation.

- To determine the impact of different ages of cultivated *Mahonia aquifolium* shrubs for water erosion control on small size mountain agro-ecosystems.
- To evaluate the impact of vegetation strips of *Mahonia aquifolium* on soil erosion by means of a soil erosion model under a variety of agro-ecosystem settings.

1.4 Research approach

1.4.1 Study areas

The research was conducted at two sites, one in France and one in Hungary. The study site in France is located in the Saignon catchment, North-East of Sisteron in the department Alpes-de-Haute-Provence. The catchment covers an area of 400 ha and is drained by one main gully. Climatic conditions are mountainous sub-Mediterranean, characterised by dry summers and moist winters when intense rain storms can occur. The average annual precipitation is 787 mm and the mean annual temperature is 10.5°C. The altitude of the study site is about 800 m above sea level facing south-west with a slope angle of 33° (Rey, 2002). The soils are derived from Jurassic black marls (Callovian and Bathonian). Weathering of the black marls results in extended gullied areas called badlands. On marly sites similar to the sampling area, Maquaire et al. (2003) measured relatively low carbonate content (from 20 to 35%) which explains the susceptibility of the soil to weathering processes.

Since the end of the 19th century, several restoration works have been carried out to control erosion and limit soil loss. As part of the restoration works, a number of species (*Pinus nigra* Arn. *ssp. nigra, Acer opalus* Mill., *Quercus pubescens* Wild., and *Robinia pseudoacacia* L.) were introduced for erosion control, which later became the dominant local tree vegetation. Shrub species such as *Ononis fruticosa* L., *Thymus serpyllum* L. and *Genista cinerea* Vill., and herbaceous vegetation *Achnatherum calamagrostis* L. (Vallauri, 1997) and *Aphyllantes monspeliensis* L. P. Beauv. are also part of the main gully vegetation.

The study area in Hungary is located in Tyúkosdűlő on the outskirts of Szentendre town, which is part of the calc-alkaline volcanic Visegrád Hills in the Danube band in the north of Hungary. The Danube band lies on the boundary of lowland, alpine, medium-height mountains. In terms of geology it consists of andesite of volcanic origin from the Miocene Era. The soil type is characterized by a generally shallow (0-25 cm depth) brown forest soil with clay illuviation. It is classified as a Luvisol by the FAO classification (Micheli, 2009). Climatic conditions that influence hydrology and erosion have typical temperate continental characteristics with a mean temperature of 9°C and an annual precipitation of 600 mm.

The study site is located in a representative small-scale farm (0.56 ha) of Hungary with a long standing horticultural background. *Mahonia aquifolium* has been cultivated on the farm for 25 years to be sold for ornamental purposes, particularly for its cut green foliage. The altitude of the study sites varies from 230 to 285 m above sea level with a south facing orientation and a slope angle of 8°. All plots contour tilled.

1.4.2 Mahonia aquifolium (Pursh) Nutt.

Division: *Magnoliophyta*
Class: *Magnoliopsida*
Order: *Ranunculales*
Family: *Berberidaceae*
Genus: *Mahonia*
Species: *Mahonia aquifolium*

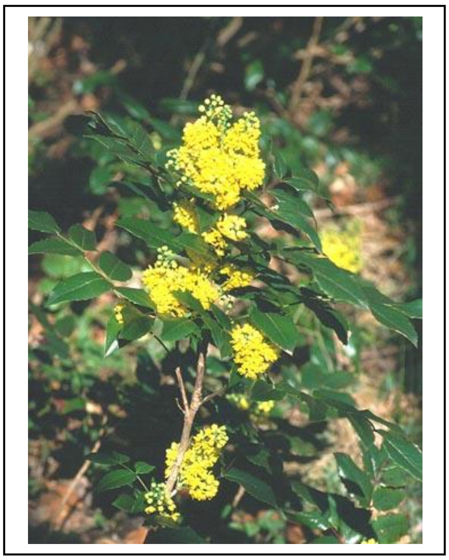


Figure 1.1 Mahonia aquifolium

Historical background

The *Berberidaceae* family is a widely distributed plant family throughout the temperate regions and the mountains of the tropics. The family contains 15 genus and approximately 700 species; 500 species with simple leaves (true Berberis) and 200 with compound leaves, *Mahonia* (Kim et al., 2004). The *Mahonia* genus can further be divided into two groups: *Orientales* and *Occidentales*; taxa from Southeast Asia belong to the *Orientales* group and taxa from North and Central America belong to the *Occidentales* group.

The species *Mahonia aquifolium* (Pursh) Nutt. or Oregon grape was first collected by Meriwether Lewis (1774-1809), an American botanist in 1806 and studied by a German botanist Frederick Pursh (1774-1820). Pursh first classified the plant as a new genus and named it *Lewisia* however in 1813, he renamed it *Berberis* as his further studies suggested that the species belonged to the existing genus *Berberis*. In the meantime Thomas Nuttall (1786-1859) an English naturalist also renamed it *Mahonia* in honor of a well-known horticulturist of the era, Bernard McMahon (1775-1816) (Mussulman, 2003). Recently botanists have once again subsumed *Mahonia* back into *Berberis* by the DNA comparison results, however, horticulturists and pharmacologists continue to use the name *Mahonia* (Stermitz et al., 2001).

Ecological parameters

M. aquifolium is an evergreen shrub, native to the forests of the Pacific Northwest of America. It grows widely from the woodlands of British Columbia to the state of Oregon (Taylor, 1956) (Figure 2.). It prefers moist forest soil, pH 6-8 with shade or semi-shade. However, due to its high abiotic tolerance (soil, water, sunlight, climate, etc.), *M. aquifolium* tolerates poor soil, is resistant to summer drought and can stand strong, direct irradiation as the hard leathery leaves protect the plant from direct sunshine. Its optimum temperature is 22°C, though it can endure temperatures as low as -29°C (Hudek, 2005; Taylor, 1956; Tóth, 1969). There are four main diseases, which can affect *M. aquifolium*: *Microsphaera berberidis*, *Cumminsiella mirabilissima*, *Phyllosticta mahoniae* and *Puccinia graminis* (Glawe, 2003; Glits and Folk, 1993).

Figure 1.2 Native distribution of *Mahonia aquifolium* in western North-America. (*Flora of North America, 1997*)

Physical characteristics

M. aquifolium is an upright evergreen shrub with diploid (2n=28) cells. It has a dominant tap root morphology (Figure 1.3a) with stems that grow up to 1.5-2 m high. Young stems are green and turn brown with maturity. Both roots and stems contain *berberin* which gives a deep yellow colour to the inner bark tissue (Figure 1.3b). The 15-25 cm long leaves alternate and hold 5-11 leaflets of 3-8 cm each (Tóth, 1969) (Figure 1.3c). These leaflets are attached directly to the stems and have a leathery and glossy cuticle. The leaflets are ovate-elliptic in shape with a serrated margin. Young leaves are bronze and with maturity they become a glossy, dark green. Mature leaves also change colours during autumn and winter from green to reddish bronze (Terpó and Grusz, 1976; Tóth, 1969).

The inflorescence bright yellow flowers bloom from early March (Figure 1.3d). The flowers are hermaphrodite with a mild fragrance. The nectar secretion originates from the *perianth*, which includes the calyx and the corolla. *Calyx* (K) is interpreted as 3+3; 2 whorled, as well as corolla (C) is interpreted as 3+3; 2 whorled. *Androecium* (A) has 6 stamens, 3 in one whorl 3 in another. *Gynoecium* has 1 carpel (*monocarpous*) with superior ovary (floral formula: K3+3 C^{N}3+3 A3+3 G$\underline{1}$) (Udvardi, 2000). The plant's pollination is entomophily (Watson and Dallwitz, 1992). The flowers are followed by edible deep blue berries which are held in clusters (Tóth, 1969) (Figure 1.3e). The berries are 6-10 mm long, 0.8-1.3 cm in diameter and contain 2-4 seeds (Figure 1.3f). Exogenous, physical dormancy applies. Immature seeds germinate within 6 weeks, mature seeds take longer and scarification is necessary before sowing.

Figure 1.3a, M. aquifolium root morphology.

Figure 1.3b, M. aquifolium stems.

Figure 1.3c, M. aquifolium leaf.

Figure 1.3d, M. aquifolium flower.

Figure 1.3e, M. aquifolium berries.

Figure 1.3f, M. aquifolium seeds.

Cultivation

M. aquifolium was introduced to Europe as an ornamental plant in 1822 and is now naturalised in many parts of Europe including Hungary (Auge and Brandl, 1997; Seidemann, 1998; Tóth, 1969). The plant has been primarily cultivated in Hungary for its cut evergreen foliage. The cultivation of these fields would involve the following stages and techniques:

- Primary tillage (40 cm deep) is preferable before installing the plantations to apply the manure into the soil.
- Plantation can be established by sowing seeds directly to beds or to containers (4-5 pieces per container).

Seeds could be collected from the older population however it is necessary to consider the entomophily pollination which could create hybrids. Scarification is necessary before sowing to break seed dormancy. After direct sowing the seedlings can either be replanted into containers after one year, or replaced from the nursery directly into beds (40 x 40 cm) after one or two years, during autumn or spring.

- Secondary tillage may be required for weed control and fertilization.
- Irrigation is not required although it has a positive influence on plant growth. It is highly recommended to avoid overhead irrigation as this increases the risk of spreading disease.

- Disease control is essential in cultivations established for ornamental purposes given the requirements of the industry.
- Harvest is possible the whole year round, but the majority of plants are harvested from September until February depending on market demand in Hungary (Hudek, 2005; Tóth, 1969).

1.4.3 Uses, benefits, plant applications

Ornamental

Horticulturalists and landscape designers often select *M. aquifolium* as the softscape in park and garden design for various reasons; it is a valuable foundation plant as well as a mass plant. It forms a favourable shrub border and mixes well with other broadleaf evergreens. It can be used for ground cover under shade or under direct sunshine. The decorative and scented flowers, the berries and the winter foliage of the plant are all valuable elements in landscaping and garden design. The colourful leaves provide valuable foliage to florists in flower arranging. *M. aquifolium* is often planted in areas where heavy traffic and other chemical pollutants are prominent due to the plants high resistance to pollution (Samecka-Cymerman and Kempers, 1999).

Natural colorant

Commercially used synthetic colorants represent the majority of dyes in all sectors, though there has been an increasing demand for natural dyes. *M. aquifolium* has been recognised and used for colouring for centuries and it is an acknowledged dye plant in North America and in Europe due to its capability for cultivation (Francis, 2003; Hancock, 1997). The inner bark of the stem and the root contain yellow dyes while the leaves and the immature fruits provide green pigments as the purple and blue colours can be obtained from the ripened fruits (Grae, 1974; Turner, 2000). These dyes are used as chemical compositions by manufacturers or as raw material in specific sectors such as textiles, food and drinks, inks, surface coatings and other sectors such as cosmetics and arts.

Herbal medicine

M. aquifolium has been used as a traditional medicine by the North American Indians for centuries. Its main chemical components are the 1. *isoquinoline* alkaloids, (e.g., b*erberine, palmatine, jatrorrhizine, columbamine, magnoflorine*) and the 2. *bisbenzylisoquinoline* alkaloids (*berbamine oxyacanthine* and *tetrandrine*) (Gray and Lachance, 1957; Kostálová et al., 2001; Lampert et al., 1998; Peng et al., 2006). Numerous experimental studies highlighted these alkaloids antimicrobial, antiproliferative, anti-inflamatory, antimalarial, antitumor and other bioactive effects (e.g. Brezová et al., 2004; Kostálová et al., 2001; Slobodníková et al., 2004; Yarnell and Abascal, 2004). The antimicrobial activity of the plant affects various organisms such as bacteria, viruses, fungi, protozoans and helminths (McCutcheon et al., 1994; Slobodníková et al., 2000; Volleková et al., 2001). These alkaloids inhibit the growth of various tumour cells (Orfila et al., 2000) and encourage antioxidant activity. Its antioxidant activity reduces the growth of *keratinocytes* which is the major cell type of epidermis. This activity is a crucial factor in the treatment of *keratinocyte hyperproliferation*, such as psoriasis (Augustin et al., 1999; Gieler et al., 1995; Muller et al., 1995; Rackova et al., 2007). Beside *psoriasis* other dermatological disorders (e.g. *dermatitis*, eczema, and fungal conditions) can also be successfully treated with the plant extract (Brezová et al., 2004). Furthermore it is a well known blood tonic and diuretic and is used in treating digestive disorders. Lans et al. (2007) give a detailed description of the plant extract used in veterinary medicine and confirms its multiple effects on the cardiovascular system, its validity as a respiratory tonic and for the treatment of wounds.

Furnishing food and cover

M. aquifolium provides food and cover for wildlife due to its all year round canopy. Flowers attract insects, birds and reptiles from late winter until early spring. Bees are most active from February to November and play a significant role in crop pollination. *M. aquifolium* represents an essential early season forage and starter food for bee families which helps to successfully establish a colony (Vaughan and Black, 2006). Berries attract animals from late summer throughout winter. During spring and summer the evergreen canopy provides an effective nesting area for many animals simultaneously along with cover from the elements and predators (Francis, 2003).

Alimentation

Both flowers and berries can be used for human alimentation. Refreshments can be obtained from the raw flowers and fruits and berries provide components for wine and brandy. The ripened berries are rich in sugar and vitamins and are used in raw or cooked dishes (Francis, 2003; Moerman, 1998).

1.5 Thesis outline

The research objectives defined in section 1.3 are addressed in Chapters 2 to 5, all of which are independent and stand-alone. Chapter 2 introduces the concepts of root tensile strength and soil reinforcement by roots for different vegetation species in France. It shows the potential of slope stabilization by vegetation.

Chapter 3 concerns the application of the two concepts of root tensile strength and soil reinforcement by *M. aquifolium* in Hungary. A distinction is made between cultivated and non-cultivated *M. aquifolium*. Cultivated *M. aquifolium* shows greater soil reinforcement potential. The results are compared with data on other species.

Chapter 4 is a case study with the quantification of surface runoff and soil loss from plots with (cultivated) *M. aquifolium* of different ages (4, 12, 20, 25 years) and 2 control plots (bare soil and grass). A decrease in surface runoff and soil loss was observed with increasing age of the *M. aquifolium* shrubs. The cumulative runoff and soil loss decreased significantly 2 years after setting up a new *M. aquifolium* plantation. This improved soil protection has been attributed to the increased soil reinforcement provided by the *M. aquifolium* roots.

Chapter 5 evaluates the effectiveness of *M. aquifolium* strips on soil erosion control under various bio-physical conditions with the use of the Revised Morgan-Morgan-Finney soil erosion model (RMMF). The RMMF model is first calibrated by using measured quantities of surface runoff and soil loss data from *M. aquifolium* plots in Chapter 4. Then the model is used to predict surface runoff and soil loss for various soil types, slope angles and cultivations with and without *M. aquifolium* strips.

The study indicates that the presence of *M. aquifolium* strips substantially reduces the soil loss rate on all studied crop fields.

Chapter 6 is the synthesis, gives an extensive overview of the major findings and implications of the studies that are the focus of this thesis.

Chapter 2

Soil reinforcement by the roots of six dominant species on eroded mountainous marly slopes (Southern Alps, France)

This chapter is adopted from:

Burylo, M., Hudek, C., Rey, F., 2011. Soil reinforcement by the roots of six dominant species on eroded mountainous marly slopes (Southern Alps, France). Catena 84, 70-78.

2.1 Introduction

Soil erosion by water is a hazard that affects both natural and cultivated lands all over the world and causes considerable soil losses. In the French Southern Alps, marly lands are subjected to severe erosion, leading to high soil erosion rates (e.g. 1.5 cm yr^{-1} in Descroix, 1994; 3.5 cm yr^{-1} in Lecompte et al., 1998), considerable soil losses (100 tons ha^{-1} yr^{-1} reported in Mathys et al., 2003) and highly unstable soils. These lands are subjected to intense gullying, ending in the formation of badlands (Poesen et al., 2003). On gully walls, the bedrock is overlain by a very loose regolith layer, composed of disintegrated marl particles, which can be transported down the slopes during intensive rainfall events and which lead to increased gullying. These shallow mass movements, described by Oostwoud Wijdenes and Ergenzinger (1998) as miniature debris flows, consist of a mixture of coarse marl fragments within a silty matrix, moving down slope as slides, gravity and fluid driven flows. Shallow landslides are a widespread erosional process in mountainous areas where conditioning factors, such as steep slopes, high weathering rates due to severe climatic conditions or lack of vegetation, often accumulate. Relatively similar soil slippage problems have been described previously in other mountainous regions (e.g. Abe and Ziemer, 1991; Schmidt et al., 2001; Schwarz et al., 2010). Nevertheless, the phenomenon we discuss here describes surficial landslides (<1 m deep) and will be referred to as miniature debris flows (MDF) hereafter. On slopes prone to instability, it is widely recognized that vegetation can significantly reduce erosion (Gray and Sotir, 1996; Morgan, 1995; Thornes, 1990). For the last 130 years, the protective role of vegetation has been extensively studied and applied to mitigate soil erosion through restoration operations on marly badlands using ecological engineering principles (Mitsch and Jørgensen, 2003; Odum and Odum, 2003). In the French Southern Alps, at the end of the 19^{th} century, huge surface areas underwent massive afforestation, primarily with Austrian Black pine (Pinus nigra Arn. subsp. Nigra), which is now a dominant species in the local flora (Vallauri et al., 2002). Recently, local scale actions, consisting of bioengineering works installed in the gullies, have been used successfully for water erosion control (Rey, 2009). After restoration operations, spontaneous vegetation growing on these marly slopes is mainly composed of juvenile individuals of trees, shrubs and grasses (Rey et al., 2005). However, locally, this vegetation can remain limited. Managing degraded lands and evaluating their vulnerability to soil slippage thus implies combining knowledge on species dynamics (Burylo et al., 2007; Rey et al., 2005) and species biomechanical characteristics such as resistance to erosive forces (Burylo et al., 2009) and potential for preventing soil slippage. Until now, few investigations have been carried out on marly soils stability (e.g. Mickovski and van Beek, 2009), or on the effects of grasses and young shrubs for improving slope stability (e.g. De Baets et al., 2008; Mattia et al., 2005; Operstein and Frydman, 2000). As a consequence, further investigations on the effect of plant roots in preventing shallow mass movements, especially at the early stages of development, where plants offer the lowest protection and where soil should be the most vulnerable, are of major interest. Plants can substantially improve slope stability and prevent soil slippage in two ways, through hydrological mechanisms lowering pore water pressure (Greenway, 1987; Gyssels et al., 2005) and through mechanical reinforcement of soil by roots (Nilaweera and Nutalaya, 1999; Waldron, 1977; Ziemer, 1981). However, in temperate regions, it is believed that root reinforcement contributes much more to shallow soils stability than hydrological factors (Gray and Sotir, 1996; Stokes et al., 2009). Plant roots provide additional cohesion to the soil and root-permeated soils are thus much stronger than soils alone to withstand soil erosion processes such as mass movements (e.g. Mickovski and van Beek, 2009; Operstein and Frydman, 2000; Ziemer, 1981). The extent to which roots reinforce the soil depends on several variables (Loades et al., 2010; Stokes et al., 2009) including root system morphology, such as root biomass, root number, root diameter or rooting depth (Wu et al., 1979), root system architecture (Dupuy et al., 2005; Mickovski et al., 2007; Reubens et al., 2007; Stokes et al., 1996), and root system mechanical properties such as root tensile strength (Operstein and Frydman, 2000; Wu et al., 1979) and pullout resistance (Nilaweera and Nutalaya, 1999; Norris, 2005). During the past thirty years, many authors made an attempt to connect root system characteristics to erosion processes and slope stability. Given the complexity of root–soil interactions, modelling and quantifying root reinforcement has remained challenging. In the late seventies, pioneering modelling contribution was provided by Wu et al. (1979) and Waldron and Dakessian (1981). Their perpendicular model is based on the Coulomb Eq. (2.1) extended to root-permeated soil by introducing increased shear strength due to roots (Eq. (2.2)).

$$S = C + \sigma_N \tan \phi \qquad (2.1)$$

$$S = C + \Delta S + \sigma_N \tan \phi \qquad (2.2)$$

where S is soil shear strength, C is soil cohesion, σ_N the stress normal to shear plane, ϕ the angle of internal friction and ΔS the increase in soil shear strength due to the presence of roots. In this model, the evaluation of ΔS (in kPa) simply depends on root tensile strength (T_R in MPa) and on the cross-sectional area of roots in the shear plane (Root Area Ratio or RAR):

$$\Delta S = K\,T_R\,RAR = 1.2T_R\,RAR \qquad (2.3)$$

where K is a factor accounting for the decomposition of T_R according to a tangential and normal component on the shear plane. From laboratory and field investigations, Wu et al. (1979) observed that K generally ranges from 1.0 to 1.3 and selected a constant value of 1.2.

This model relies on the assumptions that all roots are fully mobilized during soil shearing and that all roots break at the same time, whereas in reality, roots break progressively. Consequently, it estimates maximum and potential values of ΔS, and was found to overestimate root reinforcement (Mickovski et al., 2009; Operstein and Frydman, 2000; Pollen and Simon, 2005). Fibre bundle models, such as the RipRoot model (Pollen and Simon, 2005) consider that roots within the soil break progressively during soil failure and load is redistributed to the remaining intact roots.

Comparative analysis showed that the RipRoot approach provided better root reinforcement estimations (Mickovski et al., 2009; Pollen and Simon, 2005). Greenwood (2006) developed the computer program SLIP4EX which calculates the slope factor of safety using different methods of analysis and which includes both the mechanical and hydrological changes due to vegetation. Although the Wu and Waldron model is not the most accurate and realistic one, it remains one of the most widespread models for preliminary root reinforcement assessment. Because it is simpler and requires less input data than the above-mentioned models, it was used in the present study to rank species according to their soil stabilization potential and to compare species suitability for soil protection against shallow mass movements (e.g. Bischetti et al., 2005; De Baets et al., 2008, 2009; Mattia et al., 2005; Tosi, 2007). The aim of this paper is to evaluate and compare the suitability for preventing miniature debris flows (MDF) of six dominant species at the juvenile stage, growing on marly slopes. Juvenile individuals of each species were collected on site and we measured root tensile strength and root system distribution with depth. Their contribution to slope stability was calculated using Wu's reinforcement model and their suitability for erosion control was assessed.

2.2 Materials and methods

2.2.1 Study site

The study site is located in the Saignon catchment, situated in the North-East of Sisteron (Alpes-de-Haute-Provence department, France), a 400 ha gully catchment on marls (Figure 2.1). The climate on the test site is mountainous sub-Mediterranean, characterised by summer droughts (on average 168 mm from June to August) interspersed with intense storms. The mean annual rainfall is 787 mm and the mean annual temperature is 10.2°C with 4–5 cold months (Rey, 2002). The sampling area is south-west oriented, its altitude is about 800 m and the mean slope of gully sides is 33° (Rey, 2002).

The local vegetation is dominated by P*inus nigra* Arn. *ssp. nigra* introduced at the beginning of the last century for erosion control purposes. The other dominant tree species are *Acer opalus* Mill., *Quercus pubescens* Wild., and *Robinia pseudoacacia* L. also introduced in the 19th century. The shrubby layer mainly consists of a mixture of *Ononis fruticosa* L. and *Genista cinerea* Vill., and the grass layer of *Achnatherum calamagrostis* L. (Vallauri, 1997).

2.2.2 Soil

The soils in the study area are derived from Jurassic black marls (Callovian and Bathonian). Weathering of black marls results in extended gullied areas called badlands. The soils on gully slopes consist of superimposed layers with different structure and compaction (Maquaire et al., 2002):

– 0 to 50–100 mm depth: loose detrital cover sensitive to erosion made of structure less marl fragments and colluvial materials

– 50–100 to 450 mm depth: regolith of marls consisting of marl fragments whose compaction increases with depth (Oostwoud Wijdenes and Ergenzinger, 1998)

– 450 mm depth: the bedrock, compact, structured and cohesive. The detrital and regolith layers are partially removed by erosion processes, including shallow mass movements, causing further decompression of the underlying bedrock.

On marly sites similar to the sampling area, Maquaire et al. (2003) measured relatively low carbonate content (from 20 to 35%) which explains the susceptibility of the soil to weathering processes. Moreover, shear tests performed on weathered material showed that effective cohesion ranged from 6 to 12 kPa (Antoine et al., 1995; Maquaire et al., 2003).

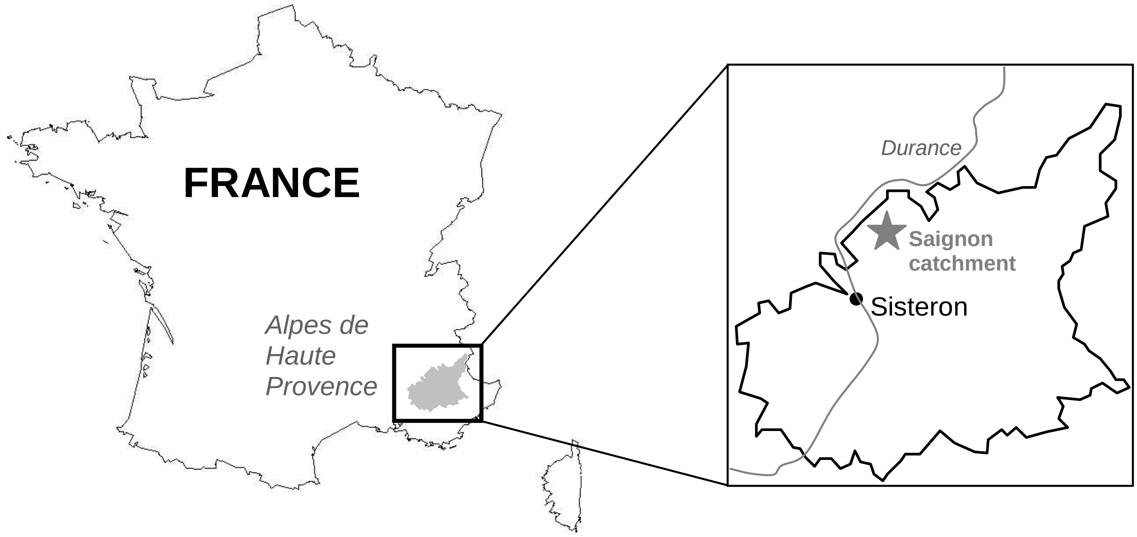


Figure 2.1 Localization map of the experimental site at Saignon catchment, in the North-East of Sisteron, France.

2.2.3 Species studied

Six species, among the most dominant in the local vegetation, were chosen for the present study: *P. nigra* Arn. *ssp. nigra, Q. pubescens* Wild.*, G. cinerea* Vill.*, Thymus serpyllum* L.*, A. calamagrostis* L. and *Aphyllantes monspeliensis* L. P. Beauv.. These species represent three different vegetation growth forms: tree, shrubby and herbaceous plants. In the Saignon catchment, *P. nigra* and *Q. pubescens* are tree species commonly found at all the stages of their development, including the juvenile stage. At this stage, these two species show a fast growing and deeply penetrating taproot system with thin lateral roots. *G. cinerea* is a widespread shrub in the area. It develops a deep tap root with long lateral roots which generate a large root system both in depth and in width. *T. serpyllum* presents a shallower root system with a relatively short tap root and longer lateral roots (see Burylo et al., 2009 for more details on root system description of woody species). *A. calamagrostis* and *A. monspeliensis* are two herbaceous species. *A. calamagrostis* is a perennial grass while *A. monspeliensis* is a perennial dicotyledonous plant. However, both show a graminoid shape, with tillers packed into tussocks and a heart root system where many fibrous roots develop from the plant base (Rameau et al., 1993). In the study area, the two species can be found as isolated tussock, with a diameter ranging from 15 to 30 cm.

2.2.4 Species sampling

Between 5 and 10 individuals of each plant species were sampled from the marly slopes in the study area. Isolated juvenile plants, with no neighbours within a 300 mm radius, were selected to limit plant–plant interactions which can dramatically affect root system development and make sampling easier. As plant age could not be determined accurately, small plants were chosen within each species. Threshold values of 20 mm and 100 mm in basal diameter were selected for woody and herbaceous species respectively, and for all species, plants less than 300 mm high were sampled. *P. nigra* and *Q. pubescens* seedlings of similar shapes and surrounding environments were collected from the same area. For the two shrubby and two herbaceous species, age determination was difficult, therefore individuals were chosen by their height and diameter. Because of the lack of soil cohesion at our study site, we could not use the traditional 'trench wall' method described by Böhm (1979). Therefore, each plant was carefully excavated by hand to keep the root system intact, up to a depth of 60 mm depending on the species. Photos of the different steps of the excavation process were taken for further measurements as well as lateral spreading of the root system. Plants were then put in plastic bags and transported to a cold room (5°C) until laboratory measurements that took place during the following week.

2.2.5 Root distribution and root area ratio measurements

During the week after excavation, roots were cleaned of remaining soil particles with a hand water jet so that we could study root characteristics. For each plant, root area ratio (RAR) was estimated following the method described by Mattia et al. (2005). Using photos of the plant root system, the spatial distribution of roots was recreated in the laboratory and the diameter of all the roots was measured every 50 mm up to the maximum rooting depth of the plant. For each depth level, the roots were then divided into diameter classes of 0.25 mm. Finally, RAR was calculated every 50 mm as the ratio of root surface area (A_R in mm^2 calculated from root diameters) to the surface area of the root-permeated soil (A in mm^2). A was calculated from the measurements of maximum lateral spreading of the root system. Hence, A differs for each plant sample but we used the same value for all RAR calculations within a plant.

2.2.6 Root tensile strength measurements

After the RAR measurements, all roots were cut off and preserved in a 15% alcoholic solution following Bischetti et al. (2005). Root tensile strength (T_R) tests were performed with a device built by the Institute of Agricultural Hydraulics of the University of Milan (Italy) and previously used in similar studies (Bischetti et al., 2005; Mattia et al, 2005). Before testing, roots were inspected and damaged roots were removed from the study. Root samples of approximately 200 mm were selected for testing and root diameter was measured at three points along root length. For woody species, root bark, when observed, was preserved for the tests. The two root ends were fixed to the clamps of the machine, of which one can move at a constant speed of 10 mm min^{-1} to apply a tensile force to the root. A load cell continuously registered the force applied to the root and we measured T_R (MPa) as:

$$T_R = F_{max} / \pi \cdot \left(\frac{D}{2}\right)^2 \tag{2.4}$$

where F_{max} is the maximum tensile force (N) registered before breaking and D is the average diameter (mm) of the root being tested. For each species, at least 15 roots with diameters ranging from 0.15 to 5 mm were tested.

2.2.7 Comparison of species suitability for soil reinforcement

To evaluate the potential increase in soil shear strength due to roots (ΔS given in Eq. (2.3)), the static perpendicular model described by Wu et al. (1979) was used.

Table 2.1 Root number distribution with depth and within diameter classes. Values are mean root number in each diameter class and depth. Growth forms are tree (T), shrubs (S) and grasses (G).

			Depth (m)										
Species	Growth form	Root diameter (mm)	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55
Pinus nigra	T	<1		2.2	4.8	2.6	0.8	0.4	0.6	0.2			
		1-2		0.6	0.8	0.8	0.4	0.2					
		> 2	1	0.8	0.2								
Quercus pubescens	T	<1	1.9	1.6	1.9	1.4	0.7	0.3	0.3	0.1	0.1	0.1	
		1-2		0.3	0.4	0.6	0.4	0.4	0.1	0.4			
		> 2	1	0.7	0.9	0.6	0.3						
Genista cinerea	S	<1	28.2	32	36.8	18.6	10.4	8.6	9.2	5.4	7.8	3.8	1.2
		1-2	2.6	2	2.2	3.2	3.2	2	0.6	0.8	0.6	0.2	0.2
		> 2	3.8	0.6	0.8	1.2	0.4	0.4	0.69	0.2	0.2		
Thymus serpyllum	S	<1	116.5	46.8	26.5								
		1-2	6.3	2.3	2								
		> 2	2.3	1.3									
Achnatherum calamagrostis	G	<1	85.8	71.2	57.2	32.8	25.6	14.4	3.6	2.2	3		
		1-2	7.4	2.6	1	0.4	0.2						
		> 2											
Aphyllantes monspeliensis	G	<1	142.5	307.3	257	192.3	149.3	94.7	51.5	21.3			
		1-2	7.7	1.7	2.2	1.3							
		> 2											

In order to account for root diameters variability, Eq. (2.3) has to be written as follows, taking into account T_R and RAR for different diameter classes:

$$S_r = 1.2 \sum_{i=1}^{N} T_{Ri} \cdot {A_{Ri}}/{A} \qquad (2.5)$$

where T_{Ri} (in MPa) and A_{Ri} (in mm^2) are T_R and A_R values for diameter class i, and N is the number of classes.
ΔS was thus calculated for each plant sample and used to compare species efficiency for soil reinforcement.

2.2.8 Data analysis and statistics

According to many authors (Norris et al., 2008), T_R decreases with increasing root diameter following a simple power law equation of the form:

$$T_R = \alpha \cdot D^{-\beta} \qquad (2.6)$$

where α and β are empirical values depending on species. The power relationship between T_R and root diameter was tested and an analysis of covariance (ANCOVA) with root diameter as a covariate, was performed to test for significant differences between species and growth forms (Tukey HSD procedure). T_R values were log transformed before analysis to meet the assumption of normal distribution.

RAR and ΔS differences between species were investigated using the Kruskal–Wallis nonparametric test as sample numbers were low and data was not normally distributed. All the analyses were carried out using STATISTICA (version 7.1 for Windows, Statsoft 1984).

Table 2.2 Results of the Kruskal–Wallis test (test statistic H and probability value p) for root area ratio (RAR) differences with depth within each species. RAR significantly decreases with depth for all investigated species.

	Pinus nigra	*Quercus pubscens*	*Genista cinerea*	*Thymus serpyllum*	*Achnatherum calamagrostis*	*Aphyllantes monspeliensis*
H	25.5	31.05	25.7	6.72	22.3	27.2
p	<0.000	<0.000	0.007	0.034	0.004	<0.000

2.3 Results

2.3.1. Root distribution and root area ratio

All species showed similar root distribution, with a decreasing number of roots with depth (Table 2.1). The largest part of root system biomass being observed in the upper 200 mm of soil. Root distribution within diameter classes is highly variable between species and growth forms. For grasses, which present a fibrous root system, the majority of roots consisted of roots smaller than 1 mm in diameter and no roots larger than 2 mm in diameter were observed. Root systems of tree species comprised very few roots, representing root morphology at the juvenile stage, made of a vigorous tap root and few laterals. Shrub species showed a third morphological type, with about half a dozen coarse roots (diameter > 1 mm) and many fine roots (diameter < 1mm). RAR significantly decreases with depth as revealed by the Kruskal–Wallis test (Table 2.2). RAR distribution with depth also revealed differences between species regarding rooting depth and RAR values (Figure 2.2). RAR for *G. cinerea* ranges from 0.053% at the soil surface to 0% at 600 mm soil depth, while RAR for *P. nigra* reaches 0.015% at the soil surface and 0% at a depth of 400 mm.

Nevertheless, there were large standard errors in RAR measurements and the Kruskal–Wallis test showed that RAR values were not significantly different either between species or between growth forms (Table 2.3) when data was presented for the six studied species together.

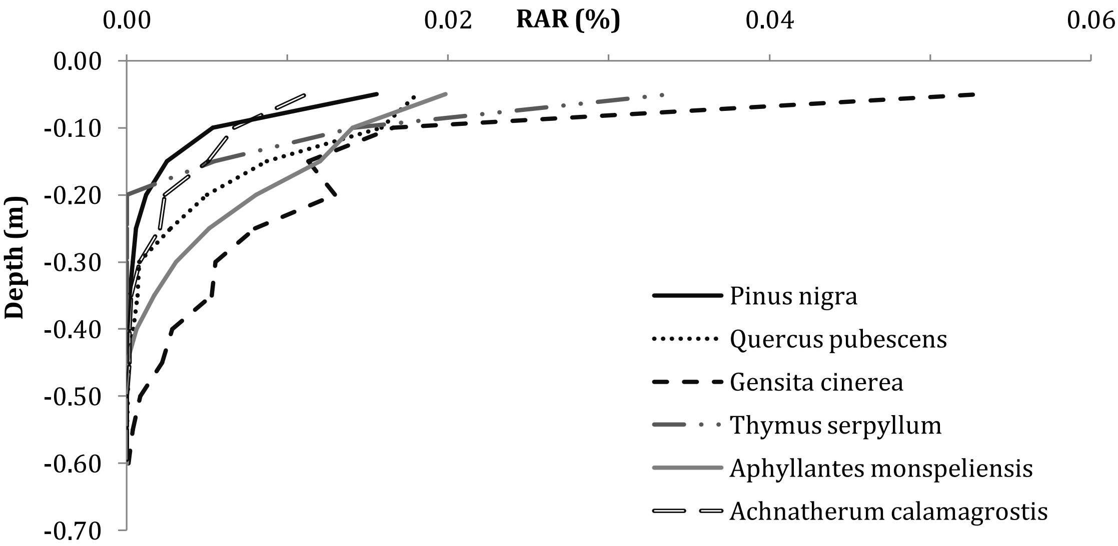


Figure 2.2 Root area ratio (RAR) distribution with depth for the six species studied.

Table 2.3 Results of the Kruskal–Wallis test (test statistic H and probability value p) for root area ratio (RAR) and root reinforcement (ΔS) differences between the six species studied (*P. nigra, Q. pubescens, G. cinerea, T. serpyllum, A. calamagrostis* and *A. monspeliensis*) and between growth forms (trees, shrubs and grasses). Data presented in the table represents all six species together.

	Depth (m)	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40
RAR									
Species									
	H	5.81	7.31	1.92	8.88	8.31	5.31	6.40	2.40
	p	0.32	0.19	0.86	0.064	0.08	0.25	0.17	0.66
Growth form									
	H	2.65	2.12	0.34	3.43	0.99	3.51	4.90	2.29
	p	0.26	0.34	0.84	0.18	0.61	0.17	0.08	0.32
ΔS									
Species									
	H	20.49	20.14	17.89	18.42	14.93	10.28	8.24	7.2
	p	0.001	0.001	0.003	0.001	0.004	0.035	0.08	0.125
Growth forms									
	H	17.30	14.30	12.86	15.64	12.85	9.44	7.21	6.82
	p	0.000	0.000	0.001	0.000	0.001	0.008	0.027	0.033

2.3.2 Root tensile strength

The results of the tensile strength tests are given in Figure 2.3. As expected, there was a decrease of T_R with increasing root diameter following the power relationship. Values of α, β and of the statistical significance of the relationships are given in Table 2.4. This relationship was observed for all species except for *G. cinerea* for which no correlation between T_R and diameter could be observed.

The results of the ANCOVA showed that root tensile strength differed significantly between species (D: $F=28.8$, $p<0.0001$; T_R: $F=14.3$, $p<0.0001$) and between growth forms (D: $F=18.5$, $p<0.0001$; T_R: $F=17.8$, $p<0.0001$ — Table 2.5). The roots of the tree species (*P. nigra* and *Q. pubescens*) were less resistant to tension than the shrubby and herbaceous species. The shrub *G.*

cinerea and the two herbaceous species (*A. calamagrostis* and *A. monspeliensis*) had the strongest roots. However, T_R values of the two latter species decreased quickly with increasing root diameter (high values of the decay coefficient β) and were similar to the other species above diameters of 1 mm. The shrub *T. serpyllum* had intermediate values of root strength.

2.3.3 Root reinforcement

By applying Eq. (2.6) to the data, we calculated ΔS, the increase of soil cohesion induced by plants roots. T_R values were re-calculated for each root diameter class (0.25 mm step) using the parameters of the power relationship given in Table 2.4. As for *G. cinerea* the strength–diameter relationship was not clear, ΔS was calculated from mean values of T_R. The results (Figure 2.4) showed that the shrub *G. cinerea* and the herbaceous species *A. monspeliensis* could provide the highest increase in soil cohesion.

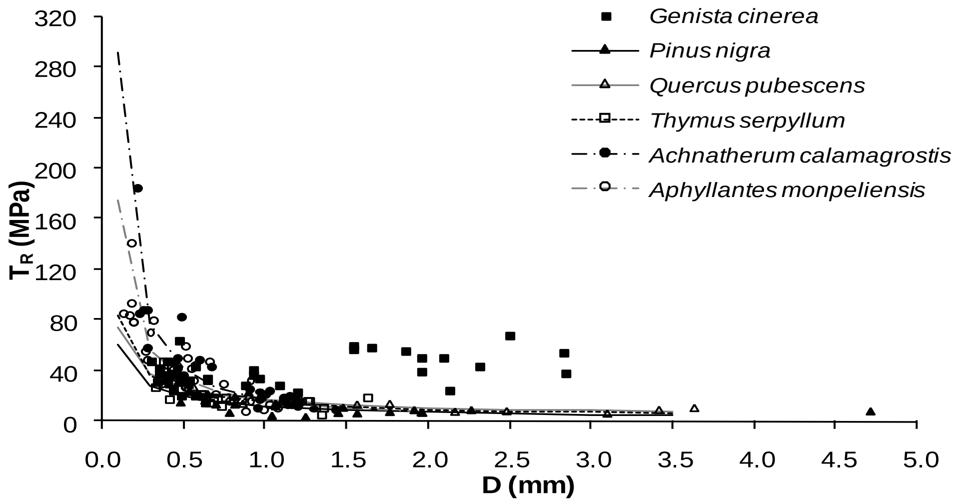


Figure 2.3 Relationship between root tensile strength (T_R, MPa) and root diameter (D, mm) for the six species studied. Points represent the measured values of T_R and curves represent the predicted T_R from the parameters α and β given in Table 2.4.

Calculated ΔS values exceeded 5 kPa in the first 200 mm of soil and were significantly higher for these two species (see Table 2.3 for the results of the Kruskal–Wallis test). As for root tensile strength, the tree species *P. nigra* and *Q. pubescens* were the least efficient for soil reinforcement with ΔS values ranging between 0.5 and 1 kPa in the upper soil layers. Root reinforcement decreased quickly with increasing soil depth for all species, and below 300 mm, ΔS values were not significantly different between species (Table 2.3).

2.4 Discussion

Root area ratio measurements showed a high variability within species which resulted in high standard errors and no significant differences between species, as revealed by the Kruskal–Wallis test (Table 2.3). This variability can be explained several ways, first and foremost, environmental heterogeneity. Many environmental factors have a strong influence on root architecture (Coutts et al., 1999). Soil properties, such as soil bulk density (Goodman and Ennos, 1999), soil moisture and fertility (Fitter and Stickland, 1991; Hodge, 2004; Taub and Goldberg, 1996), or natural obstacle like stones or stumps (Quine et al., 1991), can dramatically affect root system development. Plant–plant interactions, especially competition, also modify root growth (e.g. Craine, 2006). Root system development also depends on the genetic variability of the species. On the other hand, variability in RAR may be due to sampling and errors in measurements in the laboratory. Moreover, when measuring RAR, it was sometimes difficult to replace the root system in the original position it had in the field.

Nevertheless, species showed more differences in root number distribution within diameter classes reflecting differences in root system types (Table 2.1): tap-like root system with a vigorous main root, tap-like root system with many laterals and coronal root system (Figure 2.5). The values of RAR measured in the present study, with root crosssectional areas representing less than 0.05% of the reference areas of soil, were in the same order of those reported by De Baets et al. (2008), who studied comparable species.

Table 2.4 Parameters of the power law relationship between root tensile strength and root diameter. Significance levels: ns nonsignificant and ***p<0.001. N is the number of valid tests.

Species	N	α	β	R^2	p
Pinus nigra	25	12.41	0.69	0.50	***
Quercus pubescens	14	17.37	0.63	0.73	***
Genista cinerea	35	-	-	-	ns
Thymus serpyllum	23	14.67	0.76	0.58	***
Aphyllantes monspeliensis	30	16.57	1.02	0.75	***
Achnatherum calamagrostis	31	17.59	1.22	0.86	***

Table 2.5 Root tensile strength differences between species and growth form (ANCOVA, Tukey HSD test, α=0.05). Growth forms are tree (T), shrubs (S) and grasses (G). Letters indicate significant differences between species (column 2) and between growth forms (column 4).

Species	Significant differences				Growth form	Significant differences
Pinus nigra	A				T	A
Quercus pubescens	A	B				
Genista cinerea				D	S	B
Thymus serpyllum		B	C			
Achnatherum calamagrostis			C	D	H	B
Aphyllantes monspeliensis				D		

Other authors found higher RAR values (e.g. Abernethy and Rutherfurd, 2001; Bischetti et al., 2005) but plant development and methods of measurements were different.

Tensile strength tests confirmed that there exists a power relationship between T_R and root diameter. This well-known relationship (e.g. Bischetti et al., 2005; Mattia et al., 2005; Norris, 2005) reveals that thin roots are more resistant to tensile stresses than thick roots. However, this relationship has not been observed for *G. cinerea*. As for root architecture variability, many factors can influence root tensile strength such as root age, root bark or root structure (Genet et al., 2005). None of these possible explanations apply in the present study however as individuals of G. *cinera* were taken from the same site not more than a few metres apart. Variations in root age would more likely explain this result, as well as the low number of tests and the range of diameters tested for each species (0.3 to 3 mm), which may not have been sufficient.

Microscopy observations on root cross-sections or cellulose content measurements could provide an explanation. The values of α (scale factor) and β (decay coefficient) generally fall in the range of values already found in previous studies. Several grasses have been characterised by low scale factors and decay coefficients higher than 1 (De Baets et al., 2008; Mattia et al., 2005). For shrub species, values of α and β ranging from 4.4 to 91.2 and from −0.52 to −1.75 respectively, have been reported (Bischetti et al., 2005; De Baets et al., 2008; Mattia et al., 2005; Operstein and Frydman, 2000). De Baets et al. (2008) studied two shrub species (*Rosmarinus officinalis* and *Thymus zygis*) belonging to the same plant family as *T. serpyllum* (Lamiaceae) and found that α and β values very similar to ours (12.9 and 19.3 for α and −0.77 and −0.73 for β). For tree species, decay coefficients found in literature (Bischetti et al., 2005; Genet et al., 2005) ranged from −0.52 to −0.11 but higher scale factors were reported (from 18.4 to 60.15) compared to our measurements (12.41 and 17.37). The analysis of covariance revealed that the roots of shrubs and herbaceous species were the most resistant to tensile stresses.

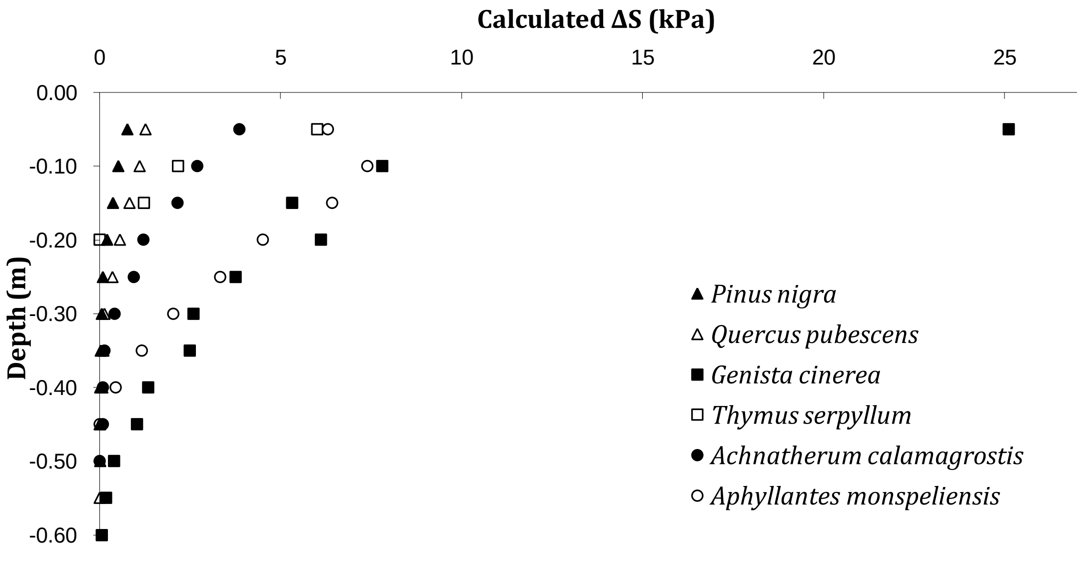


Figure 2.4 Soil reinforcement (calculated ΔS in kPa) provided by the roots of the six species studied. Points represent the mean values of calculated ΔS at each depth.

De Baets et al. (2008) studied the root tensile strength of 25 Mediterranean species, mostly shrubs and herbs, and found no significant strength differences between the two growth forms. Generally speaking, species which have the strongest roots are those with high values of α and low values of β. This observation might be attributed to differences in root structure between species. Genet et al. (2005) showed that cellulose concentration influenced root strength properties, higher cellulose concentrations resulting in stronger roots. Moreover, lignin concentrations also strongly determine root tensile strength. Hathaway and Penny (1975) demonstrated that Young's modulus decreased with increasing lignin/cellulose ratio. Therefore, it can be assumed that roots of tree species are weaker in tension than fibrous roots because of higher lignin content in fibrous root systems. The values of root reinforcement calculated with assumed parameters in Wu's model generally ranged between 0 and 10 kPa in the upper 20 cm of soil and fell under 5 kPa in the deeper soil layers. These values are in the same order of magnitude of the values reported in Mattia et al. (2005), but lower than the ones reported by De Baets et al. (2008). Again, the analysis showed that herbaceous and shrub species provide more soil reinforcement than tree species. For example, at 10 cm depth, the additional cohesion provided by the roots of *A. monspeliensis* and *G. cinerea* is 14 and 15 times greater respectively than that of *P. nigra* and 6.5 and 7 times greater respectively than that of *Q. pubescens*. De Baets et al. (2007) follow this idea as they found that the increase in soil cohesion due to roots was significantly higher for soils permeated with fibrous roots of grasses than for soils permeated with tap-like root systems.

Nevertheless, the results of the present study must be analyzed with caution. Values were calculated with a perpendicular static model designed on the basis of assumptions leading to important simplifications of the process. An important assumption is that all roots are mobilized in tension when the soil shears, and reach their maximum tensile strength at the same time before breaking. Such models give potential maximum root reinforcement and overestimate the additional soil cohesion provided by roots (Mickovski et al., 2009; Operstein and Frydman, 2000; Pollen and Simon, 2005). Thus, the values of soil reinforcement calculated in the present work must be regarded as relative values allowing species comparison according to their efficiency for soil stabilization and not as absolute values.
The results of the present study suggest that shrubs and herbaceous species, in particular *G. cinerea* and *A. monspeliensis*, are the most efficient for soil reinforcement. These growth forms have either fibrous root systems with many fine roots resistant to tension (*A. monspeliensis*) or tap-like root systems with a mixture of woody coarse roots and many fine and strong roots (*G. cinerea* — Figure 2.4). Both species have a significant protective effect against MDF, reinforcing the soil to a depth corresponding to the plant rooting depth (up to 550 mm on individuals tested). Combined with the knowledge on vegetation dynamics and ecological site properties, these results can help evaluat the vulnerability of degraded lands to erosion or the efficiency of restoration actions. Previous studies have demonstrated that after environmental disturbance or land restoration, herbaceous species first recolonize the substrate (Burylo et al., 2007; Cammeraat et al., 2005). Then, vegetation cover evolves and the proportions of shrub and tree species slowly increase. In particular, in marly gullies of the French Southern Alps, *A. monspeliensis* and *A. calamagrostis* represent an important part of the colonizing vegetation (Rey et al., 2005).

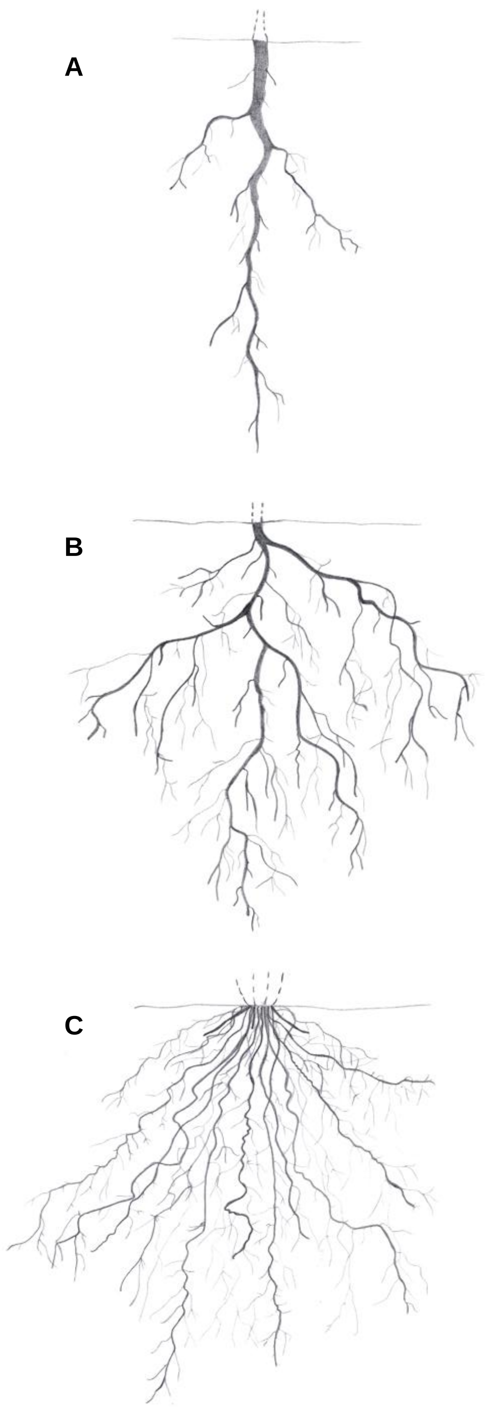


Figure 2.5 Schematic representation of the three types of root systems studied. (A) Tap-like root system of juvenile trees (*P. nigra* and *Q. pubescens*) with a vigorous central vertical root and few fine laterals, (B) Tap-like root system of shrubby species (*G. cinerea* and *T. serpyllum*) with an identifiable larger central root and many thinner laterals and (C) heart root system of graminoïd-shaped herbaceous species (*A. calamagrostis* and *A. monspeliensis*) with many fibrous roots.

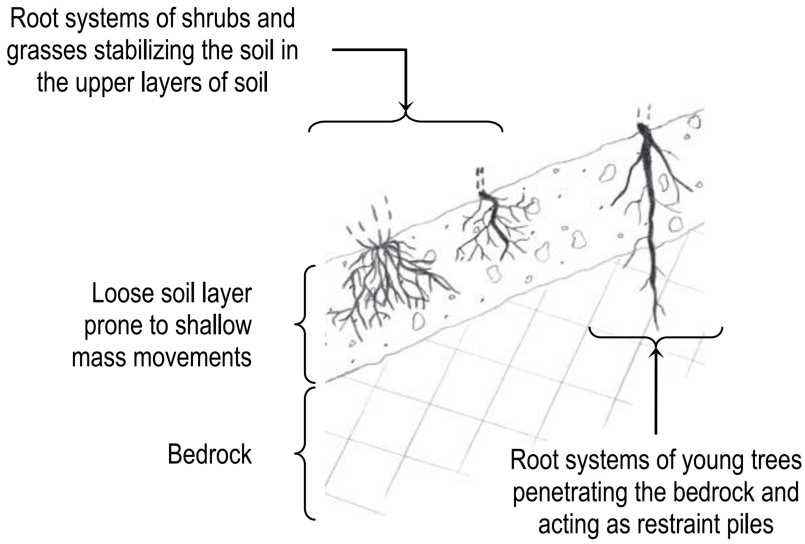


Figure 2.6 Schematic representation of the combined effect of trees, shrubs and herbaceous species for shallow slope stabilization at the early stages of plant development.

Therefore, vegetation that colonizes marly lands soon after restoration could quickly and efficiently stabilize shallow soil layers, thereby increasing the effects of restoration works. Then, the growth of tree seedlings, shown to be less efficient in the first years of development than herbaceous species and shrub species, could fix the upper layers of soil to the bed rock by penetrating into the underlying bedrock (Styzcen and Morgan, 1995). Moreover, tree roots can penetrate into bedrock discontinuities and act as restraint piles firmly anchoring the root-permeated soil to the bedrock (Figure 2.6). Evaluating the suitability of species for erosion control should also include knowledge on species resistance to different erosion processes (De Baets et al., 2009). Erosive constraints can be seen as environmental filters that determine which species from the regional pool can persist (Keddy, 1992), and thus actually prevent shallow mass movements. Burylo et al. (2009) studied the resistance to uprooting of 12 species growing in eroded marly lands, among which *P. nigra, Q. pubescens, G. cinerea* and *T. serpyllum*. These four species showed contrasting anchorage strengths. *G. cinerea* was found to be one of the most resistant while *P. nigra* was among the least resistant species. *T. serpyllum* and *Q. pubescens* had intermediate anchorage strengths. Therefore, global species suitability to prevent MDF can be specified by taking into account species resistance to uprooting. *P. nigra*, used for massive afforestation at the beginning of the last century, proved not to be the most efficient species for root reinforcement of soils. On the other hand, *G. cinerea* would be very interesting both for sustainable land colonization, due to its high resistance to uprooting, and for soil stabilization. *T. serpyllum* and *Q. pubescens*, post-pioneer and late succession species, would have an intermediate efficiency to prevent soil slippage. These two latter species could be interesting when erosion is already partially controlled, for example to restore soil structure. The anchorage strength of *A. monspeliensis* and *A. calamagrostis* has not yet been evaluated, but uprooting tests on Vetiver grass showed that this graminaceous species possessed the root strength to withstand torrential runoff (Mickovski et al., 2005). *A. calamagrostis* has been used in land restoration (Barrouillet, 1982) as it is suggested to be highly resistant as well.

2.5 Conclusion

Measurements of Root Area Ratio (RAR) and root tensile strength were conducted on six species growing on eroded marly lands to evaluate root reinforcement of soil using Wu's perpendicular model and to compare species efficiency in preventing miniature debris flows (MDFs). The results presented here expand the knowledge on the biomechanical characteristics of grasses and woody species growing on mountainous marly lands. Results confirmed that thin roots can resist higher tensile stresses than thicker roots, although roots with larger diameters need higher tensile forces to break. Furthermore, this study concluded that grasses and shrubs provided higher increase in soil shear strength in the topsoil than tree species in the early stages of their development. Combined with existing knowledge on vegetation dynamics, ecological site properties and species resistance to erosion, these results can help in evaluating land vulnerability to erosion and the efficiency of restoration actions in eroded marly lands.

Chapter 3

Root system traits of *Mahonia aquifolium* and its potential use in soil reinforcement in mountain horticultural practices

This chapter is adopted from:

Hudek, C., Burylo, M., Rey, F., 2010. Root system traits of *Mahonia aquifolium* and its potential use in soil reinforcement in mountain horticultural practices. Scientia Horticulturae 125, 504-511

3.1 Introduction

Since the political changeover in Hungary in 1989 the structure of agriculture has changed from collectivisation to economic restructuring (Bouma et al., 1998). The transformation brought about mixed ownership and a majority of small-scale (<1 ha) farms which suffered from a lack of various resources, e.g., lack of capital and equipment (Burger and Szép, 2007). The number of people employed in agriculture and its related sectors has shown a dramatic decrease (693,000 people in 1990 and 183,000 in 2007) (KSH, 2009). This led to many farms with great horticultural traditions being abandoned. There is approximately 80–100 million metric tons of soil loss every year in Hungary (Németh et al., 2005). Mountain horticultural ecosystems are particularly affected by this problem as the majority of soil loss is linked to the hilly parts of the country (Transdanubia, Northern Mountains). Soil loss reduces the quantity and alters the quality of the soil, decreasing the sustainable plant productivity. These mountain horticultural ecosystems require greater attention in terms of slope stability as slopes are more vulnerable to failure.

Vegetation is able to improve soil stability with its root system and foliage. In cultivations where the canopy is lacking for a large part of the year the root system plays the most significant role in soil stabilization; roots increase the resistance of the soil by modifying its mechanical and hydrological properties (e.g., Gray and Sotir, 1996; Styczen and Morgan, 1995). Plant roots improve soil structure and increase the soils organic matter content (Angers and Caron, 1998). They lower pore water pressure and increase soil shear strength (Hamza and Anderson, 2005; Wu, 1995). Vegetation root strength and distribution affect shallow mass stability by increasing the shear strength of the soil through root reinforcement (Gray, 1995; Reubens et al., 2007). The most effective roots for soil reinforcement are fine (diameters between 1 and 20 mm), densely distributed, flexible roots near the soil surface (Styczen and Morgan, 1995). For any given root mass, fine roots provide greater pullout resistance due to their higher surface area (Gray and Sotir, 1996). Roots with a diameter larger than 20 mm have less significance in terms of soil reinforcement (Reubens et al., 2007). This is because they cannot employ their maximum tensile strength before slipping through the soil, as the main function of larger size roots is to anchor (Bischetti et al., 2005). Therefore larger sized roots are less suitable for increasing soil cohesion in the upper layer (Bischetti et al., 2005; Tosi, 2007).

The tensile strength of roots depends on the plant species, the environment, the diameter of roots and their orientation in the soil, as well as any seasonal variations that take place (Gray and Sotir, 1996). However, Bischetti et al. (2005) assert that environment is not a modifying factor under any circumstances. Plant effectiveness for slope stability mainly depends on the resistance of the roots to tension as well as on the root density, orientation and distribution within the soil profile (Coppin and Stiles, 1995). To express this relationship, Wu (1976) developed a soil reinforcement model which has been widely used in soil reinforcement studies ever since (e.g., Bischetti et al., 2005; Gray and Sotir, 1996). Effective vegetation selection for slope stabilization relies on factors such as stabilization objectives as well as soil and site conditions. In terms of mass stability, woody vegetation is preferable to herbaceous or shrub species due to its stronger and deeper root structure (Gray and Sotir, 1996). In terms of intercepting rainfall and preventing surficial erosion, herbaceous vegetation is better suited due to its dense, near surface root mat and surface cover by its foliage (Gray and Sotir, 1996). Shrubs are preferable on shallower depths (Gray and Sotir, 1996). They have comparable tensile strength to trees but due to their shallower root system, they cannot provide the same buttressing.

Mahonia aquifolium (Pursh) Nutt. is an evergreen shrub native to the forests of the Pacific Northwest of America. Since 1822 *M. aquifolium* has been recognised and cultivated as an ornamental plant throughout Europe (Seidemann, 1998; Terpó and Grusz, 1976). It has been acknowledged for its pharmacological use in human and veterinary medicine (e.g., Lans et al., 2007; Slobodníková et al., 2004) as well as its use in human alimentation (Moerman, 1998). Moreover, *M. aquifolium* is used as a natural colorant (Grae, 1974) as well as food and cover for wildlife (Francis, 2003; Vaughan and Black, 2006). Due to its tolerance to chemical pollutants it is also effectively employed in urban landscaping (Samecka-Cymerman and Kempers, 1999; Tóth, 1969). With its high abiotic tolerance, it is extremely hardy and adaptable for cultivation under various conditions (Lans et al., 2007). *M. aquifolium* populations could play a significant role in surficial erosion control (Hudek and Rey, 2009).

Until 2007, the Hungarian government encouraged farmers to grow *M. aquifolium* for ornamental purposes by subsidizing the establishment of new plantations (Anonymous, 2004).The harvest of foliage takes place between September and February, when the entire canopy is removed to ground level. After harvest, the root system of *M. aquifolium* plays the only protective role in soil fixation. Therefore it is important to determine how effective the root system of *M. aquifolium* could be for soil protection. Even though *M. aquifolium* has many favourable features in horticulture, there is no scientific study published on its root traits and morphology or its potential function on shallow mass stability and suitability for hilly areas. Therefore, the objective of this paper was to study the root morphological characteristics of *M. aquifolium* in order to determine its efficiency in soil reinforcement. For this, Wu's (1976) and Waldron's (1977) models were applied to horticultural farming practices under mountainous conditions.

As *M. aquifolium*'s root structure has never been subject to scientific evaluation, it has been important to distinguish the difference, if any, between cultivated (C) and non-cultivated (NC) root morphology to better determine its potential implications in horticultural engineering for slope stability. This is with the view to filling our knowledge gap and moving towards a universal database to be used for future ecological engineering in horticultural studies. Therefore individual plants from C and NC field conditions were measured and compared for root area ratio (RAR) followed by the root tensile strength (T_R) tests. Comparisons were then made to other previously studied species that were used or potentially could be used for slope stabilization. These results were used to calculate the additional soil shear strength provided by the roots at various depths.

Table 3.1 Soil texture, organic carbon (OC), total N (TN), soil C:N ratio and soil organic matter (SOM) results from the farm and garden experimental sites at Tyúkosdűlő in Szentendre, Hungary.

Soil properties	Units	Farm	Garden
Physical			
<2μ	g kg^{-1}	390	235
2-20μ	g kg^{-1}	180	117
20-50μ	g kg^{-1}	127	90
50-200μ	g kg^{-1}	152	200
200-2000μ	g kg^{-1}	151	358
Chemical			
OC	g kg^{-1}	19.4	9.9
TC	g kg^{-1}	1.69	0.86
C:N	ratio	11.5	11.4
SOM	g kg^{-1}	33.6	17.1
$CaCO_3$	g kg^{-1}	<1	<1

3.2 Materials and methods

3.2.1 Study area description

The study was conducted in Tyúkosdűlő (47°41′46″N; 19°04′07″E) which belongs to the Visegrád region in the north of Hungary. In terms of geology, the parent material consists of andesite of volcanic origin from the Miocene Era. The altitude of the study site varies from 230 to 285 m above sea level. The soil type is brown forest soil with clay illuviation which is generally shallow (0–25 cm depth) with a soil texture of clay loam. Climatic conditions are temperate continental with a mean temperature of 9°C and an annual precipitation of 600 mm. During the monitored period rainfall distribution was evenly shared between spring and summer (175 mm each). This was followed by a total precipitation of 145 mm in autumn. The lowest precipitation level fell during winter at 57 mm.

3.2.2 Farm and garden description

The study site is located in a representative small-scale farm (0.56 ha) of Hungary with a long existing horticultural background. *M. aquifolium* has been cultivated on the farm for 25 years to be sold for ornamental purposes, particularly for its cut green foliage. Soil samples from the farm and garden sites were taken before experimentation to analyse the soil texture, organic carbon (OC), total N (TN), soil C:N ratio, soil organic matter (SOM) and CaCO3. Table 3.1 shows the results of soil analysis both for the farm and garden sites. These results show that there were differences both in the physical and chemical soil properties of the two study sites, which is due to the difference in cultivation methods. Both sites face south with a slope angle of 13–14%. Once the plantation was established, the soil surface was only partially covered during the first 2 years which left the surface vulnerable to the elements. There was no irrigation at the plots; manure was applied to the beds before planting, with a further 0.03–0.05 kg m^{-2} of N (46%) fertiliser each spring. Four to five times a year weed control was necessary manually and/or with a cultivator. Disease control was essential several times a year and the plants were harvested from September until February. The NC plant samples were taken from the farmer's private garden. These seedlings received no cultivation, fertilisation or irrigation. Weed control and disease control were neglected.

3.2.3 Vegetation sampling

Fifteen individual C and NC plants were excavated. The harvested plants were seedlings aged between 1 and 3 years so as to evaluate plant efficiency at a young age. Excavation of older plants can often lead to root damage, jeopardising the accuracy of the final results. Due to the firmness of the clay soil the 'trench wall' method (Böhm, 1979) and 'core-break' sampling (Schmid and Kazda, 2002) were considered too complex to employ. Therefore the plant specimens were excavated by hand and when necessary with small tools or water (Mattia et al., 2005; Tosi, 2007). Each plant was photographed, marked, placed in an individual plastic bag (containing soil to ensure the roots stayed moist) and kept at 5°C until measurements were taken. Photos of the position of the root system which were taken during excavation were later used in the laboratory to replicate the original position of the root system in the soil. The repositioned roots were observed for any general trends or patterns in their morphology that was suggestive of their origins. The root distribution was recorded by counting the number of roots at each 5 cm interval from the beginning to the end of each root system.

3.2.4 Root area ratio measurements

Water was used to clean the remaining soil particles from the roots before measurements were taken. This was followed by the re-positioning of the root system to simulate the original position in the field. The diameter of the roots was measured at 5 cm intervals on the soil profile with a digital calliper from the ground surface until the end of the root system. These roots were also counted and placed in different diameter classes at each interval to obtain the RAR (dividing the root cross-sectional area by the surface area of horizontal planes) (Mattia et al., 2005; Schmid and Kazda, 2002).

3.2.5 Tensile strength tests

The instrument which was used to perform the root tensile strength tests was built by the Institute of Agricultural Hydraulics of the University of Milan and previously used in numerous other studies on tensile strength (T_R) (e.g., Bischetti et al., 2005; Hudek et al., 2007). The measuring equipment comprised a rectified guide with a mobile bogie. This was powered by a 0.09 kW motor. There was a speed reduction of 1:343. The speed reduction maintained the linear speed at a steady 10 mm min^{-1}; tensile force was measured by interchangeable load cells (50 and 500 daN), while displacement was measured by a potentiometer transducer (Bischetti et al., 2003). Plant roots were stored in a 15% alcoholic solution (Bischetti et al., 2005) until the laboratory tensile strength tests began. The conserved roots were measured at both ends and at the midpoint to obtain the mean diameter. Only healthy and undamaged roots with a minimum length of 15 cm were considered due to the instrument's limitations. Keeping or removing the bark of the roots would affect the results of the test (Gray and Sotir, 1996; Schmidt et al., 2001) so in the present study the bark remained intact so as to better evaluate the behaviour of the roots in their natural state.

Tensile strength (MPa) was obtained from the following equation:

$$T_R = \frac{F_{max}}{\pi} \cdot \left(D/_2\right)^2 \qquad (3.1)$$

where T_R is the root tensile strength, F_{max} is the maximum force (N) required to cause failure and D is the average root diameter (mm). Moreover, T_R is strongly affected by root diameter. The relationship between T_R and diameter is generally described by a simple power equation (Gray and Sotir, 1996):

$$T_R(D) = \alpha D^{\beta} \qquad (3.2)$$

where T_R is the root tensile strength, D is the root diameter and α (scale factor) and β (rate of strength decrease) stand for the empirical constants which vary between plant species. The α and β empirical constants are important in making an improved comparison between species as the T_R is strongly affected by root diameter. The T_R results vary significantly depending on the method of testing used (Bischetti et al., 2005); therefore, all the species listed in Table 3.2 were tested using the same measurement method in each of the studies by Bischetti et al., 2005, Hudek et al. 2007 and Mattia et al., 2005.

3.2.6 Soil reinforcement model

Soil shear strength (S_s kPa), measuring soil cohesiveness and resistance to shearing forces, is defined by the Mohr–Coulomb equation (Morgan and Rickson, 1995):

$$S_s = C + \sigma \tan \theta \qquad (3.3)$$

where C is soil cohesion, σ the normal stress on the shear plane and θ the angle of internal friction. Soil failure occurs when $\tau \geq S_s$ (where τ is the shear stress) (Gray and Sotir, 1996; Roering et al., 2003).

Vegetation provides additional cohesion to the soil. Therefore:

$$S^* = S_s + S_r \qquad (3.4)$$

where S* is soil–root system resistance (kPa) and S_r (kPa) represents the extra soil shear strength provided by the roots (Wu, 1995). According to Wu's model (Wu, 1976), S_r is defined by the following equation:

$$S_r = t_R(\sin\delta + \cos\delta \cdot \tan\theta) \qquad (3.5)$$

where t_R is the mobilised root tensile strength of roots per unit area of soil, δ (°) the angle of root deformation in the shear zone and θ (°) the angle of internal friction of the soil. However, Wu et al. (1979) showed that for most species, the term ($\sin\delta + \cos\delta.\tan\theta$) can be estimated to be 1.2. Therefore:

$$S_r \approx 1.2 t_R \tag{3.6}$$

The t_R can be calculated by using two plant root traits which are: T_R (MPa), representing the average root tensile strength and RAR (%), representing the surface area of roots per unit of soil area and which gives an estimation of root density in soil (Greenway, 1987). Therefore:

$$S_r = 1.2 T_R \cdot RAR = 1.2 T_R \cdot {}^{A_R}/_{A} \tag{3.7}$$

where A_R (mm^2) is the total cross-sectional area of roots intersecting a soil profile and A (mm^2) the total cross-sectional area of the soil profile. Finally, in order to account for variability of root diameters, Eq. (3.7) has to be written as follows, calculating T_R and RAR for different diameter classes (Bischetti et al., 2005):

$$S_r = 1.2 \sum_{i=1}^{N} T_{Ri} \, {}^{A_{Ri}}/_{A} \tag{3.8}$$

where T_{Ri} and A_{Ri} are T_R and A_R values for diameter class i, and N the number of classes. S_r can be calculated for each species and for different soil depths in order to study the evolution of additional root cohesion with depth.

Table 3.2 Root tensile strength (T_R), values of scale factor (α), rate of strength decrease (β), goodness of fit (R^2) and life forms ((MM) mesophanerophyton, (M) microphanerophyton, (N) nanophanerophyton, (Ch) chamaephyton, (H) hemikryptophyton) of *Mahonia aquifolium* and other compared species.

Species	Life form	Mean Tensile strength (MPa)	α	β	R^2	References
Mahonia aquifolium	N	19.2	15.57	-0.44	0.76	Present study
Thymus serpyllum	Ch	22.3	14.67	-0.76	0.58	Hudek *et al.*, 2007
Pinus nigra	MM	15.2	12.41	-0.69	0.50	Hudek *et al.*, 2007
Quercus pubescens	M, MM	14.4	17.37	-0.62	0.73	Hudek *et al.*, 2007
Achnatherum calamagrostis	H	40.2	17.58	-1.22	0.86	Hudek *et al.*, 2007
Aphyllanthes monspeliensis	H	48.9	16.57	-1.02	0.75	Hudek *et al.*, 2007
Alnus viridis	M, N	20.4	34.76	-0.69	0.34	Bischetti *et al.*, 2005
Corylus avellana	M	67.8	60.15	-0.75	0.57	Bischetti *et al.*, 2005
Salix caprea	N, M	47.8	34.50	-1.02	0.82	Bischetti *et al.*, 2005
Salix purpurea	M	51.4	26.33	-0.95	0.55	Bischetti *et al.*, 2005
Larix deciduas	MM	66.1	33.45	-0.75	0.68	Bischetti *et al.*, 2005

Picea abies	MM	38.9	28.10	-0.72	0.72	Bischetti *et al.*, 2005
Fraxinus excelsior	MM	36.8	35.73	-1.10	0.71	Bischetti *et al.*, 2005
Fagus sylvatica	MM	57.4	41.65	-0.97	0.78	Bischetti *et al.*, 2005
Atriplex halimus	N	23.1	73.00	-0.60	0.25	Mattia *et al.*, 2005
Pistacia lentiscus	M	15.4	91.20	-0.45	0.16	Mattia *et al.*, 2005

3.3 Results

3.3.1 Root distribution and root morphology

The highest root density was found at the 5 cm soil layer for both cultivated (C) and non-cultivated (NC) plants. However the mean number of roots was significantly higher for C plants compared to NC ($t = 2.90$, $^{**}p < 0.01$, Two-sample t-test). C plants had a mean root number of 98, 78, 53, 39 and 24 at 5, 10, 15, 20 and 25 cm soil depth respectively. NC plants had a mean root number of 56, 17, 29, 6 and 7 at 5, 10, 15, 20 and 25 cm soil depth respectively. At 30 and 35 cm soil depth the NC plants had a mean root number of 1 while the C plant roots only reached 25 cm soil depth. Table 3.3 shows the percentage of the total mean root count in different diameter classes and soil levels for C and NC plants. Both C and NC plants had the highest percentage of their total mean root count in the > 0.5 mm diameter class at 5 cm soil level. The largest root diameter for cultivated *M. aquifolium* was 7.62 mm, while for non-cultivated *M. aquifolium* the largest root diameter was 4.37 mm. The results strongly suggest that cultivation results in a higher plant root count. All examined *M. aquifolium* roots showed dominant tap root morphology but with noticeable differences between C and NC plants. Non-cultivated seedlings presented only a few lateral and sinker roots (Figure 3.1a–c) although their tap roots were longer compared to plants from cultivation, which showed a more developed lateral and sinker root structure (Figure 3.2a–c). Non-cultivated *M. aquifolium* seedlings develop a tap root before lateral roots, resulting in a herringbone topology, similar to many woody species (Reubens et al., 2007). With maturity the root structure becomes more complex. Some NC plants' tap root forked into two while some C plants' tap root divided into three or more branches. Both C and NC plants' root structure showed acute bends, but these are more prevalent with NC plants.

3.3.2 Root area ratio (RAR)

Figure 3.3 shows the RAR with depth for *M. aquifolium* under C and NC field conditions. Cultivated *M. aquifolium* plants have a significantly higher mean RAR with depth than plants from a non-cultivated environment ($t = 3.67$, $^{**}p < 0.01$, Two-sample t-test). The highest RAR value, 0.04%, was obtained for C plants at 5 cm soil depth and reached its lowest at 25 cm with 0.02%. Non-cultivated *M. aquifolium* also had its highest RAR value at 5 cm with 0.025% and reached its lowest value (0.005%) at 35 cm. In both cases an increase of soil depth resulted in a decrease in RAR. This decrease approximates a logarithmic law.

3.3.3 Root tensile strength (T_R)

A total of 25 individual *M. aquifolium* roots were successfully measured. The diameter of the tested roots varied between 0.2 mm and 4.9 mm with a mean T_R of 19.2 MPa. The mean T_R results showed no significant difference between plants from a C or NC environment ($t = 1.81$,

**p > 0.01, Two-sample t-test). Figure 3.4 shows the relationship between T_R and root diameter for *M. aquifolium*. It shows that an increase in root diameter results in a decrease in T_R which confirms the power law relationship (Eq. (3.8)). Thin roots were most resistant to tension and as the diameter of the roots rose, T_R decreased. The α value (15.57) of *M. aquifolium* is comparable with the five species tested by Hudek et al. (2007). Its β value (−0.45) is also comparable with *Pistacia lentiscus* tested by Mattia et al. (2005) although *M. aquifolium* has the highest β value of all the listed species in Table 3.2. However it is necessary to emphasize that α and β values should only be interpreted together. Comparing the mean T_R results of *M. aquifolium* to other plant values in Table 3.2, shows that *Quercus pubescens, Pinus nigra* and *Pistacia lentiscus* have weaker T_R values, while *Thymus serpyllum*, *Alnus viridis* and *Atriplex halimus* have comparable results. However for precise comparison reasons, it is necessary to compare not only the strength of the root but the relevant root diameter as well. Though for detailed comparison it is recommended to evaluate the results together in a graph. By presenting the relationship between T_R and root diameter for *M. aquifolium* together with five other species (Figure 3.5) shows that *M. aquifolium*'s fine roots (< 1 mm) are weaker than the fine roots of four of the other species (*Q. pubescens, Aphyllanthes monspeliensis, T. serpyllum, Achnatherum calamagrostis*). However, roots of *M. aquifolium* with a diameter larger than 1 mm show greater strength compared to *T. serpyllum* (> 1 mm), *A. monspeliensis* and *A. calamagrostis* (from 1 to 1.2 mm). With *Q. pubescens*, *M. aquifolium* shows a greater strength with root diameters larger than 1.8 mm.

Table 3.3 The percentage of the total mean root count in different diameter classes and soil levels for cultivated and non-cultivated plants.

	Root diameter (mm)	**Soil depth (cm)**						
		5	**10**	**15**	**20**	**25**	**30**	**35**
Non cultivated	> 0.5	47.17%	13.64%	21.02%	3.12%	4.54%	0.56%	0.56%
M. aquifolium	0.51-1.0			1.42%	0.85%	0.56%	0.28%	0.28%
	1.01-1.5			0.56%	0.28%	0.28%		
	1.51-2.0		0.28%	0.85%	0.28%	0.28%	0.28%	
	2.01-2.5			0.56%				
	2.51 <	0.84%	0.56%	0.56%	0.28%			
Cultivated	> 0.5	32.19%	25.90%	17.13%	12.73%	7.57%		
M. aquifolium	0.51-1.0	0.52%	0.60%	0.77%	0.25%	0.17%		
	1.01-1.5	0.17%	0.09%	0.17%		0.08%		
	1.51-2.0		0.09%			0.08%		
	2.01-2.5	0.17%	0.09%			0.08%		
	2.51 <	0.18%	0.18%	0.26%	0.24%	0.24%		

a) b) c)

Figure 3.1 Root morphological characteristics of *Mahonia aquifolium* seedlings under non-cultivated soil conditions at different ages: (a) 1-year-old, (b) 2 years old and (c) 3 years old.

a) b) c)

Figure 3.2 Root morphological characteristics of *Mahonia aquifolium* seedlings under cultivated soil conditions at different ages: (a) 1-year-old, (b) 2 years old and (c) 3 years old.

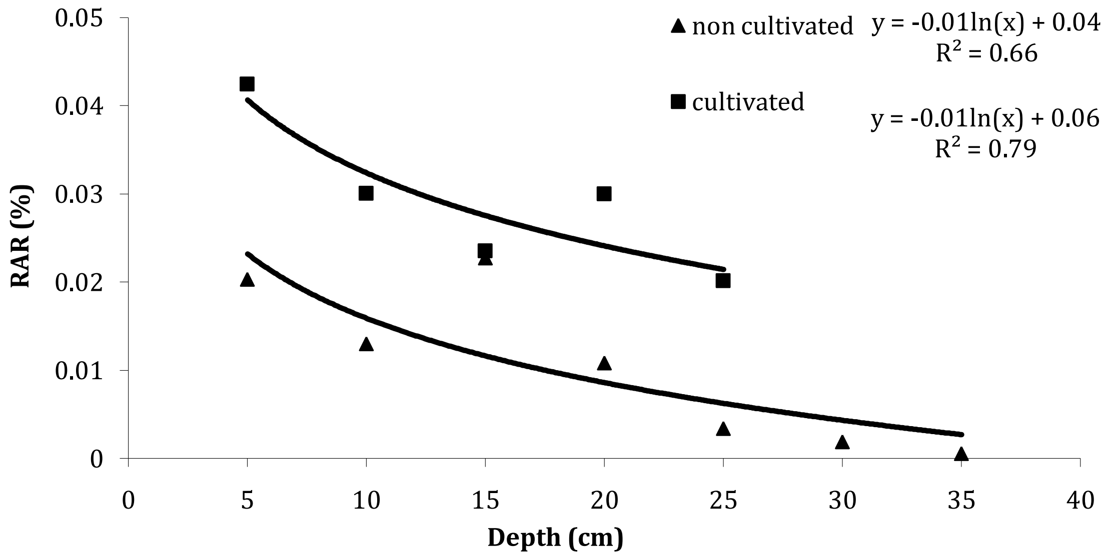


Figure 3.3 Root area ratio (RAR) with depth for *Mahonia aquifolium* from cultivated (C) and non-cultivated (NC) soil conditions.

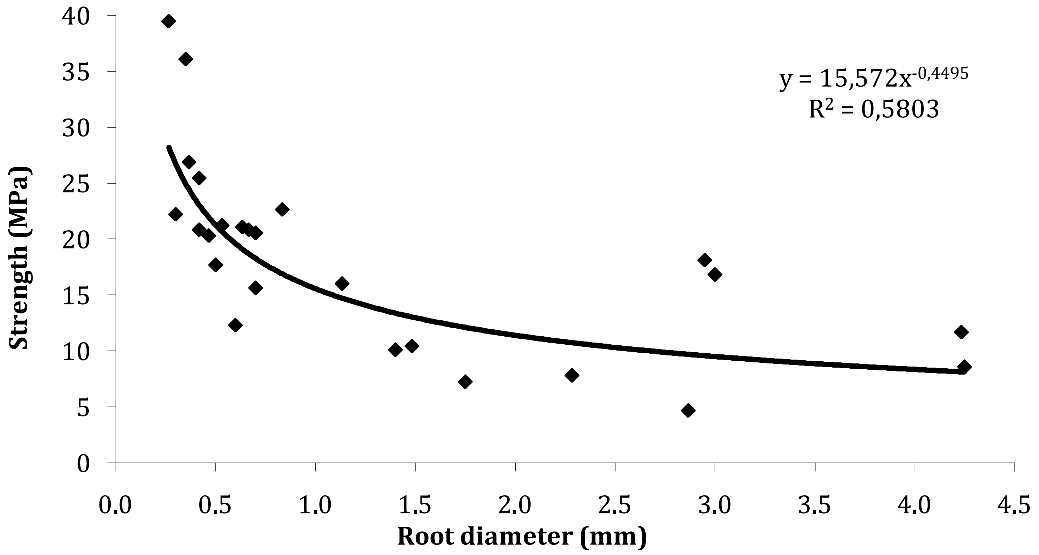


Figure 3.4 Relationship between root tensile strength and root diameter for *Mahonia aquifolium*.

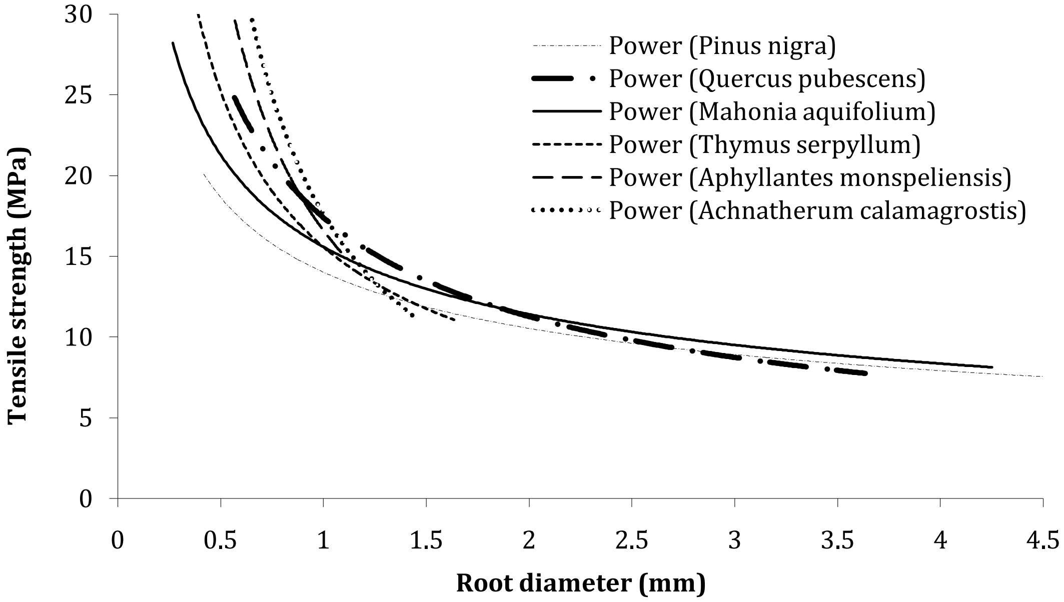


Figure 3.5 The relationship between root tensile strength and root diameter for *Mahonia aquifolium, Quercus pubescens, Aphyllanthes monspeliensis, Thymus serpyllum, Achnatherum calamagrostis* and *Pinus nigra.*

3.3.4 Additional soil shear strength provided by the roots (S_r)

The S_r results for cultivated and non-cultivated *M. aquifolium* are presented in Figure 3.6. A significant difference existed between the results of cultivated and non-cultivated *M. aquifolium* ($t = 3.67$, $^{**}p < 0.01$, Two-sample t-test). The strongest S_r was obtained for cultivated *M. aquifolium* at 5 cm soil depth with 9.7 kPa. The strongest Sr result for the non-cultivated *M. aquifolium* was found at 15 cm soil depth with 5.2 kPa. The weakest results for both C and NC plants were obtained at the end of their root system; for cultivated *M. aquifolium* at 25 cm soil depth with 4.6 kPa and for non-cultivated *M. aquifolium* at 35 cm soil depth with 0.1 kPa. As the plants RAR decreased, their S_r results decreased as well.

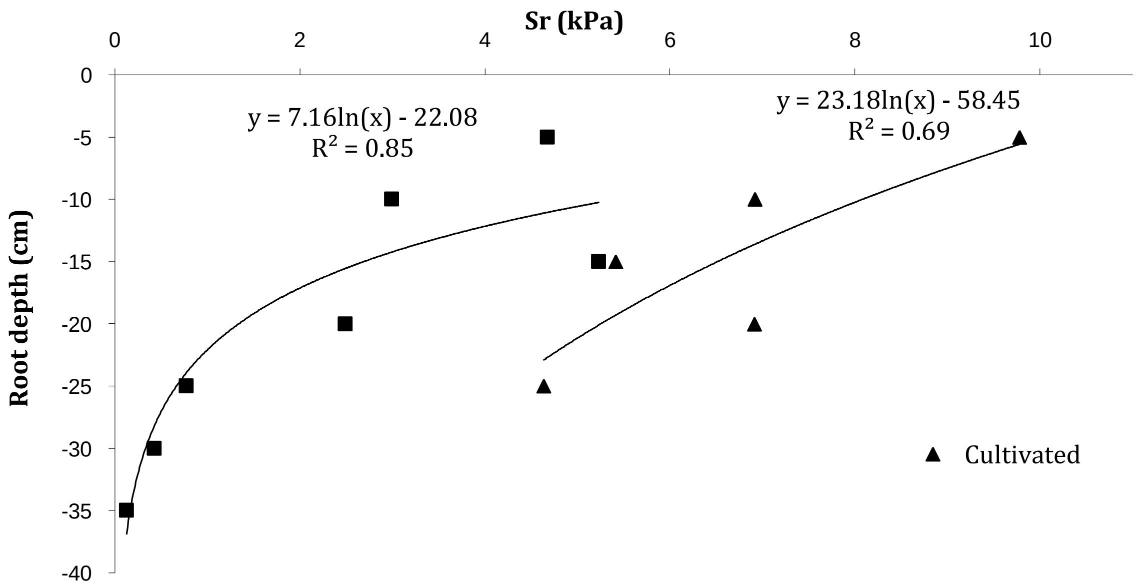


Figure 3.6 Additional soil shear strength provided by cultivated and non-cultivated *Mahonia aquifolium* roots.

3.4 Discussion

It was expected that both cultivated and non-cultivated *M. aquifolium* seedlings would have a dominant taproot morphology as it is largely held that root morphology is controlled by genetic characteristics (Gray and Sotir, 1996; Gyúró, 1974). However, the difference in the distribution of the taproot morphology can be explained by the fact that root morphology is also controlled by environmental conditions (e.g., local soil and climatic conditions) (Gray and Sotir, 1996; Gyúró, 1974). Roots under poor soil conditions develop a longer root structure with fewer branches (NC) in contrast to roots under a eutrophic and porous soil structure where roots can develop and branch better (C) (Gyúró, 1974; Hamza and Anderson, 2005). Compact soil impedes the majority of fibrous, fine roots from penetrating through soil layers which causes a decrease in fibrous root development in NC areas (Mattia et al., 2005). The effect of shallow tillage results in a more developed root structure in the top soil layer (Gyúró, 1974; Hamza and Anderson, 2005). This could be an additional reason for such dense root structures in C *M. aquifolium* plants.

Cultivation helps the plant to increase its root density which can help to increase the protection of the top layer of the soil as the high fine root count has a greater effect on soil fixation than a few coarse roots (Reubens et al., 2007). Due to the denser root structure of the C plants, increased evapotranspiration can also better protect the soil against over saturation. The acute bends of the plants root structure suggest the presence of obstructions in the soil. The discrepancy between the C and NC samples is most likely to occur as during cultivation there is a greater chance of obstacles being removed. Numerous other studies (e.g., Bischetti et al., 2005; Marler and Discekici, 1997; Tosi, 2007) have confirmed that the number of roots and their activity (Dhandar and Singh, 1989) is highest in the upper soil layer, followed by a slow decrease from then on, which means RAR decreases with depth. This is due to a decrease in nutrient content and increased soil compactness with depth. The discrepancy in RAR between the C and NC plants could be attributed to how nutrients are more evenly distributed throughout the soil by cultivation. In addition the clay soil of the non-cultivated field, due to its high degree of compactness, restricts the development of the fine roots.

The mean T_R results of *M. aquifolium* fell within the range that most species offer (10–40 MPa) (Gray and Sotir, 1996). The mean T_R results between the C and NC plants confirm the results of Bischetti et al. (2005) i.e. environment is not a modifying factor of root T_R under any circumstances (cultivation has no significant impact on *M. aquifolium*'s root tensile strength). The rarity of T_R tests on small roots (Genet et al., 2005; Mattia et al., 2005) makes *M. aquifolium* results difficult to compare to other plant results. In addition, the T_R results vary significantly depending on the method of testing used (Bischetti et al., 2005). Bischetti et al. (2005) and De Baets et al. (2008) assert that species with a high scale factor and a low decay rate are the most resistant to tension, though it is important to emphasize that α and β values should only be interpreted together. Species results displayed together in a graph can provide a revealing comparison on T_R/D relationships. However the required information on species is not always available to delineate them on a graph.

Studies on previously unstudied plants can help improve vegetation selection for future projects in ecological engineering in horticultural studies. A universal measurement system or improved compatibility between existing measurement systems is the most apparent means of ultimately bridging the information gap. Cultivated *M. aquifolium* has a well-developed root system with clustered lateral and sinker roots from the first year on and moderate tap root growth. Its T_R is comparable to various tree species without their adverse effects (i.e. weight surcharges, rigidity, and wind loading). These properties advocate its suitability for shallow slope stabilization in previously cultivated, abandoned lands where slope stabilization is an immediate concern. It is necessary to emphasize that an increase in soil shear strength only takes place when a number of roots penetrate through a shear stress plane (Tsukamoto and Kusakabe, 1984). For this reason, cultivated *M. aquifolium* at a young age can only provide additional soil shear strength at shallow slopes (25 cm). In light of this, young cultivated *M. aquifolium* plants would perhaps be better used in preventing soil erosion when the soil layer is deeper than 25 cm. On the other hand non-cultivated *M. aquifolium* has a faster growing, deeper penetrating tap root with poor lateral and sinker root development at an early age. Its T_R is identical to cultivated *M. aquifolium*. Therefore non-cultivated *M. aquifolium* could be considered less suitable for increasing soil cohesion at a young age. It is more likely that roots would act primarily as individual anchors and slip through the soil without employing their maximum tensile strength (Bischetti et al., 2005). With maturity the root system of non-cultivated *M. aquifolium* becomes more complex and could represent a long term stabilization agent. However, further testing must be carried out on older non-cultivated specimens to confirm with greater certainty its long term suitability in slope stabilization for horticultural engineering. Therefore it can be suggested that after setting up a new *M. aquifolium* plantation for slope stabilization, plants should be cultivated in a conventional way for the benefit of a well-developed root system in the early stage of plant growth.

If slope stabilization is not an immediate concern, a more sustainable cultivation method such as conservation tillage (e.g. reduced tillage or no till) could reduce the input costs of the farm which consequently would increase the profitability. In addition, it is not only of environmental but socio-economic importance to prevent land abandonment in mountainous areas by providing alternatives that allow farmers to continue horticultural farming practice in small-scale farms. As *M. aquifolium* has a high abiotic tolerance, a suitable root system for shallow slope stabilization at a young age and a diverse marketability, it can be suggested that *M. aquifolium* provides an important, horticultural plant alternative to small-scale mountain horticultural ecosystems and could improve the economic strength of rural mountain communities. This land use development model could help revitalise and repopulate the abandoned small-scale mountain rural communities in Hungary.

It is hoped that the findings of this study could also convince decision makers to reinstate the subsidy for *M. aquifolium* plantations in horticulture. Having established its restorative and protective potential in ecological engineering, it is perhaps relevant to consider its potential socio-economic impact. Given its multi-functionality, further studies of *M. aquifolium* as a component of mountain horticultural ecosystem rehabilitation should be carried out. As the young age of the tested plants meant that there was a lack of small sized roots available for measurement, it would be of interest to complete further testing on older specimens with a greater number of smaller sized roots. This will improve our knowledge on *M. aquifolium*'s lifespan as effective prevention of soil erosion.

3.5 Conclusion

This study provides the first empirical information on *M. aquifolium*'s root structure and its possible application in slope stabilization. The results of this study increase our knowledge about the morphology of *M. aquifolium*'s root system through the T_R and RAR tests, both in cultivated and non-cultivated soil conditions. It provides additional information on T_R and RAR to the existing database on new species, to be used in current and future hill slope stability studies in horticultural engineering. The root morphological results showed that there were significant differences between the cultivated and non-cultivated *M. aquifolium* plants. *M. aquifolium* under cultivation has a higher root density than those which are not under cultivation whereas the tap root of the non-cultivated plants grows deeper and more elaborately than the cultivated plants. This can help us better define the plants potential implications in horticultural engineering for soil stability. The T_R results confirmed that there was no significant difference between the cultivated and non-cultivated plant specimens in terms of tensile strength. The study also confirmed that the tensile strength of roots depends on the plant species and the diameter of roots. A greater increase of soil shear strength by roots was obtained by cultivated *M. aquifolium* due to its dense root system near the soil surface where the soil is generally the weakest. Even with fine roots of a lower T_R, *M. aquifolium*'s root structure is comparable in terms of slope stabilization with other plant species that are used or could potentially be used for slope stabilization.

Chapter 4

Studying the effects of *Mahonia aquifolium* population on small-scale mountain agro-ecosystems in Hungary with the view to minimising land degradation

This chapter is adopted from:

Hudek, C., and Rey, F., 2009. Studying the effects of Mahonia aquifolium populations on small-scale mountain agro-ecosystems in Hungary with the view to minimise land degradation. Land Degradation & Development 20, 252–260.

4.1 Introduction

In the 20th century, the structure of agriculture in Eastern European countries, including Hungary, first changed from (1) polarised ownership to (2) collectivisation and then with political changes, to (3) economic restructuring (Bouma et al., 1998). Polarised ownership was represented by small-scale, private farming with low input and yields. Collectivisation put greater focus on high yield production. Chemical fertilisers, pesticides and herbicides were introduced to new cropping technology along with new high yield crop varieties. These changes in land use practices resulted in harmful effects to the environment (Bouma et al., 1998). After 1989, the privatisation of land led to mixed ownership and a huge majority of small-scale (< 1 ha) farms. The market orientated production system and sustainability became the main priorities but a lack of capital goods in the agriculture sector hindered any development. Today, we can say that agriculture was one of the great losers of the changeover (Karsai, 1999). A large percentage of the rural population's primary or only source of income is from agricultural activities; this includes the hilly areas of Hungary.

Land use changes in agriculture can exacerbate land degradation (Cammeraat et al., 2005; Dunjó et al., 2003; Jordan et al., 2005; Pardini et al., 2003; Withers et al., 2007). During the last century land degradation caused by inappropriate land use management had become widespread in hilly areas of Hungary (Gábris et al., 2003). Hungary has currently some 9.3% weakly, 9.6% moderately and 6% strongly eroded areas (Németh et al., 2005). This results in approximately 80–110 million metric tons of topsoil loss every year (Németh et al., 2005). This is mostly linked to the Transdanubium and Northern hilly part of the country. The vulnerability of hillsides to erosion necessitates finding the best possible land use pattern to reduce soil loss, minimise any erosion processes and help sustain the environment in order to provide an important source of income for the rural population. This would help rehabilitate not only the physically damaged environment but also the social and cultural traditions which have suffered because of the economic migration from these rural areas.

Vegetation selection for slope stabilisation is important. Vegetation enhances slope stability by: (1) protecting the soil by reducing the energy of rainfall and runoff with its foliage; (2) increasing the resistance of soil by modifying its mechanical and hydrological properties with its root system and foliage (Styczen and Morgan, 1995). This second role in particular is significant for vegetation which is cultivated for its foliage and submitted to harvesting as the foliage is absent during certain periods of the year. Woody vegetation is superior in terms of mass movement stability due to its strong and deep sinker and tap-root structure (Gray and Sotir, 1996). Herbaceous vegetation is better at intercepting rainfall and preventing surficial erosion due to its dense, near surface root mat and surface cover provided by its foliage (Gray and Sotir, 1996). Shrubs affect the upper layers to a depth of 1.5 m with their root system (Styczen and Morgan, 1995) and are preferable on shallower depths as they avoid the adverse effects of trees (i.e. weight surcharges, rigidity and wind loading) (Gray and Sotir, 1996).

The highest degree of soil reinforcement by roots is obtained when root density is high near the soil surface where the soil is generally the weakest. Moreover, fine flexible roots with diameters between 1 and 20 mm are the most effective roots for soil reinforcement in the upper soil layer (Styczen and Morgan, 1995). This is because larger sized roots act primarily as individual anchors, mobilising only a small amount of their tensile strength before slipping through the soil and are therefore less suitable for increasing soil cohesion in the upper layer (Bischetti et al., 2005; Tosi, 2007). Fine roots also have superior pullout resistance due to their higher surface area (Gray and Sotir 1996). It is well known that root morphology is controlled by genetic characteristics and environmental conditions (Gray and Sotir, 1996; Thyll, 1992) but with any species, root structure will also change with age (Reubens et al., 2007). In many woody species, seedlings develop a taproot before the lateral roots, resulting in a herringbone topology, and with maturity the root structure becomes more complex (Reubens et al., 2007). It is not only of environmental but socio-economic importance to prevent land abandonment in mountainous areas by providing alternatives that allow farmers to continue farming.

Oregon grape [*Mahonia aquifolium* (Pursh) Nutt.] is a native, evergreen shrub of western North America. It was introduced to Europe as an ornamental plant in 1822 and is now naturalised in many parts of Europe including Hungary (Seidemann, 1998; Tóth, 1969; Zámbó, 1995). It is also used as a natural colorant, herbal medicine in human and veterinary medicine; it provides food and cover for wildlife and is also part of human alimentation (e.g. Grae, 1974; Hudek, 2005; Moerman, 1998; Samecka-Cymerman and Kempers, 1999). It has a high abiotic tolerance which makes it even more favourable and capable for cultivation under various conditions (Lans et al., 2007; Terpó and Grusz, 1976; Tóth, 1969). Because of its favourable root morphology and high tolerance of chemical pollutants, it could potentially be used in bioengineering at cut slopes and urban landscaping (Lans et al., 2007; Terpó and Grusz, 1976; Tóth, 1969). Moreover, stems grow rapidly and can reach heights of up to 1.5–2 m. Whenever *M. aquifolium* is cultivated for its cut green foliage it is harvested from September to February depending on market demand. During harvest the entire aboveground part of the plant is cut down as close as possible to ground level. This helps to assure the best quality of foliage for the next season which is a determining factor in market pricing. So even though the dense canopy of *M. aquifolium* is a determining factor in reducing the energy of raindrops, which is responsible for soil particle detachment, it can only play a role in erosion control for a limited time. After harvest, the root system of *M. aquifolium* plays the only protective role in erosion control. Therefore, the root system of *M. aquifolium* is even more important for sustainable soil protection.

M. aquifolium is a woody shrub with a strong and deep vertical sinker and tap-root system (Hudek et al., 2010). It possesses the beneficial properties of trees for mass movement prevention without the adverse effects (i.e. weight surcharges, rigidity and wind loading). It has a complex network of fine roots in the upper layer for surficial erosion control and the added advantage of an anchor-like tap-root. *M. aquifolium*'s root structure is potentially comparable to other plant species in terms of erosion control and it provides additional cohesion to the soil which increases the soil shear strength therefore it would be well suited for erosion control. However, under cultivation, *M. aquifolium*'s root system changes (Hudek et al., 2010). Cultivated *M. aquifolium* plants show a well-developed lateral and sinker root structure in the top 0–15 cm of soil layer compared to uncultivated plants. At this depth, its root density is significantly higher than at lower soil levels (Hudek et al., 2010). Cultivation helps *M. aquifolium* to increase its root density which could help to better protect the top layer of the soil from erosion as the large number of fine roots result in a higher overall tensile strength than a few coarse roots (Reubens et al., 2007).

The aim of this study was to test if *M. aquifolium* could play a significant role in surficial erosion control. More precisely, we investigated the efficiency of cultivated *M. aquifolium* age groups in surficial water erosion control under mountainous conditions in Hungary. For this, we measured the surface runoff and transfer of sediment from a long existing horticultural farming area.

4.2 Materials and methods

4.2.1 Study area

The study area is located in the Danube band in the north of Hungary (Figure 4.1). The Danube band lies on the boundary of lowland, alpine, medium-height mountains. The study area belongs to the Visegrád region. In terms of geology, it is related to the Börzsöny, as they both consist of andesite of volcanic origin from the Miocene Era (Karátson et al., 2006). Climatic conditions that influence hydrology and erosion have typical temperate continental characteristics with a mean temperature of 9°C and an annual precipitation of 600 mm. According to Bacsó (1973), an index number (0–70) indicates the increasing risk of erosion. The index number varies between 40 and 50 in the studied area.

4.2.2 Farm Description

The study was conducted at a typical small-scale farm (0.56 ha) regarded as a secondary source of income. This involves the *M. aquifolium* plantations, animal husbandry (rabbits and chickens), a bee farm, the *M. aquifolium* nursery and a kitchen garden. The farm has had a strong horticultural background (vineyards and orchards) for centuries and the conversion from the previous farm structure to the present was gradual. *M. aquifolium* has been cultivated there for 25 years to be sold for ornamental purposes, particularly for its cut green foliage. All cultivated *M. aquifolium* plots followed the same planting pattern, cultivation techniques and harvesting time. Two-year-old seedlings from a certified nursery were used to install the plantations (6.6 plants m^{-2}) where there is no irrigation. Manure was applied to the soil just before planting and subsequently every fifth year after that. A further 0.03–0.05 kg m^{-2} N fertiliser is used every year during spring time. Four to five times a year weed control is necessary manually and/or with a cultivator. Disease control is necessary several times a year. As previously stated, *M. aquifolium* is harvested from September until February; cut down as close as possible to ground level thereby assuring the best quality of foliage for the next season. As a result of 'clear cutting' all studied age groups of *M. aquifolium* population had the same canopy structure.

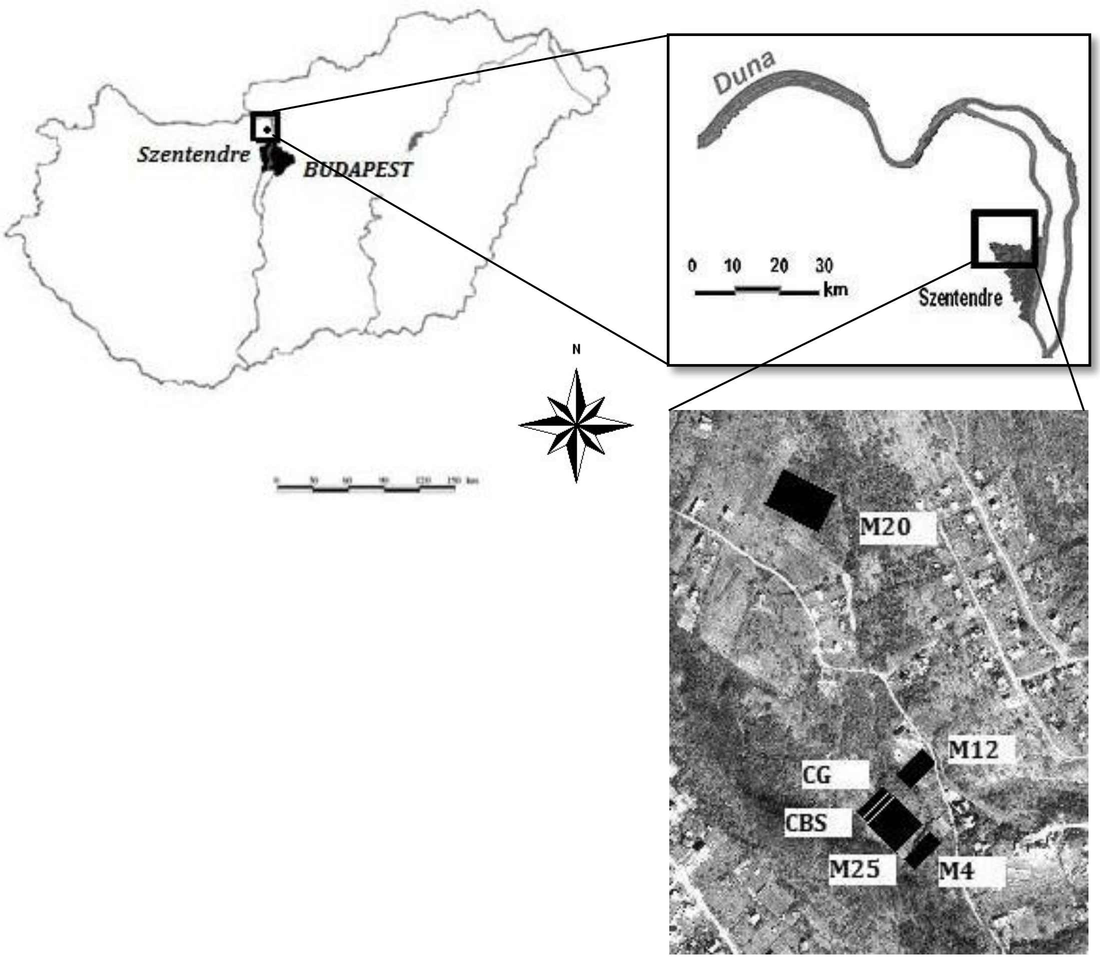


Figure 4.1 Location of the study area and the experimental sites at Tyúkosdűlő in Szentendre, Hungary.

4.2.3 Experimental Site

The experiment was carried out under field conditions at Tyúkosdűlő, located in the outskirts of Szentendre (47°41′45″N, 19°04′07″E). The altitude of the study area varied between 230 m and 285 m a.s.l. The soil type is brown forest soil with clay illuviation which is generally shallow (0–25 cm depth). Six hill slopes, with a total area of 0.33 ha were selected on which to measure runoff and erosion. All selected fields, four cultivated and two controlled, were farmlands. These individual fields were physically separated from each other; therefore they had no influence on each other's collected samples. All fields were facing south with a slope angle of 13–14% and with the same slope length of 30 m. The four cultivated plots had four different ages of *M. aquifolium*; 4 years old in the 210 m^2 area (M4), 12 years old in the 340 m^2 area (M12), 20 years old in the 1656 m^2 area (M20) and 25 years old in the 910 m^2 area (M25). A bare soil field (CBS) of 88 m^2 and a grass field (CG) of 108 m^2 represented the control fields. All plots were contour tilled.

The duration of the study period was from 1 June 2007 to 31 May 2008. The harvest during the experimentation took place in October 2007 resulting in a 6 month absence of the aboveground vegetation. A local meteorological station was installed for the duration of the study period, giving data on temperature and total precipitation on a daily basis. Pipes and collector tanks were installed at the lower end of the slope at all six plots in order to collect surface runoff and sediment during the period of experimentation. In cases when the rainfall event was small and resulted in a negligible amount of runoff, no sample was taken. Any runoff that was left in the tanks was collected after the next valuable rainfall event. Pipes and tanks were emptied and cleaned of retained sediment after every collection. The runoff water was filtered for suspended sediment which was added to the collected sediment.

4.2.4 Statistical Evaluation

The effects of treatment on runoff and soil loss were analysed by an analysis of variance (ANOVA) after verifying the variance of normality and homogeneity. Fisher's least significant difference (LSD) post hoc tests ($p<0.05$) were used to analyse the smallest significant differences between pairs of treatments. Statistical analyses were performed by using the program STATISTICA Version 8.0 (StatSoft©) for Windows (StatSoft Inc., 2007).

4.3 Results

4.3.1 Rainfall Distribution

There were a total of 86 rainfall events during the monitored period (Figure 4.2) with a total precipitation of 551.5 mm. The highest frequency of rainfall occurred in September 2007 and March 2008 with 11 rainfall events each month, the least in February 2008 with 1 rainfall event. The wettest month was August 2007 with a total of 96 mm of rain and the driest was February 2008 with 1 mm. The heaviest rainfall in a single day during the experimentation took place on the 5th June with 35 mm.

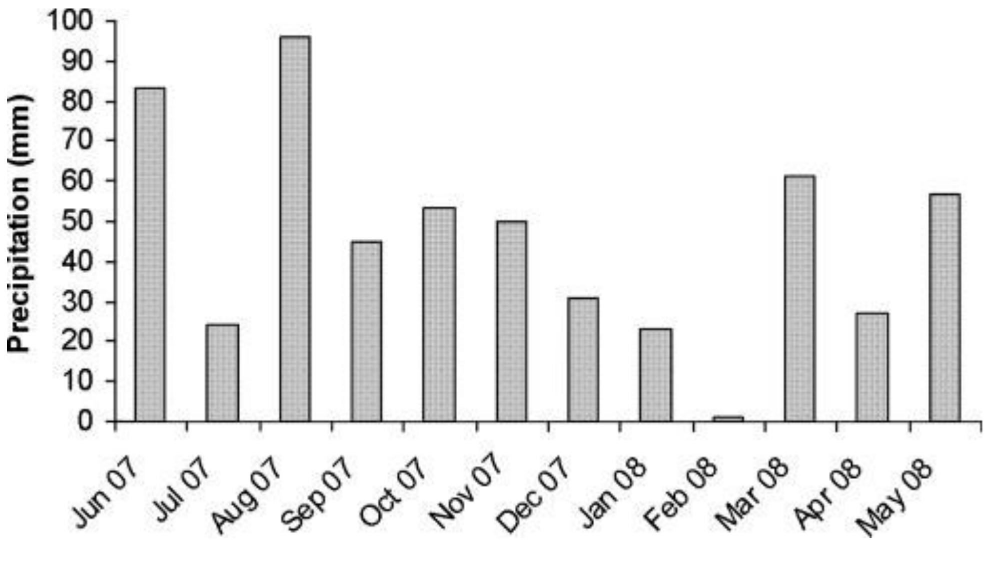


Figure 4.2 Measured monthly precipitation during the study period (June 2007 – May 2008) at Tyúkosdűlő, Szentendre, Hungary.

4.3.2 Runoff and Soil Loss

A total of 17 erosive episodes were evaluated. The volume of runoff and soil loss was site specific. The cumulative runoff graph (Figure 4.3) of the six different experimental plots showed that the most cumulative runoff was captured from the two control sites; CBS (382.9 mm), CG (258.5 mm), followed by the cultivated plots: M4 (118.2 mm), M12 (91.1 mm), M20 (68.5 mm) and M25 (63.8 mm). When results from plot CBS were compared to the results of the shrub population, the following decreases in runoff were obtained: 69, 76, 82 and 83% with increasing population age (M4, M12, M20, M25). These results confirm that when compared to the two control plots (CG, CBS) the *M. aquifolium* plantations (M4, M12, M20, M25) significantly reduced runoff. The results also indicate that 2 years after setting up a new *M. aquifolium* plantation (with 2-year-old seedlings) the cumulative runoff decreased by 69% compared to the bare soil field. When results from the grass plot (CG) were compared to the results of the shrub population the following decreases in runoff appeared: 54, 64, 73 and 75% with increasing population age (M4, M12, M20, M25). Among the cultivated plots' cumulative runoff results showed differences between ages. Less cumulative runoff was found at the older *M. aquifolium* cultivations than at the younger plots. When M25 was compared to the younger M20, M12 and M4 plantations it had 7, 30 and 46% lower cumulative runoff, respectively. The cumulative runoff results also showed that after 20 years of cultivation, there is a considerably smaller decrease in runoff. The ANOVA test result confirmed significant differences between treatments in the quantity of runoff ($F=18.36$, $p<0.000$). The differences between individual means are presented in Table 4.1.

The cumulative soil loss graph (Figure 4.4) shows that the lowest cumulative soil loss was collected from CG (0.005 kg m^{-2}) followed by the shrub plantations: M25 (0.228 kg m^{-2}), M20 (0.356 kg m^{-2}), M12 (0.492 kg m^{-2}) and M4 (0.562 kg m^{-2}). The highest result was given by plot CBS with a total of 2.2 kg m^{-2} soil loss. When results from plot CBS were compared to the results of the shrub population, the following decreases in soil loss appeared: 74, 77, 83 and 89% with increasing population age (M4, M12, M20, M25). When results from plot M25 were compared to the results of the other shrub populations, the following increases in soil loss were gathered: 36, 53 and 59% with decreasing population age (M20, M12, M4). Results also confirmed that *M. aquifolium* populations significantly reduce soil loss compared to the bare soil surface ($F=5.98$, $p<0.0001$). The differences between individual means are presented in Table 4.2.

The cumulative runoff and soil loss results of different age groups of cultivation show that the oldest population of *M. aquifolium* has the lowest cumulative runoff and sediment results and as the population's age decreases the cumulative runoff and sediment values increase.

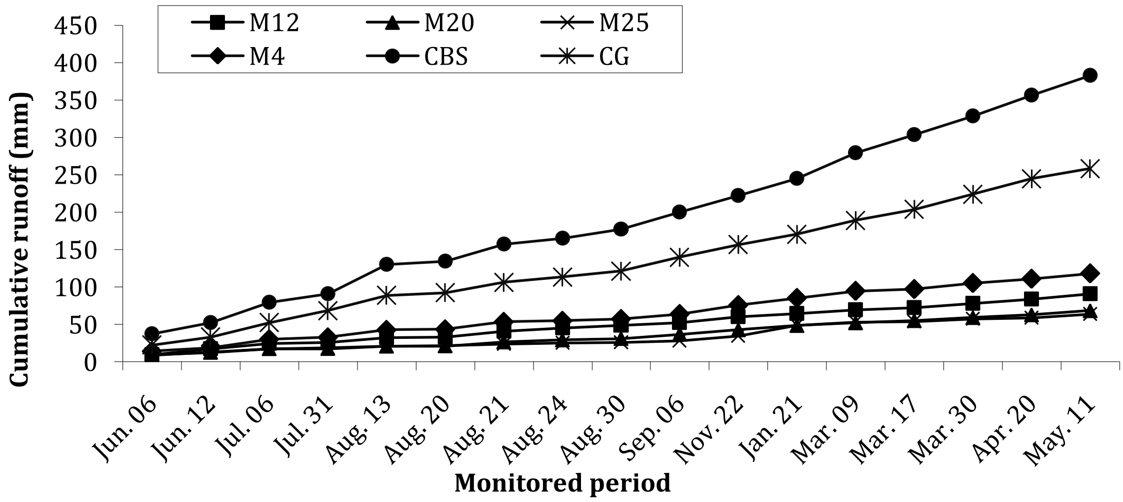


Figure 4.3 Cumulative runoff results of the six different experimental plots during the study period.

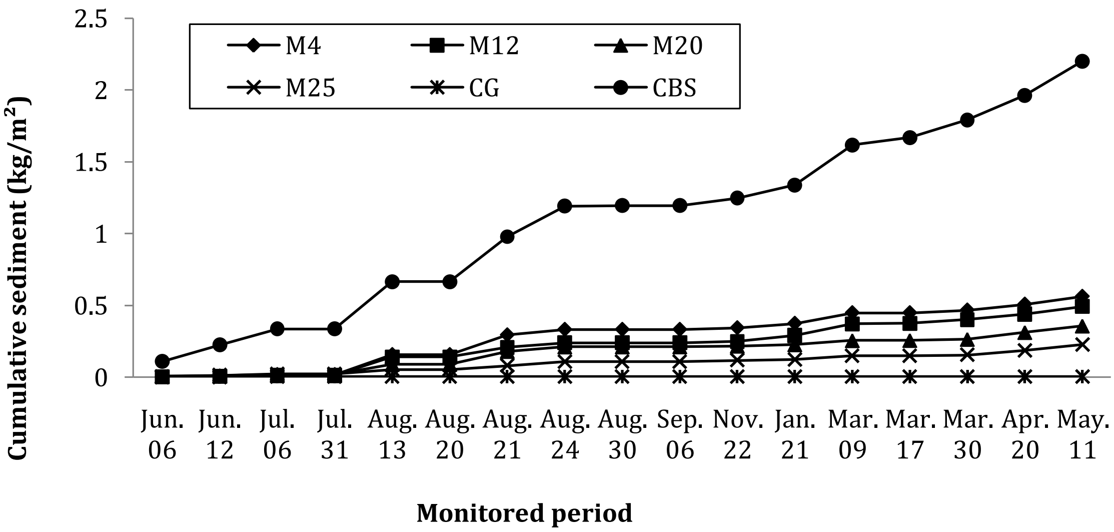


Figure 4.4 Cumulative soil loss results of the six different experimental plots during the study period.

Table 4.1 Significance level of the post hoc LSD test values to test the differences in runoff between pairs of plots.

Treatment	M4	M12	M20	M25	CG	CBS
M4		0.501268	**0.044313**	**0.006735**	**0.000703**	**0.000007**
M12	0.501268		0.176124	**0.038830**	**0.000065**	**0.000000**
M20	**0.044313**	0.176124		0.466027	**0.000000**	**0.000000**
M25	**0.006735**	**0.038830**	0.466027		**0.000000**	**0.000000**
CG	**0.000703**	**0.000065**	**0.000000**	**0.000000**		0.211787
CBS	**0.000007**	**0.000000**	**0.000000**	**0.000000**	0.211787	

Statistically significance at $p<0.05$ marked bold.

Table 4.2 Significance level of the post hoc LSD test values to test the differences in soil loss between pairs of plots

Treatment	M4	M12	M20	M25	CG	CBS
M4		0.670335	**0.034775**	0.290548	0.282304	**0.008385**
M12	0.670335		0.084282	0.512039	0.359666	**0.002010**
M20	**0.034775**	0.084282		0.304580	0.777771	**0.000003**
M25	0.290548	0.512039	0.304580		0.507569	**0.000304**
CG	0.282304	0.359666	0.777771	0.507569		**0.037532**
CBS	**0.008385**	**0.002010**	**0.000003**	**0.000304**	**0.037532**	

Statistically Significance at $p<0.05$ marked bold.

4.4 Discussion

In the present study results showed that the increasing population age of cultivated *M. aquifolium* resulted in a decrease in runoff and soil loss. This is in agreement with previous research which showed that the root structure becomes more complex with maturity (Reubens et al., 2007) resulting in a greater protective function in terms of soil erosion. Therefore, the age of a cultivated *M. aquifolium* population is a determining factor in its effectiveness in erosion control.

The fact that 2 years after setting up a new *M. aquifolium* plantation, the cumulative runoff decreased by 69% and the cumulative soil loss decreased by 74% (Table 4.3), indicates that *M. aquifolium* populations play a significant role in erosion control within a short period of time. This is due to their fast growth and development which provides better surface cover and ultimately better soil protection. Fast growing and developing plant species perform better in terms of soil stabilisation (Andreu et al., 1998; Reubens et al., 2007).

The grass plot (CG) had high runoff results but this was not reflected in the sediment results as the undisturbed, more compact surface of the soil is largely impenetrable by precipitation and a high root density means it is almost impossible for the runoff to transport soil particles. Even though grass would provide the most effective erosion protection from the six studied plots, the land is ideally suited for horticultural purposes; *M. aquifolium* cultivation provides a higher income and incentive for farmers. Even though vineyards and orchards were cultivated for centuries at the study area farmers are not interested in restoring the old plantations and terraces. This is due to the high establishing and maintenance costs of the cultivations and the strong competition in the market with other larger farms. In contrast, *M. aquifolium* has relatively low establishing and maintenance costs together with a wide marketability e.g. fitoterapy, alimentation, ornamental purposes.

Studies carried out on the effects of other species (e.g. *Medicago arborea*, *Psoralea bituminosa*, *Lavandula stoechas*) on runoff and soil loss compared to bare soil provided weaker results than *M. aquifolium* (Andreu et al., 1998; Durán et al., 2006). Other species (e.g. *Genista umbellate* and *Thymus* *baeticus*) showed comparable results whilst others (e.g. *Thymus serpylloides, Santolina rosmarinifolia* and *Salvia lavandulifolia*) gave stronger runoff and soil loss results than *M. aquifolium* (Durán et al., 2006). These studies expressed the effects of plant species on runoff and soil loss when compared to bare soil as a percentage. So, while these comparisons are not definitive they can be taken as an indicator of the value of these plants in terms of soil protection.

Even though *M. aquifolium* populations can help prevent runoff and soil loss on mountain slopes, selecting the appropriate tillage system for any given environmental condition or cultivation results in a further decrease in soil loss and an increase in available water in the soil (Myers and Wagger, 1996). To accompany a *M. aquifolium* plantation with reduced cultivation or conservation tillage would further improve its protective function. Keeping the soil surface permanently covered is a fundamental principal of conservation tillage (e.g. covering the soil with living or dead mulch). To change from conventional tillage to conservation tillage would not only be a step towards reducing top soil loss but also a step towards more sustainable land use management. The use of a permanent sward of grasses or mulches in permanent cultivations (e.g. orchards and vineyards) has been a recommended method of soil management since the 1950s (Lipecki and Berbec, 1997). Besides surface protection they also play a significant role in weed control which would also reduce the threat of agricultural residues reaching off-site ecosystems.

Even with conventional farming it would be beneficial to reduce cultivation before harvesting the canopy or provide adequate crop cover during the period when the soil is at the maximum risk of erosion (when the plant canopy is absent). This would help to further reduce runoff and soil loss from the farm. This land use development model could help revitalise and repopulate the abandoned small-scale mountain rural communities in Hungary. As a potentially important economic activity in mountainous areas of Hungary it could positively address many socioeconomic problems as well the problem as land degradation. A community with greater economic strength and confidence would likely see a reduction in illegal logging, illegal fire wood collection and illegal hunting activities. It could also decrease the economic migration from the rural areas which would help protect the cultural heritage.

Farmers' primary demand from agriculture is profitability. Without satisfying this demand our effort to prevent or restore soil degradation is jeopardised. Therefore, we can suggest that *M. aquifolium* could suit not only the environmental conditions, but also could satisfy economic and market demand and prevent land abandonment in small-scale mountainous areas in Hungary.

Table 4.3 Age, size, cumulative runoff and sediment results at the different study sites.

Plot	Age (year)	Size (m^2)	Cumulative runoff (mm)	Cumulative sediment (kg m^{-2})
M25	25	910	63.89	0.228
M20	20	1656	68.57	0.356
M12	12	340	91.11	0.492
M4	4	210	118.21	0.562
CBS	—	88	382.96	2.200
CG	—	108	258.56	0.005

4.5 Conclusion

This study is a first step towards understanding the potential of *M. aquifolium* in surficial erosion control. The measured surface runoff and transfer of sediment results confirm the hypothesis that a cultivated *M. aquifolium* population could play an efficient role in surficial water erosion control in mountainous conditions in Hungary. The results showed that *M. aquifolium* plantations have a significant influence on the quantity of surface runoff and the yield of sediment. Soil protection increases with the age of the plant population and shows that two years after setting up a new *M. aquifolium* plantation, the cumulative runoff significantly decreased. Therefore, *M. aquifolium* is ideal for small-scale farm practices on mountainous areas. This is due not only to its reduction of soil loss and runoff, but also to its low costs and requirements of little physical maintenance and its various means of marketability.

Chapter 5

Modelling soil erosion reduction by *Mahonia aquifolium* on hillslopes in Hungary: the impact of soil stabilization by roots

This chapter is under review as:
Hudek, C., Sterk, G., Van Beek, L.P.H., De Jong, S.M., (submitted) Modelling soil erosion reduction by Mahonia aquifolium on hillslopes in Hungary: the impact on soil reinforcement by roots. Catena, submitted.

5.1 Introduction

In Hungary there is a total of 5.5 million ha of agricultural land and 47% of this is classified as private farm lands with a typical farm size of 3 ha (KSH, 2011). About 80% of the country's horticultural plant production is linked to these private farm holdings (Szabó, 2007). Soil erosion affects about 30 to 40% of the land in Hungary (Centeri et al., 2001). The majority of soil loss is linked to the hilly regions of the country affecting 1.3 million ha of land (Kertész and Loczy, 1996). Conventional agricultural activities are often the main cause of soil degradation on hillsides (Heuser, 2010).

Soil erosion decreases the fertility of soil and leads to the need for additional fertilization of cultivated lands. In turn, this creates an additional cost to farm inputs (Centeri et al., 2009). However, small scale farm owners can rarely factor the costs of soil conservation into their farming budget due to a lack of profit (Centeri et al., 2009). When soil erosion occurs on small-scale farms the resulting reduction in cultivatable soil often leads to land abandonment. Appropriate plant selection with suitable cultivation and soil conservation techniques on hillslopes can result in a decrease in soil loss and an increase in available water in the soil, thereby allowing and encouraging continued agricultural activity (Myers and Wagger, 1996).

Mahonia aquifolium (Push) Nutt has been cultivated in Hungary for decades primarily for its cut green foliage (Hudek and Rey, 2009). The harvest of the foliage takes place during autumn and winter, and involves the removal of the entire canopy. The dense foliage plays a significant role in raindrop energy reduction, but after harvest its root system provides the only protective function against soil loss (Hudek et al., 2010). Roots increase the stability of the soil by improving its mechanical and hydrological properties (e.g. Gray and Sotir, 1996; Styczen and Morgan, 1995). Plant roots improve soil structure and increase the soil's organic matter content (Angers and Caron, 1998). Roots can increase surface roughness and increase infiltration capacity thus reducing the volume and velocity of surface runoff (Reubens et al., 2007). The tensile strength of roots as well as their adhesive properties help to reinforce the soil and reduce soil erosion (Greenway, 1987). The most effective root system for soil erosion control is a dense root network with a large number of fine roots close to the soil surface (Bischetti et al., 2005; Gyssels, 2005; Reubens et al., 2007; Wu, 1976).

In a previous field study (Hudek et al., 2010) the root system of cultivated *M. aquifolium* was found to be well suited for shallow soil stabilization from an early age. The *M. aquifolium* root study showed that a cultivated plant has in general a well developed, dense, lateral and sinker root system, and the densest root area ratio (0.04%) in the top 5 cm soil layer where the soil is generally weakest. The study also showed that the mean number of roots and the root area ratio (RAR) were significantly higher for cultivated *M. aquifolium* plants compared to non-cultivated ones. A gradual decrease in the mean number of roots and RAR with depth was also observed. However, there was no significant difference found between the root tensile strength (T_R) of cultivated and non-cultivated *M. aquifolium*. In addition to the root data, surface runoff and soil loss data were collected from the experimental plots with cultivated *M. aquifolium*. Those data were collected with the intention of testing the impact of *M. aquifolium* on slope stabilization. The field study confirmed the effectiveness of cultivated *M. aquifolium* on water erosion control (Hudek and Rey, 2009).

In addition to its suitability for soil protection, *M. aquifolium* can provide income to small-scale private farm owners, improving the long-term economic strength of these hillslope farms and consequently help prevent or reduce ongoing land abandonment. The use of permanent vegetation strips between crops on cultivated slopes is an effective way to trap runoff and sediment and reduce the risk of soil as well as agro-chemicals escaping from farmlands and polluting the off-site environment (Biamah et al., 1993). In this study it is hypothesized that contour strips of *M. aquifolium* on sloping agricultural fields are an effective method to control surface runoff and to reduce soil loss. A modelling approach was applied to evaluate the efficiency of *M. aquifolium* under various bio-physical conditions on reducing soil erosion. The application of a soil erosion model to predict soil loss and surface runoff from small-scale farms provides valuable insight in to the suitability of erosion control measures for both farmers and soil conservationists as experimental data are rarely available. It also makes sense from a logistics point of view as field experiments are expensive and time consuming and cannot be executed under all conditions. Data availability and prediction accuracy of models are among the most important factors for model selection (Moehansyah et al., 2004). Robustness and a strong physical basis are also important if a model is to be applied to different conditions.

Various erosion models (e.g. USLE, EUROSEM, WEPP) have been successfully applied in Hungary to predict soil loss and surface runoff from cultivated hillslopes (Centeri et al., 2009). However, previous field studies on *M. aquifolium* cultivation (Hudek and Rey, 2009; Hudek et al., 2010) resulted in a limited amount of input data for model applications. Therefore a model was sought which could estimate the annual soil loss from a field-size hillslope with limited available field data. Hence, the Revised Morgan-Morgan-Finney model (RMMF) was selected for this study. The RMMF is an empirical model with a relatively strong physical basis. It requires little input data, is easy to understand and apply, and has already been effectively used in different environments (e.g. Lopez-Vicente et al., 2008; Morgan, 2001; Shrestha et al., 2004; Vigiak et al., 2005).

A limitation of the RMMF model is that it does not include the impact of plant roots on soil erodibility. Yet, numerous studies have shown that plant roots notably increase the soil's resistance to erosion (e.g. Gyssels et al., 2005). In those model studies, in which the effect of roots (grass mixture and carrot) was quantified (e.g. De Baets et al., 2008; De Baets and Poesen, 2010), the model equations were based on extensive laboratory datasets. But even in the absence of such detailed datasets, there is a need for the inclusion of a simple, yet effective parameterization of root effects in erosion models. The RMMF model incorporates the effects of vegetation both on the water and the sediment phase of erosion processes exclusively in terms of the above ground biomass. Infiltration is implicitly related to the root depth and root water uptake but does not depend solely on it. The same holds for the detachment of sediment by surface runoff, which depends on the soil cohesion in the RMMF model. Whilst the effect of roots can be quantified conceptually through an additional root cohesion term (Morgan et al., 1995), vegetation effects on sediment entrainment are mostly hydraulic. They reduce the contact area between water and soil and thereby reducing the velocity and shear stress of the overland flow layer (Siepel et al., 2002). Although not explicitly quantified, root effects could be said to arise from the same mechanisms (Gyssels et al., 2005). While roots increase the soil surface roughness and porosity, change the soil structure and reduce the susceptibility to crust formation, thus leading to better infiltration rates and less surface runoff (Greenway, 1987; Reubens et al., 2007), such effects are difficult to quantify conceptually. Consequently, an empirical approach was adopted here in which roots were assumed to result in increased infiltration and less runoff.

The aim of the present study is therefore to evaluate the impact of *M. aquifolium* strips on hillslope erosion by means of the RMMF model. The following objectives have been defined in this study:
1. To incorporate through calibration the effects of *M. aquifolium* roots in the RMMF model using measured quantities of surface runoff and soil loss from experimental plots;
2. To quantify the reductions in surface runoff and soil loss caused by strips of *M. aquifolium* on a variety of agricultural hillslopes in Hungary.

5.2 Materials and methods

5.2.1 Field study description

The studied *M. aquifolium* fields were located on the outskirts of Szentendre which is part of the calc-alkaline volcanic Visegrád Hills in the north of Hungary. The area has a temperate continental climate. The altitude of the fields ranges from 230 to 285 m above sea level. During the field experiment (June 2007-May 2008), the total precipitation on the experimental fields was 551.5 mm from 86 rainfall events, which is within the range of the average yearly precipitation (500-600 mm) of the area. The major part of the rainfall was evenly shared between spring and summer (175 mm each) and the lowest precipitation was observed during winter (57 mm). All studied plots had a slope angle of 8° with a south facing orientation. The soil type is one of the main soil types of Hungary, characterized by a generally shallow (0-25 cm depth) brown forest soil with clay illuviation. It is classified as a Luvisol by the FAO classification (Micheli, 2009).

Four cultivated *M. aquifolium* plots of four different ages were studied to investigate the effectiveness of *M. aquifolium* on runoff and soil erosion control (Hudek and Rey, 2009).
These plots were 4, 12, 20 and 25 years old (M4, M12, M20 and M25), with surface areas of 210 m^2, 340 m^2, 1656 m^2 and 910 m^2 respectively and the same slope length (30 m). A fifth plot of 88 m^2 and with the same length served as a control bare soil plot (CBS). The CBS and the *M.*

aquifolium plots received the same cultivation and management. The harvest of all four *M. aquifolium* age groups took place during October which involved the harvest of the entire canopy, leaving the soil surface without ground and litter cover for months (from mid-October till mid-February).

Soil loss and surface runoff were measured for 17 rain storms during the entire experimental year. The other 69 rain events were too small to cause any surface runoff. The measured surface runoff and soil loss varied between the study plots. The highest cumulative runoff was measured from the CBS plot, and, as the age of the *M. aquifolium* plantation increased, the amount of cumulative surface runoff decreased. The highest cumulative soil loss also occurred on the CBS plot followed by the youngest *M. aquifolium* plot (M4), and as the age of the plantation increased the cumulative soil loss decreased.

5.2.2 The RMMF model

Morgan et al. (1984) developed an empirical soil erosion model to predict soil loss from field-sized hillslopes. The model was improved in 2001 (Morgan, 2001) and since then it has been referred to as the Revised Morgan, Morgan and Finney (RMMF) model. The RMMF model separates the soil erosion process into a water phase and a sediment phase. The water phase determines the annual energy of rainfall available to detach soil particles and the annual volume of surface runoff. The sediment phase determines the annual rate of soil particle detachment by rainfall and surface runoff, and the annual sediment transport capacity of the surface runoff.

5.2.2.1 Estimation of rainfall energy

Effective rainfall (ER) expresses the annual amount of rainfall reaching the ground surface after interception by vegetation canopy. ER is estimated in the model by the following equation:

$$\mathrm{ER} = \mathrm{R}(1 - \mathrm{A}) \qquad (5.1)$$

where R is the annual rainfall (mm) and A is a proportion (between 0 and 1) of the canopy interception. The ER is divided into rainfall that reaches the soil surface as leaf drainage (LD) and the rainfall that reaches the soil as direct throughfall (DT). Leaf drainage is calculated as:

$$\mathrm{LD} = \mathrm{ER\,CC} \qquad (5.2)$$

where CC is the canopy cover, equal to the proportion of the plant foliage covering the ground as viewed vertically from above. CC is expressed as a proportion between 0 and 1.
The remainder of the ER becomes the DT:

$$\mathrm{DT} = \mathrm{ER} - \mathrm{LD} \qquad (5.3)$$

The annual energy of the effective rainfall KE (J m^{-2}) is the sum of the kinetic energy of the leaf drainage ($KE(LD)$) and direct throughfall ($KE(DT)$):

$$\mathrm{KE} = \mathrm{KE(LD)} + \mathrm{KE(DT)} \qquad (5.4)$$

The kinetic energy of the leaf drainage is defined as (Brandt, 1990):

$$\mathrm{KE(LD)} = \mathrm{LD}(15.8 \cdot \mathrm{PH}^{0.5} - 5.87) \quad (5.5)$$

where PH (m) is the height of the plant canopy where PH > 15 cm otherwise KE is negative. The kinetic energy of the direct throughfall is calculated as:

$$\mathrm{KE(DT)} = \mathrm{DT}(11.9 + 8.7 \log \mathrm{I}) \quad (5.6)$$

where I (mm h^{-1}) is the typical value for the location-specific intensity of erosive rain.

5.2.2.2 Estimation of surface runoff

The annual surface runoff Q,(mm) is calculated from:

$$\mathrm{Q} = \mathrm{R} \exp\left({}^{-\mathrm{R_c}}/_{\mathrm{R_o}} \right) \quad (5.7)$$

where Rc (mm) is the soil moisture storage capacity and Ro (mm) is the mean annual rainfall divided by the number of rainy days per year. The value for Rc is defined by the following equation:

$$\mathrm{R_c} = 1000\ \mathrm{MS\ BD\ EHD} \left({}^{\mathrm{E_t}}/_{\mathrm{E_o}} \right)^{0.5} \quad (5.8)$$

where MS (wt%) is the soil moisture content at field capacity, BD (Mg m^{-3}) is the bulk density of the soil surface layer, EHD (m) is the effective hydrological depth of the soil and Et/Eo is the ratio of actual to potential evapotranspiration. The EHD is a parameter that accounts for the entire soil hydrology. A high value of EHD (> ~0.07) indicates a high saturation capacity of the soil and a smaller volume of surface runoff will be generated.

5.2.2.3 Soil particle detachment

The total annual kinetic energy (KE) is used to calculate the annual soil detachment by raindrop impact F (kg m^{-2}):

$$\mathrm{F} = \mathrm{K\ KE}\ 10^{-3} \quad (5.9)$$

where K (g J^{-1}) is the soil detachability index.
The soil particle detachment rate by surface runoff H (kg m^{-2}) is calculated by:

$$\mathrm{H} = \mathrm{ZQ}^{1.5}(\sin \mathrm{S})(1 - \mathrm{GC})10^{-3} \quad (5.10)$$

where Z is the resistance of the soil, S (°) is the slope steepness and GC is the proportion (between 0 and 1) of the soil surface protected by the vegetation or crop cover on the ground. The soil resistance (Z) is a function of the soil cohesion (COH in kPa):

$$\mathrm{Z} = 1/(0.5\ \mathrm{COH}) \quad (5.11)$$

The *COH* (kPa) can be measured on saturated soil with a torvane.
The value of the total annual rate of soil particle detachment *J* (kg m^{-2}) is equal to the sum of the detachment by raindrops and by surface runoff:

$$J = F + H \qquad (5.12)$$

5.2.2.4 Transport capacity of surface runoff

The value of the annual sediment transport capacity of surface runoff *G* (kg m^{-2}) is calculated as:

$$G = C\,Q^2\,(\sin S)10^{-3} \qquad (5.13)$$

where *C* is the crop cover management factor. The *C* value is a combination of the *C* and *P* values of the Universal Soil Loss Equation (Wischmeier and Smith, 1978).

Soil erosion can either be detachment limited or transport limited. When the surface runoff capacity exceeds the available detached sediment ($G > J$) the erosion process is detachment limited. When there is more detached material available than the surface runoff transport capacity ($G < J$) the erosion process is transport limited. To calculate the annual soil loss of the experimental plots, the *J* and *G* values are compared. The lower of the two values is limiting and equal to the annual soil loss rate.

5.2.3 Model input data

Meteorological model input data was collected from previous field studies (Hudek and Rey, 2009; Hudek et al., 2010). If input data were not available, recommended values by Morgan (2005) were used. A local meteorological station provided the rainfall records required for the model: annual rainfall (R) and the number of rainy days in a year (Rn). Unfortunately, the station does not provide data on rainfall intensity (I) so the typical value for temperate climates (10 mm h^{-1}) was used in the model (Morgan, 2005).

The soil detachability index (K) was taken from literature data based on the soil genetic classification and the soil texture of the studied plots (Stefanovits, 1966). Standard methods were used to measure the soil moisture content at field capacity (MS) and the top soil bulk density (BD) values of each studied plot (Gyori et al., 1998). Soil cohesion (COH) was determined from data collected by Morgan (2005). Morgan and Duzant (2008) published recommended values for the effective hydrological depth (EHD) in the RMMF model guide.
However, in the present study, EHD was used to calibrate the model as it was expected to increase with root development across the plots.

The landform parameter value, slope steepness (S) was measured by using a clinometer. The land cover parameters plant height (PH), ground cover (GC) and canopy cover (CC) were monitored weekly throughout the growing season. The monitoring of GC and CC was carried out by visual estimation (Anderson, 1986). The crop cover management factor (C) values were based on data recommended by Morgan (2005) and Morgan and Duzant (2008) in relation to land use types (tea, cocoa and coffee have been used as indicative for *M. aquifolium*). The value of the rainfall interception (A) was estimated from literature data based on similar plant architectures (coffee, tea, shrubs) (Basayigit and Dinc, 2010; Vigiak et al., 2005; Vigiak et al., 2006).

The ratio of actual to potential evapotranspiration (Et/Eo) was computed using the FAO guidelines (Allen et al., 1998) for potential evapotranspiration (Eo) and using the Thornthwaite-type monthly water balance model (Dingman, 2002) for actual evapotranspiration value (Et). These methods use monthly weather data, and assume a certain soil depth and soil type. To obtain the Eo value, first the reference evapotranspiration value (ETo) was determined with the Hargreaves method (Allen et al., 1998). This was followed by the calculation of the crop-specific potential evapotranspiration value for non-typical vegetation, referring to types or arrangements of crops that are not listed or described in the above-mentioned FAO guideline. The actual evapotranspiration Et over the year and the corresponding (Et/Eo) ratio were calculated after correction for the available moisture over the year using the Thornthwaite model.

5.2.4 Model calibration and application

5.2.4.1 Model calibration

The most sensitive parameters of the RMMF model for the water phase are MS, BD and EHD. These parameters are used for the calculation of Rc. Since field measurements were able to give site-specific values for MS and BD the calibration of these parameters was not considered. However, neither field measurements nor specified literature data were available for EHD, and therefore this parameter was used for model calibration on surface runoff. EHD was adjusted for each plot individually until the observed and predicted surface runoff closely matched.

For the sediment phase the K and C parameters were considered for model calibration. Parameter K is important when the erosion process is detachment limited, and parameter C is important when the erosion process is transport limited. The initial K and C parameter values were taken from literature data (Morgan, 2005), and were changed for each individual plot to match modelled sediment transport with observed values. Since the data of the RMMF model are inherently uncertain, the first-order-second-moment (FOSM) method (Ang and Tang, 1975) was used to study the effects of parameter uncertainty in parameter calibration. The FOSM method is based on the first-order terms of the Taylor series expansion about the mean value of each input variable and requires up to the second moments (mean and variance) of the uncertain variables (Maskey and Guinot, 2003). The FOSM method allows the estimation of uncertainty in the output variable without knowing the shapes of probability density functions of input variables in detail. The mean value and the standard deviations of the input variables are enough to compute the mean value and standard deviation of the output (Maskey and Guinot, 2003).

Eq. 5.14 is the function *y* of random input variables *X1, X2,… Xn*:

$$Y = y(X_1, X_2, \ldots X_n) \tag{5.14}$$

Eq. 5.15 is the calculated average or expected value of the performance function:

$$E(Y) = y\left(\bar{X}_1, \bar{X}_2, \ldots \bar{X}_n\right) \tag{5.15}$$

Eq. 5.16 is the variance of *Y*:

$$Var(Y) = \sum_i \sum_j \left(\frac{\partial y}{X_i} \frac{\partial y}{X_j} \bigg| m \right) Cov(X_i, X_j) \quad (5.16)$$

Where the quantity of $\partial y/\partial X_i$ is the sensitivity of *Y* to the input variable X_i, $|m$ refers to that all partial derivatives are evaluated at the mean values of X_i, X_j and $Cov(X_i,X_j)$ is the covariance between Xi and Xj.
If it can be assumed that input variables are unrelated, the partial derivatives can be approximated by differences in the computed outcome, and the variance estimated from:

$$Var(Y) = \left(\frac{\Delta Y(X_1)}{2} \right)^2 + \left(\frac{\Delta Y(X_2)}{2} \right)^2 + \ldots + \left(\frac{\Delta Y(X_n)}{2} \right)^2 \quad (5.17)$$

The differences are evaluated as the difference in the outcome *Y* when the input variable X_i is changed respectively by ± 1 standard deviation, all other variables remaining equal (Ang and Tang, 1975).

5.2.4.2 Model application

The model application to larger cultivated lands on hillslopes with permanent *M. aquifolium* strips required the division of a hypothetical cultivated area into smaller homogenous areas. In this study the impact of *M. aquifolium* strips on soil erosion control of a 100 m long cultivated field at various slope angles (8°, 12°, and 16°) and soil types (loam (Lo), clay loam (CL) and sandy loam (SL)) with different crops (maize, wheat, bean) and bare soil with and without *M. aquifolium* strips were evaluated. The impact of *M. aquifolium* strips was studied once by placing a 10 m strip at the end of the cultivated fields, and once by placing them in the middle and at the end. Soil input parameter values (Table 5.1) (MS, BD and COH) for the selected soil type were taken from Morgan (2005) and value K was taken from Stefanovits (1966). The land cover parameter values PH, GC and CC were taken from Morgan and Duzant (2008), and input data A, C and Et/Eo were taken from Morgan (2005). The initial EHD values were also based on values from Morgan (2005), which were subsequently modified according to the results of the model calibration of *M. aquifolium*.

To be able to calculate the propagation of surface runoff and sediment transport along the 100 m long hillslope, it was divided into ten sections of 10 m each. For each section the amounts of surface runoff and sediment transport were calculated using the following procedure: the surface runoff along the slope was calculated by adding the volume of surface runoff generated in a particular section to the surface runoff coming from the immediate upslope section. The model does not allow for infiltration of surface runoff, which is a simplification of the true erosion process. The surface runoff of the first (top) section was calculated according to Eq. 5.7. This amount in mm was converted to a volume per meter width by multiplying Q_1 with the length of the slope section (L_1):

$$Q_1^{'} = 10^{-3} Q_1 L_1 \quad (5.18)$$

Where $Q_1^{'}$ is in m^2. For the second section, the total volume of surface runoff is equal to the volume that was generated by the section itself plus the volume flowing in from uphill:

$$Q_2^{''} = 10^{-3} Q_2 L_2 + Q_1^{'} \quad (5.19)$$

Where $Q_2^{''}$ is again in m^2. For a hillslope consisting of i = 1,…, n sections, Eq. 5.19 can be generalized to:

$$Q_i^{''} = 10^{-3} Q_i L_i + Q_{i-1}^{''} \quad (5.20)$$

The $Q_0^{''}$ is the boundary condition and usually equal to zero, meaning that there is no inflow coming from uphill.

For the calculations of soil detachment by surface runoff (Eq. 5.10) and transport capacity (Eq. 5.13) the surface runoff volume needs to be converted to mm again. This is done by dividing the surface runoff volume by the cumulative length of the hillslope:

$$Q_i^{cum} = 10^3 \frac{Q_i^{''}}{\sum_{j=1}^{i} L_j} = \frac{Q_i L_i + 10^3 Q_{i-1}^{''}}{\sum_{j=1}^{i} L_j} \quad (5.21)$$

Where Q_i^{cum} is the cumulative surface runoff in mm along the hillslope.

The actual sediment transport along the hillslope (ST in kg m^{-1}) depends on the calculated amounts of detachment and the transport capacity of the surface runoff. For the calculation of detachment by surface runoff (Eq. 5.10) and transport capacity (Eq. 5.13), the Q_i^{cum} values are used for each slope section. The sediment transport calculation starts with calculating the transport capacity at the end of a section:

$$G_i^{'} = G_i L_i \quad (5.22)$$

Where $G_i^{'}$ is in kg m^{-1}. Next, the sediment transport deficit is calculated by withdrawing the incoming sediment transport from above from the transport capacity of the section:

$$ST_i^{def} = G_i^{'} - ST_{i-1} \quad (5.23)$$

ST_0 is the boundary condition and usually equal to zero, meaning that no sediment is entering from uphill. Depending on the value of ST_i^{def} the following rules apply:

- If $ST_i^{def} < 0 \rightarrow ST_i = G_i^{'}$ (deposition in section)
- If $ST_i^{def} = 0 \rightarrow ST_i = G_i^{'}$ (transport only; no soil loss or deposition)
- If $ST_i^{def} > 0$ then ST_i depends on the total detachment of the section:

- If $(F_i + H_i)L_i \geq G_i^{'} \rightarrow ST_i \ = G_i^{'}$ (detachment exceeds transport capacity)
- If $(F_i + H_i)L_i < G_i^{'} \rightarrow ST_i \ = ST_{i-1} + (F_i + H_i)L_i$ (transport capacity exceeds detachment)

5.3 Results and discussion

5.3.1 Model input data

Table 5.1 lists the mean values of the soil, landform and land cover input values of all studied plots. All four age groups of *M. aquifolium* had the same PH, CC and GC values, as the canopy harvest took place at the same time for each plot, and the re-growth of the aboveground vegetation occurred at the same rate. During the study period the percentage of CC and GC of the *M. aquifolium* plots varied between 0-0.9, and 0.1-0.9 respectively which gave an average weighted percentage of 0.31 for CC and 0.42 for GC. The PH of the plantation also varied during the study, (0 m to 0.8 m) giving an average weighted value of 0.22 m. As the A value is strongly influenced by the CC, GC and PH, the A value (0-0.25) varied with changes in the CC, GC and PH values through the study period. The weighted average value was 0.11 for the *M. aquifolium* plots, which means that the ER on the *M. aquifolium* plots was 484.8 mm, while for the CBS plot ER was the same as the annual rainfall (551.5 mm).

Table 5.1 Mean soil, landform and land cover input parameters of the CBS and all the *M. aquifolium* plots at Szentendre, Hungary.

Land use	Soil type	MS (wt %)	BD (Mgm^{-3})	Et/Eo (ratio)	K (g J^{-1})	COH (kPa)	A (0-1)	C	CC (0-1)	GC (0-1)	PH (m)	S (°)
CBS	Clay loam	0.24 (±0.01)	1.01 (±0.05)	0.05 (±0.03)	0.25	10	0	1.00	0	0	0	8
M. aquifolium	Clay loam	0.24	1.01	0.30	0.25	10	0.11	0.30	0.31	0.42	0.22	8

MS refers to soil moisture content at field capacity, BD to bulk density, K to soil detachability, COH to cohesion of the surface soil, Et/Eo to ratio of actual to potential evapotranspiration, A to canopy interception, C to crop cover management factor, CC to canopy cover, GC to ground cover, PH to plant height and S to slope steepness. Values between brackets indicate the measured or estimated standard deviation, as used in the FOSM analysis.

The highest value of Et/E0 was obtained at the initial and late plant stages (0.70 and 0.55 respectively). The lowest value of Et/E0 was obtained from the time of canopy harvest to the beginning of the initial stage (0.05). The initial K value of all plots was set to 0.25 g J^{-1}.

5.3.2 Model assessment

Table 5.2 shows the observed and predicted surface runoff and soil loss results after model calibration, together with the optimized EHD variables. The lowest value of EHD was obtained for the CBS plot (equivalent to a soil moisture storage capacity, Rc, of 2.33 mm) followed by the cultivated *M. aquifolium* plots in order of age (respective Rc values of 9.95 mm, 11.55 mm, 13.40

mm and 13.80 mm respectively). Given the exponential dependence of infiltration on the mean daily intensity (Eq. 5.7), this suggests that infiltration increases by 170% for a 4 year old *M. aquifolium* when compared to a bare plot. The calibrated EHD values suggest the beneficial influence of a developing root system on soil hydrology, meaning that the older the rooting system, the higher the infiltration capacity. This is in line with the results of Hudek et al. (2010), which show that rooting depth and density (RAR) changed with age during the early stages of a *M. aquifolium* plantation. It is important to note that this beneficial influence is not infinite as RAR cannot increase continuously and hence the reduced effect of RAR on erosion will level out eventually (De Baets et al., 2008). Figure 5.1a shows the total surface runoff as well as the propagated uncertainty as obtained with the FOSM method. While the predicted surface runoff is inherently uncertain and similar for the *M. aquifolium* plots, the decreasing trend with age seems to be upheld. The obtained EHD values after calibration (Table 5.2) are lower than those found in literature data, e.g. Morgan (2005) or Morgan and Duzant (2008). It has been recognized that the EHD value varies with surface crusting and the different rooting depth and density of the vegetation (Morgan and Duzant, 2008). In the present study it is assumed that the level of surface crusting did not change between the plots as all plots have the same soil type and cultivation technique.

Table 5.2 Observed and predicted soil loss and runoff values of the CBS, M4, M12, M20 and M25 plots after model calibration with the final estimates of EHD variables.

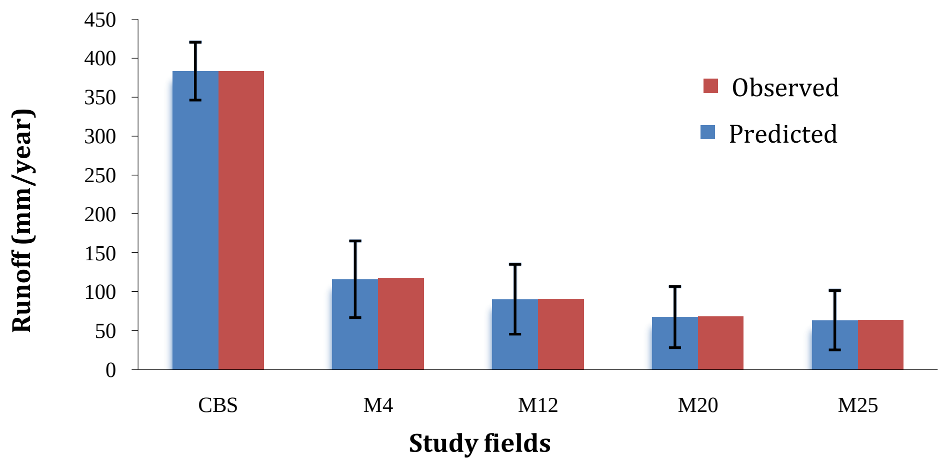
Plot	**Observed values**		**Predicted values**		**Calibrated EHD value**
	Runoff (mm)	Soil loss (kg m^{-2})	Runoff (mm)	Soil loss (kg m^{-2})	(m)
CBS	383.0	2.20	383.4	3.05	0.043
M4	118.2	0.56	116.7	0.57	0.075
M12	91.1	0.49	91.1	0.35	0.087
M20	68.6	0.36	68.1	0.19	0.101
M25	63.9	0.22	64.0	0.17	0.104

Table 5.2 also shows that the predicted soil losses are in reasonable agreement with the measured values for the *M. aquifolium* plots. The CBS plot gave the highest annual soil loss, followed by the *M. aquifolium* plantations, again in order from youngest to oldest. Slight under-predictions of soil loss were obtained for the M12 (0.14 kg m^{-2}), M20 (0.17 kg m^{-2}) and M25 (0.05 kg m^{-2}), while the prediction for the M4 plot was nearly similar to the measured value. It was assumed that differences between predicted and measured soil losses in the order of 0.05 – 0.17 kg m^{-2} are small and within the error margin of soil loss measurements. Since the simulated soil loss is lower than the observed values, the erosion process is transport limited for all *M. aquifolium* plots assuming that all inputs are correct. This means that any beneficial influence that could arise from the armouring function of roots is relatively small and lost against parameter uncertainty. In contrast, the model overpredicted the soil loss for the CBS plot, which indicated a detachment limited erosion process for the CBS plot. Therefore, it was decided to further improve the model on soil loss for the CBS plot only. The CBS plot had a greater number of rocks than the *M. aquifolium* plots, and therefore the original K value (0.25 g J^{-1}) was modified accordingly. The calibrated K value was 0.18 g J^{-1}, which resulted in a predicted soil loss of 2.25 kg m^{-2}. The presence of rocks in the CBS plot is due to the fact that prior to the study the plot had not been

subject to the same intensity of cultivation as the *M. aquifolium* plots. When farmers cultivate a field they tend to remove the rocks from the surface, leaving fewer rocks in cultivated fields compared to bare soil.

Uncertainty in the input results in slightly larger uncertainties in the case of soil loss (Figure 5.1b). While all *M. aquifolium* plots are distinct from the bare plot, the simulated soil loss decreases more rapidly with age than observed and levels off for the older plots (M20, M25), making the soil loss for these plots more similar to one another than is actually the case.

(a)



(b)

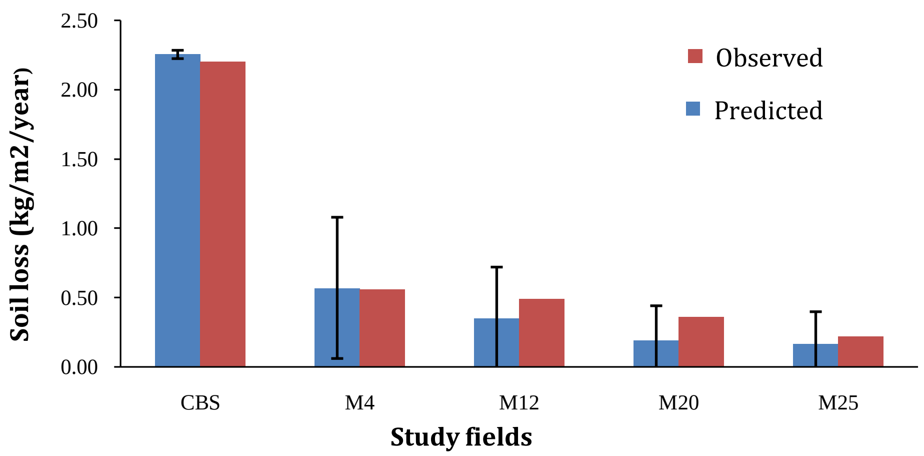


Figure 5.1a) Observed and predicted surface runoff and *b)* soil loss results of the five study plots (CBS, M4, M12, M20 and M25) together with the FOSM error propagation analysis of the RMMF model applied to a) runoff and b) soil loss forecasts. Error bars indicate the propagation of the uncertainty in the parameters of Table 5.2.

It is important to note that the RMMF model operates on a yearly scale. This leads to a loss of information in the management factor (C) in Eq. 5.13 and in the available pore space for infiltration as captured by the Et/Eo ratio in the computation of Rc in Eq. 5.8. This has implications as the *M. aquifolium* plots are bare for a substantial period of the year. Therefore the model cannot be expected to behave adequately when erosion is conditioned by isolated rainstorms that fall on very different soil surfaces in terms of interception and soil moisture status. The soil will be much dryer and the Rc larger when *M. aquifolium* has leaves and is photo-synthetically active. Despite this, the model performs adequately in assessing soil conservation effectiveness.

While this study did not reveal an appreciable reinforcing effect of roots with regards to the detachment of sediment by surface runoff, conceptually, the effect of roots can be quantified by means of an additional root cohesion term (Morgan, 1996). Previous erosion model studies have shown that root density in the top soil layer has an effect on soil erosion (e.g., De Baets et al., 2007). Although the contribution of roots to the overall shear strength of the soil can be expressed by the reinforced earth theory (Vidal, 1966), and can be expressed as an additional root cohesion (e.g., Waldron, 1977; Wu et al., 1979), the loading conditions under soil erosion vary and the values are indicative of the fixating effect of roots on soil erosion at best. In spite of the fundamental differences, quantitative estimates of root reinforcement have been applied and suggested in soil erosion modelling (Morgan, 1996), most likely in the absence of relevant data. It is unlikely that roots themselves operate through the soil resistance (Z in Eq. 5.11) as the bond between roots and soil is always less than that between soil particles themselves. However, roots do influence soil resistance, which is linearly related to the detachment by surface runoff (H in Eq. 5.10) by bearing some of the force of the overland flow which would otherwise be borne by the soil alone.

5.3.3 Impact of *M. aquifolium* strips on different crop fields

Model predictions of surface runoff and soil loss were first made for fields of 100 m in length; a bare soil surface (Bs), a maize crop (Ma), a wheat crop (Wh), and a bean crop (Be). The modelling was carried out on three different slope gradients: 8°, 12° and 16° (S8, S12 and S16), and three soil types: clay loam, loam and sandy loam (CL, Lo and SL). This was followed by the estimation of surface runoff and soil loss from the 100 m field with a 10 m wide *M. aquifolium* strip (M) at the end of the slope (Bs+M, Ma+M, Wh+M and Be+M).

Finally the model was run to estimate surface runoff and soil loss by placing a 10 m wide *M. aquifolium* strip in the middle and a 10 m strip at the end of the fields (Bs+M+Bs+M, Ma+M+Ma+M, Wh+M+Wh+M and Be+M+Be+M).

Table 5.3 lists the mean soil, landform and land cover input parameter values of the selected crop fields and soil types. The EHD value during the selected crops' vegetative period is based on the calibrated EHD value (0.075 m) of the 4 year old *M. aquifolium* plot. The EHD value used for the *M. aquifolium* strips are also based on the calibrated EHD values of the M4 plot.

Table 5.3 Input parameter values of the three selected crops (maize, wheat and bean) and soil types (loam, clay loam and sandy loam).

Land use	PH (m)	CC (0-1)	GC (0-1)	A (0-1)	C	Et/Eo (ratio)	EHD (m)	Soil type	MS (wt %)	BD (Mgm^{-3})	K (g J^{-1})	COH (kPa)
Maize	0.30	0.16	0.12	0.06	0.80	0.21	0.051	**Loam**	0.20	1.30	0.25	3
Wheat	0.23	0.27	0.10	0.10	0.76	0.23	0.053	**Clay loam**	0.24	1.01	0.25	10
Bean	0.30	0.16	0.12	0.06	0.82	0.20	0.051	**Sandy loam**	0.28	1.20	0.30	2

PH refers to plant height, CC to canopy cover, GC to ground cover, A to canopy interception, C to crop cover management factor, Et/Eo to ratio of actual to potential evapotranspiration, EHD to effective hydrological depth, MS to soil moisture content, BD to bulk density, K to soil detachability and COH to cohesion of the surface soil.

The highest runoff results were found on the Bs fields followed by the Be, Ma and Wh fields respectively (Table 5.4). The volume of runoff varied between the different types of soil. The lowest predictions were found on SL soil and the highest on CL. None of the studied fields showed any variation in the volume of runoff with changes in the slope gradient. This is due to the fact that the EHD, MS and BD values are independent of slope steepness in the model.
There is a steady reduction in the volume of surface runoff on all studied crop fields due to the presence of *M. aquifolium* strips (Table 5.4). The lowest volume of runoff was found in all cases when the *M. aquifolium* strips were placed both in the middle and at the end of the fields. The reduction in surface runoff was up to 7% when the *M. aquifolium* strip was placed at the end of the cultivated field and up to 13% when the strips were placed in the middle and at the end of the studied field. These results only partly reflect the actual volume of surface runoff reduction due to the presence of *M. aquifolium* strips; in reality more surface runoff may be lost to re-infiltration. One of the weaker points of the RMMF model is that it fails to take this re-infiltration into account.

Table 5.4 Runoff results (mm/year) of different crop fields under various soil types and slope gradients with and without *M. aquifolium* strips.

Field conditions	**Slope category and soil type**								
	S8-CL	**S12-CL**	**S16-CL**	**S8-Lo**	**S12-Lo**	**S16-Lo**	**S8-SL**	**S12-SL**	**S16-SL**
Bs	383.4	383.4	383.4	373.5	373.5	373.5	333.2	333.2	333.2
Bs+M	356.8	356.8	356.8	346.5	346.5	346.5	306.3	306.3	306.3
Bs+M+Bs+M	330.1	330.1	330.1	319.6	319.6	319.6	279.4	279.4	279.4
Ma	229.2	229.2	229.2	215.0	215.0	215.0	163.3	163.3	163.3
Ma+M	217.9	217.9	217.9	203.9	203.9	203.9	153.4	153.4	153.4
Ma+M+Ma+M	206.7	206.7	206.7	192.9	192.9	192.9	143.4	143.4	143.4
Wh	212.5	212.5	212.5	198.3	198.3	198.3	147.0	147.0	147.0
Wh+M	202.9	202.9	202.9	188.9	188.9	188.9	138.8	138.8	138.8
Wh+M+Wh+M	193.4	193.4	193.4	179.5	179.5	179.5	130.5	130.5	130.5
Be	232.5	232.5	232.5	218.3	218.3	218.3	166.5	166.5	166.5
Be+M	220.9	220.9	220.9	206.9	206.9	206.9	156.3	156.3	156.3
Be+M+Be+M	209.3	209.3	209.3	195.5	195.5	195.5	146.0	146.0	146.0

S8, S12 and S16 refer to a slope gradient of 8°, 12° and 16° respectively. CL, Lo and SL refer to the soil type clay loam, loam and sandy loam respectively. Bs is a bare soil field, Bs+M is a bare soil + a *M. aquifolium* strip at the end of the field, Bs+M+Bs+M is the bare soil + *M. aquifolium* strips in the middle and at the end of the field. Ma is the maize field, Ma+M is the maize + a *M. aquifolium* strip at the end of the field, Ma+M+Ma+M is the maize + *M. aquifolium* strips in the middle and at the end of the field. Wh is the wheat field, Wh+M is the wheat + a *M. aquifolium* strip at the end of the field, Wh+M+Wh+M is the wheat + *M. aquifolium* strips in the middle and at the end of the field. Be is the beans field, Be+M is the beans + a *M. aquifolium* strip at the end of the field, Be+M+Be+M is the beans + *M. aquifolium* strips in the middle and at the end of the field.

The highest soil loss predictions were found on the Bs fields (Table 5.5). The results of the model prediction (Table 5.5) of *M. aquifolium* strips on different crop fields show a great reduction in soil loss on all selected crop fields. A 10 m long *M. aquifolium* strip at the end of the cultivated maize (Ma) field reduced soil loss by 67% when compared to the maize field without strips. By adding an additional 10 m long strip in the middle of the field, the reduction further improved to 70%. When the wheat (Wh) field was combined with *M. aquifolium* strips at the end of the field, the reduction in soil loss was 66%. When it was combined with strips in the middle and at the end of the field, the reduction in soil loss was 70%. The highest soil loss reduction of 73% was predicted by the model when the *M. aquifolium* strips were placed at the end and in the middle of the bean (Be) field. When the strip was placed only at the end of the bean field it resulted in a 68% reduction in soil loss. These soil loss reduction results clearly confirm the importance of the *M. aquifolium* strips at the end of the cultivated fields. These strips act as vegetative filter strips filtering sediments from the surface runoff, but let most of the water pass through.
The amount of soil loss varied between the different types of soils. The lowest prediction was found on SL soil and the highest on CL. All fields showed a steady increase in soil loss with increasing slope gradient (Table 5.5). Placing *M. aquifolium* strips on a 16° slope on a selected crop field resulted in a lower soil loss than the same selected crop field on an 8° slope without strips. This indicates that an even higher steepness of slopes can be used for agricultural or horticultural cultivations if the field is combined with *M. aquifolium* strips.

Even though there is a great reduction in the total soil loss leaving the cultivated field, the erosion damage inside the fields has to be taken into consideration as well. Placing an additional *M. aquifolium* strip on a higher part of the field decreases erosion inside the field and adds to the reduction of soil loss.

Table 5.5 Simulated soil loss (t/ha/year) for different crop fields under various soil types and slope gradients with and without *M. aquifolium* strips.

Field conditions	**Slope category and soil type**								
	S8-CL	**S12-CL**	**S16-CL**	**S8-Lo**	**S12-Lo**	**S16-Lo**	**S8-SL**	**S12-SL**	**S16-SL**
Bs	20.46	30.57	32.85	19.41	29.00	38.44	15.45	23.09	30.61
Bs+M	5.31	7.94	10.53	5.01	7.49	9.93	3.92	5.85	7.76
Bs+M+Bs+M	4.55	6.80	9.01	4.27	6.37	8.45	3.26	4.87	6.46
Ma	5.85	8.74	11.58	5.15	7.69	10.20	2.97	4.43	5.88
Ma+M	1.98	2.96	3.93	1.74	2.59	3.44	0.98	1.47	1.94
Ma+M+Ma+M	1.78	2.66	3.53	1.55	2.32	3.08	0.86	1.28	1.70
Wh	4.82	7.20	9.54	4.20	6.27	8.31	2.31	3.45	4.57
Wh+M	1.72	2.57	3.41	1.49	2.23	2.95	0.80	1.20	1.59
Wh+M+Wh+M	1.56	2.33	3.09	1.35	2.01	2.66	0.71	1.06	1.41
Be	6.21	9.27	12.29	5.47	8.18	10.84	3.18	4.76	6.31
Be+M	2.04	3.04	4.04	1.79	2.67	3.54	1.02	1.52	2.02

Be+M+Be+M	1.83	2.73	3.62	1.60	2.38	3.16	0.89	1.33	1.76

S8, S12 and S16 refer to a slope gradient of 8°, 12° and 16° respectively. CL, Lo and SL refer to the soil type clay loam, loam and sandy loam respectively. Bs is a bare soil field, Bs+M is a bare soil + a *M. aquifolium* strip at the end of the field, Bs+M+Bs+M is the bare soil + *M. aquifolium* strips in the middle and at the end of the field. Ma is the maize field, Ma+M is the maize + a *M. aquifolium* strip at the end of the field, Ma+M+Ma+M is the maize + *M. aquifolium* strips in the middle and at the end of the field. Wh is the wheat field, Wh+M is the wheat + a *M. aquifolium* strip at the end of the field, Wh+M+Wh+M is the wheat + *M. aquifolium* strips in the middle and at the end of the field. Be is the beans field, Be+M is the beans + a *M. aquifolium* strip at the end of the field, Be+M+Be+M is the beans + *M. aquifolium* strips in the middle and at the end of the field.

Applying permanent vegetation strips between crops is an effective soil conservation technique for minimising soil loss from cultivated fields (e.g. Durán Zuazo et al., 2008, Wu et al., 2010). Yet farmers still see vegetation strips as an off-putting factor in farming practice due to the loss of a section of land from crop production. Grass strips, beside their soil conservation purpose, are also often used to provide fodder for lifestock. Farms withouth lifestock would benefit from *M. aquifolium* strips as they provide marketable cut foliage which would compensate farmers for the loss of yield from the main crop. In addition, Sudhishri et al. (2008) highlighted that plots with vegetative strips resulted in a lower level of erosion rate which resulted in a lower rate of organic carbon loss, which in turn increased crop yield.
Most studies on permanent vegetative strips focused on warm-season grasses in tropical, subtropical and Mediteranean areas (Sudhishri et al., 2008, Thierfelder et al., 2005, Wu et al., 2010) and rarely focused on species which have the ability to perform successively under not only dry but cold conditions (Wu et al., 2010). Due to the high abiotic tolerance of *M. aquifolium* (Hudek et al., 2010) it has the advantage of being able to be used under various climatic conditions. Given that there is comperatively little research data on shrubs, particularly in cold climatic conditions, the present study provides valuable new data on these two fronts.

5.4 Conclusion

The main purpose of this model study was to evaluate the effectiveness of *M. aquifolium* in reducing soil erosion on hillslopes and to support of small-scale farmers and soil conservationists in making informed decisions when field data, time and money are limiting factors. The study confirmed that after model calibration the RMMF model can provide immediate information with a close prediction rate of annual soil loss and runoff on *M. aquifolium*'s suitability for cultivation on hillslopes.
The model predicted soil loss and runoff results would follow the same pattern as the observed values i.e. decreasing with increasing age of the *M. aquifolium* plantations. The model gave accurate runoff predictions for the CBS, M25, M20 and M12 fields and slightly under-predicted for the M4 field. The model prediction on soil loss gave an accurate result for the M4 field; it slightly under-predicted the M12, M20 and M25 fields and slightly over-predicted the CBS field.

In *M. aquifolium* cultivations, EHD was an important indicator of the root parameter values of the plantation. The study confirmed that the EHD value increases with the age of the plant which is indicative of an increase in RAR and rooting depth which have a great influence on soil hydrology. The EHD values of *M. aquifolium* provide a valuable addition to the existing knowledge bank which has relatively little data on shrubs. Furthermore it also demonstrates how the EHD changes with age on shallow soil.

Although outclassed by the effect on the EHD in the present case, the root system may also have a mechanical effect on the sediment production. Due to the fact that all *M. aquifolium* plots gave a transport limited erosion process it was not possible to evaluate any mechanical influences as they affect only the detachment by surface runoff.

This study also determined by model simulations the effectiveness of *M. aquifolium* strips on larger cultivated lands on hillslopes with the RMMF model. The *M. aquifolium* strips were tested on three different slope angles, soil types and crop cultivations with two forms of *M. aquifolium* strips. One strip is located at the end of the cultivated fields and the second strip in the middle and/or at the end of the fields. The *M. aquifolium* strips caused a steady reduction in the volume of runoff and the amount of soil loss on all studied fields. The lowest volume of runoff and soil loss was found when the *M. aquifolium* strips were placed in the middle and at the end of the fields. The volume of runoff and the amount of soil loss varied between the different types of soil.

M. aquifolium strips on a 16° cultivated slope resulted in lower soil loss than the same crop field on an 8° slope without strips. These results confirm our hypothesis that contour strips of *M. aquifolium* on sloping agricultural fields can be an effective method of reducing surface runoff and soil loss. The results also indicate that steeper slopes can also be used for agricultural plant production if *M. aquifolium* strips are applied. The conclusion of this study is that the RMMF model can be an effective tool to evaluate soil conservation measures and that the *M. aquifolium* strips could reduce surface runoff and soil loss from small-scale and large-scale agricultural fields on the hillslopes of Hungary.

Chapter 6

Synthesis

6.1 Introduction

Soil degradation is a worldwide phenomenon affecting billions of people both directly and indirectly (Oldeman, 2000). Agro-ecosystems are predominantly responsible for soil degradation due to intensive, ecologically unsustainable land use and management techniques (Baxter et al., 2013). Hillsides are particularly sensitive to soil degradation by water erosion, and therefore agricultural activities on such sloping lands require greater attention towards soil conservation methods to reduce soil erosion (Thyll, 1992). This would minimise the damage caused by soil loss and runoff both on-site and off-site. The soil erosion processes on the agricultural hillsides of Hungary (55% of all croplands) are often exacerbated by the problems of small farm size (<1 ha) and the lack of various resources (e.g., lack of capital and equipment) (Burger and Szép, 2007). Maintaining sufficient vegetation cover could minimize erosion processes on hillsides and help to sustain soil quality and provide income and stability to smallholder farmers in the long term.

Degraded lands require vegetation with higher tolerance to stress and disturbance. Plant establishment for slope stabilization and erosion control requires species with the ability to establish rapidly and with low production costs (Morgan and Rickson, 1995). The number of suitable plant species decreases with increasingly extreme site conditions. It is required to consider the behaviour of the selected plant community both in the short-term and long-term to be able to determine the precise management requirements (Rickson, 1995).

The study described in this thesis focussed on *Mahonia aquifolium* (Pursh) Nutt. or Oregon grape and determined its potential for soil erosion control. *M. aquifolium* is a well known ornamental, evergreen shrub in Hungary. The plant was introduced to horticulture for its cut, evergreen foliage used in flower arrangements and as a decorative garden plant in landscape architecture. Furthermore, its application in human and veterinary treatments has recently received considerable attention (Lans et al., 2007; Yarnell and Abascal, 2004). Alternative uses such as for alimentation or natural dye (Grae, 1974; Hancock, 1997) have not been widely recognized yet, but could increase its marketability, which is crucial for successful adoption by smallholder farmers. Several studies have mentioned its capability to adapt to different soil and site conditions (e.g. Terpó and Grusz, 1976; Tóth, 1969) though its potential use in soil protection had not been studied before.

The aim of this study was to first examine the properties of the root system then quantify its effectiveness in preventing surface runoff and reinforcing the soil thereby reducing erosive processes. The following specific research questions were defined for the research:

1) How do various plant species and their root morphological differences contribute to soil reinforcement? (Chapter 2)

2) What are the root morphological differences between cultivated and non cultivated *M. aquifolium* and how do they affect its potential in soil reinforcement in soil conservation? (Chapter 3)
3) What effect does the *M. aquifolium* population have on minimising soil degradation, and does the age of the plant population have an influence on its effectiveness as erosion control? (Chapter 4)
4) How effectively do *M. aquifolium* strips contribute to soil erosion control under various bio-physical conditions? (Chapter 5)

6.2 Soil reinforcement by vegetation roots

It is generally accepted that vegetation plays a substantial role in soil erosion reduction (Gray and Sotir, 1996; Morgan, 1995). In the last century the protective role of vegetation to reduce soil erosion has been widely investigated for restoration operations. Plant roots increase the resistance of the soil by modifying its mechanical and hydrological properties (e.g., Gray and Sotir, 1996; Styczen and Morgan, 1995). Root characteristics are determining factors in successful soil reinforcement. Hence, in Chapter 2 it was evaluated how effective different plant species are for soil erosion control.

Six species from the mountainous sub-Mediterranean climate zone of France were selected to study their suitability for soil reinforcement. The selected species are widespread in the study area and included two tree species, *Pinus nigra* Arn. *ssp. nigra* and *Quercus pubescens* Wild., two shrub species, *Genista cinerea* Vill. and *Thymus serpyllum* L., and two herbaceous species, *Achnatherum calamagrostis* L. and *Aphyllantes monspeliensis* L. P. Beauv.. Root morphology, root area ratio and root tensile strength measurements were made to determine and compare the plants effectiveness in soil reinforcement.

The results showed variations between the studied plant species in their root area ratio, yet the differences were not significant. This variability can be explained by the environmental heterogeneity or genetic variability of the species. All studied species had their highest root area ratio value in the upper 20 cm soil layer and as the soil depth increased the number of roots and the root area ratio values decreased. The majority of root tensile strength measurements confirmed that thin roots are more resistant to tensile stresses than thick roots. Both the herbaceous and shrub species proved to have the most resistant roots for tensile stress, while the lowest resistances were found for the tree species. For *G. cinerea*, however, there was no correlation found between root tensile strength and root diameter. This can be attributed to variations in root age resulted in this deviation. To support this hypothesis the plant's root cross-sections or cellulose content should be examined. Genet et al. (2005) stated that higher cellulose concentrations result in stronger roots.

The study showed that root reinforcement decreased quickly with increasing soil depth for all species. Below 30 cm of soil depth, no significant difference was found between species in the increase of soil cohesion provided by plant roots. Still the greatest increases in soil cohesion were obtained for the *G. cinerea* shrub and the *A. monspeliensis* herb, while *P. nigra* and *Q. pubescens* had the lowest soil cohesion values. These results imply that both shrubs and herbaceous species have advantages over tree species in terms of soil reinforcement. Shrubs and herbaceous species have a high amount of fine roots, which are more resistant to tension compared with tree roots, which are coarser and fewer in number.

The findings of this study allow to determine how hillslopes susceptible to erosion processes can be protected using root reinforcement. Whilst herbaceous and shrub species provide effective erosion protection from an early age, tree species are probably more effective at anchoring soil layers to underlying bedrock due to their dominant taproot morphology (Styzcen and Morgan, 1995). Each species possesses its own specific qualities, some of which may help to reduce soil erosion processes. These specific qualities must be considered in the selection of suitable plant species for particular bio-physical conditions (De Baets et al., 2009). For example, *P. nigra* has been used for re-afforestation throughout Europe for over a century, yet the root tensile strength results in Chapter 2, shows that *P. nigra* has poor soil reinforcement qualities. *G. cinerea*, while not a tree species, could prove more effective in large scale re-afforestation projects due to its greater resistance. *T. serpyllum* and *Q. pubescens* are post-pioneer and late succession species recommended to apply in restoration processes when erosion is partly controlled. The anchorage strength of *A. monspeliensis* and *A. calamagrostis* having not yet been subject to scientific evaluation, can be said to possess the protective qualities of most grass species with roots particularly resistant to runoff and upheaval (Mickovski et al., 2005).

6.3 Root morphology and functional traits of *M. aquifolium*

The root system traits of *M. aquifolium* and its potential use in soil reinforcement were studied in Chapter 3. Effective vegetation selection for slope stabilization relies on factors such as stabilization objectives as well as soil and site conditions. *M. aquifolium* has been an established ornamental plant and widely cultivated throughout Europe for centuries, and until 2007 the growing of *M. aquifolium* was subsidized by the Hungarian government (Anonymous, 2004). Cultivation in the study area involves contour tillage and fertilization of the field, mechanical and chemical weed and disease control and the harvest of the aboveground biomass. When the canopy is harvested, the roots are its only means of soil protection, but it was unknown how much soil protection is provided by *M. aquifolium*'s root system. Hence, the objective of Chapter 3 was to study the root morphological characteristics of *M. aquifolium* and to determine the efficiency of cultivated and non cultivated *M. aquifolium* in soil reinforcement.

Measurements were carried out on 1, 2 and 3 year old cultivated and non-cultivated *M. aquifolium* seedlings. All studied specimens were measured and compared for root area ratio and root tensile strength. There were similarities and variations in root morphology between cultivated and non-cultivated *M. aquifolium* plants. The similarities can be attributed to the fact that genetics are a controlling factor in root morphology (Gray and Sotir, 1996; Gyúró, 1974). The differences can be explained by the fact that root morphology is also influenced by environmental conditions (e.g., local soil and climatic conditions) (Gray and Sotir, 1996; Gyúró, 1974). Cultivation of *M. aquifolium* led to a more eutrophic and porous soil structure, which resulted in a well developed lateral and sinker root structure. There was a significantly higher mean root count with less extensive tap root growth for cultivated plants when compared with non-cultivated plants. The soil of the non-cultivated *M. aquifolium* plants was generally more compact, and hampered the development of fibrous, fine roots.

A benefit of cultivation is a greater number of fine roots and a more complex root morphology, particularly in the upper soil layer. This in turn provides superior soil fixation over coarse roots which are fewer in number. Another positive aspect caused by cultivation is that the dense, fine root structure promotes evapotranspiration and reduces the chance of waterlogged lands. Also, nutrients are more evenly distributed throughout the soil for cultivated *M. aquifolium* which is another reason why cultivated *M. aquifolium* plants have a significantly higher mean root area ratio than plants from non-cultivated lands.

The results of Chapter 3 show that cultivated *M. aquifolium* improves soil stability on hillsides more than non-cultivated *M. aquifolium*. The root characteristics of the cultivated plants reinforce its suitability for soil erosion control even at a young age. Due to the moderate tap root growth, young cultivated *M. aquifolium* can only provide additional soil shear strength on shallow slopes (< 25 cm deep). The root system of non-cultivated *M. aquifolium* only becomes more complex and more valuable as a soil stabilizing agent over a much longer period. Therefore its value as a long term stabilization agent in horticultural engineering should be determined by further testing on older non-cultivated plantations displaying a greater number of smaller roots.

It is recommended that new *M. aquifolium* plantations on hillsides should be cultivated from establishment to promote a complex, fine root structure in the upper soil layer to increase soil stabilization. The study also confirmed that environmental factors that are subject to change under cultivation do not modify root tensile strength under any circumstances as there were no differences found between cultivated and non-cultivated plants. To encourage the establishment of *M. aquifolium* plantations, however, it is of equal importance to highlight their potential economic and social impact on rural areas, not only the environmental benefits the plant provides.

6.4 The efficiency of cultivated *M. aquifolium* populations for water erosion control

Cultivated *M. aquifolium* populations were tested to determine their efficiency in water erosion control on small size mountain agro-ecosystems (Chapter 4). After harvest, the root system of the plant plays the only protective role in erosion control. The foliage is generally collected between September and February, depending on market demand. When the foliage is harvested, all aboveground vegetation is cut down to ground level leaving the soil surface exposed. As the effect of *M. aquifolium* on soil erosion was generally unknown, it was studied how the *M. aquifolium* plants affect soil erosion processes, and if the age of the plant population has an influence on its effectiveness for erosion control.

The field work was carried out in an area with a long tradition in horticultural farming and involved recording amounts of surface runoff and sediment loss from the experimental fields. The studied plant populations were divided into four different age groups. The youngest group was the 4 year old population, followed by the 12, 20 and 25 year old groups. The measurements from the *M. aquifolium* fields were compared with measurements from a bare soil field (control plot) and a grass field. All cultivated plots were maintained with conventional tillage. Soil loss and surface runoff were measured after every rainfall event from each studied field, resulting in a total of 17 erosive rainfall events during one full year.

All cultivated *M. aquifolium* plantations showed a significant reduction in soil loss and surface runoff compared with the bare control plots. Also, the soil loss and surface runoff were progressively lower with increasing population age of the cultivated *M. aquifolium*. This is in line with the results of Reubens et al. (2007), who showed that mature plants develop a more complex root structure which consequently can provide a greater protection against soil erosion. The age of a cultivated *M. aquifolium* plantation was shown to be a determining factor in its performance as erosion control, but a cultivated plantation will already provide effective stabilization within a few years after establishment.

Though grass provided the most effective erosion protection from the six studied plots, the land is ideally suited for horticultural purposes and *M. aquifolium* cultivation can provide more income to farmers. Vineyards and orchards, which have been cultivated in the study area for centuries, are no longer seen as a viable option. Farmers are not interested in restoring the old plantations and terraces due to the high cost of establishment and maintenance involved, and due to the strong competition from larger farms. Yet *M. aquifolium* has relatively low establishing and maintenance costs and the produce has a good marketability for instance for fitoterapy, alimentation, and ornamental purposes.

Shifting the tillage system from conventional to conservation tillage could further reduce soil loss and runoff on sloping fields with *M. aquifolium* and result in more sustainable land use. With any tillage system, maintaining canopy cover and providing adequate ground cover during the period when the leaves have been harvested would help to further reduce runoff and soil loss. However, most farmers would place the financial aspects above environmental sustainability, and without *M. aquifolium*'s wide marketability addressing these financial concerns, it would be difficult to promote the crop as a realistic option for shallow soil stabilization in mountain agro-ecosystems.

6.5 *M. aquifolium* strips for water erosion control

The topic of Chapter 5 was the effectiveness of *M. aquifolium* strips for soil erosion control under various bio-physical conditions. Numerous studies have highlighted the fact that vegetation strips can play an important role in soil erosion control (e.g., Morgan, 2007; Van Dijk et al., 1996), but strips of *M. aquifolium* have never been tested for this purpose. As the previous studies (Chapter 3 and Chapter 4) proved that cultivated *M. aquifolium* can be an effective plant for water erosion control, it was evaluated how effective *M. aquifolium* vegetation strips can reduce erosion on hillslopes. The Revised Morgan-Morgan-Finney soil erosion model (RMMF) was applied to estimate the soil loss and surface runoff from fields under diverse bio-physical conditions. Using this model, various soil types (clay loam, loam and sandy loam), slope angles (8°, 12° and 16°) and cultivations (bare soil, maize crop, wheat crop and bean crop) were tested with and without *M. aquifolium* strips.

The RMMF model was first calibrated by using measured quantities of surface runoff and soil loss from the experimental *M. aquifolium* plots (Chapter 4). The parameters effective hydrological depth, which accounts for the entire soil hydrology, and soil detachability index were used for model calibration. The calibrated values of effective hydrological depth differed for each plot. The effective hydrological depth was the lowest for the bare soil plot, and progressively increased with the age of the *M. aquifolium* plants. This suggests that with increasing population age the infilration capacity of the soil increases and the volume of surface runoff generated on the plots decreases. These results demonstrate the beneficial influence of a developing root system on soil hydrology, meaning that the older the rooting system, the higher the infiltration capacity although obviously this correlation is not infinite.
The control bare soil plot required a further calibration of the soil detachability index. This can be explained by the fact that the plot contained a higher amount of rocks as prior to the study the plot had not been subject to the same intensity of cultivation as the *M. aquifolium* plots.

After calibration, the RMMF model was used to test a number of hillslope scenarios, with and without *M. aquifolium* strips. As expected, the highest runoff and soil losses were obtained for hillslopes without vegetation strips. The presence of a ten metre wide *M. aquifolium* strip at the end of the hillslope resulted in lower surface runoff and soil loss amounts. Surface runoff reduction was 7% with one *M. aquifolium* strip at the end of the hillslope, and increased to 13% when another ten metre wide *M. aquifolium* strip was placed in the middle of the hillslope. In reality it is likely that the reduction of surface runoff would be higher, because the current RMMF model does not include re-infiltration of surface runoff. Soil loss reduction was between 66 and 68% for all studied hillslopes when one *M. aquifolium* strip was applied at the end of the fields, and further increased to values between 70 and 73% with an additional strip in the middle of the hillslope. These results confirm the efficiency of the *M. aquifolium* strips on erosion control. Even though there is only a slight improvement in soil loss reduction by an additional strip in the middle of the cultivated field, the erosion damage inside the fields has to be taken into consideration as well. Therefore the on-site erosion damage could be reduced by the additional *M. aquifolium* strip in the middle of the cultivation.

The model predictions also indicate that agricultural or horticultural cultivations can succeed on even steeper slopes if *M. aquifolium* strips are applied. Still farmers need to be encouraged to apply them on sloping fields. One of the advantages of applying *M. aquifolium* vegetation strips is its marketable cut foliage which could compensate farmers for the loss of yield from the main crop. In addition, by decreasing the soil loss rate, and thus conserving more nutrients in the soil, the yield of the main crop could be sustained at relatively high levels.

It has been demonstrated that the RMMF model can successfully predict surface runoff and soil losses from cultivated *M. aquifolium* fields. It has been also indicated that the use of *M. aquifolium* strips could be an effective soil conservation measure on sloping agricultural fields. These model results for *M. aquifolium* as a permanent vegetative strip are a valuable addition to existing work on vegetative barriers (e.g., Wu et al., 2010) and root reinforcement by shrubs. It contributes information on a species that is able to perform successfully under both dry and cold conditions (in contrast to the majority of work that focuses on tropical, arid or Mediterranean environments.

6.6 Recommendations for future research

The study described in this thesis is the first to evaluate the impacts of *M. aquifolium* on slope stabilization, but it is by no means complete. A number of challenging research issues remain. For instance, it would be of interest to conduct further testing on older *M. aquifolium* shrubs. This would improve the knowledge about the development of the root morphology, and could determine the lifespan of *M. aquifolium* as an effective soil erosion control method. The morphological and functional trait studies on the roots of the cultivated and non-cultivated *M aquifolium* shrubs demonstrate that cultivated plant roots can offer better soil protection in the early stages. This means that cultivation leads to a more suitable root morphology development that provides better protection against soil erosion on hillslopes. However, cultivation during the early growth stage leaves the soil surface more vulnerable to rainfall as the root system is still underdeveloped. Therefore, it would be of interest to study how the root system of *M. aquifolium* develops under various tillage methods, such as reduced tillage and conservation tillage, with the view to maximise the seedlings' root development and minimise soil degradation from the early growth stage onwards. Another possible research topic would be to study if changing from conventional tillage or reduced tillage to no tillage would have any significant influence on the root development of older plants, with the view of reducing the required input costs for establishing *M. aquifolium* plantations.

The increasing age of cultivated *M. aquifolium* under the conventional tillage system resulted in a significant decrease in surface runoff and soil loss. Soil tillage increases soil fertility in the short term but also increases soil degradation in the medium and long term, creating an unsustainable environment. Over the last two decades, conservation tillage has become a rapidly growing approach worldwide. Technological developments made conservation tillage applicable and suitable for various climatic conditions, soil types and farm sizes (FAO, 2008). Keeping the soil surface permanently covered is a fundamental principal of conservation tillage. To fulfil the potential of conservation tillage in *M. aquifolium* plantations, it is necessary to introduce additional ground cover to the plantation. However, groundcover can compete with *M. aquifolium* for water and nutrients, hindering the development and the yield of the cultivated plant. Furthermore, groundcover could also raise the risk of diseases in the cultivation, and thus the selection of suitable ground cover in *M. aquifolium* plantations would be a key decision. Any *M. aquifolium* plantation, even under traditional cultivation, would benefit from some type of groundcover to combat erosion. This is especially true shortly after its establishment when the soil is only partly covered by the underdeveloped canopy. Even in older *M. aquifolium* plantations, sufficient surface cover is absent after the harvest of the canopy, increasing the risk of water erosion. Therefore it would be of interest to investigate the suitability of different ground covers (swards or mulches) for *M. aquifolium* plantations.

The RMMF soil erosion model was used to predict surface runoff and soil loss for various soil types, slope angles and cultivations with and without *M. aquifolium* strips. The results of the investigation showed that *M. aquifolium* strips substantially reduced the soil loss rate on all studied fields. However these results were only predictions therefore it would be recommended for future research to test the simulations on an experimental farm in practice and further monitor the runoff and soil loss under field conditions. This would help reassure farmers and policy makers on the effectiveness of *M. aquifolium* strips on soil erosion control. In addition the width of strips was arbitrarily set at ten metres. It would be interesting to investigate the optimal width of the *M. aquifolium* strips on the cultivated fields to determine the balance between the vegetative strips and the main crop. This research should not only consider bio-physical aspects, but also include socio-economic assessment of the costs and benefits of the *M. aquifolium* strips.

6.7 Limitations of the study

Although this study provides the first empirical information on the root system traits of *M. aquifolium* and their potential role in soil reinforcement in both cultivated and non cultivated soil conditions, the study was limited to testing only juvenile plants from one to three year old as testing on older plants could lead to root damage caused by excavation. Due to the firmness of the clay soil, the 'trench wall' method (Böhm, 1979) and 'core-break' sampling (Schmid and Kazda, 2002) were considered too complex to employ. Information on older cultivated and non-cultivated *M. aquifolium*'s root system would give a better indication of its effectiveness as soil reinforcement throughout its life span, not only at an early age.

While the study confirmed that cultivated *M. aquifolium* populations play an efficient role in water erosion control in mountainous conditions in Hungary by significantly reducing the amount of soil loss, the study was limited because the data collection period was only one year. A field study over a longer period of time would enable to observe the role of *M. aquifolium* in soil protection under different meteorological conditions. Annual weather patterns are variable, occasionally producing extreme weather conditions, which would give a more complete view on *M. aquifolium*'s protective effects on soil erosion. In addition long term data would enable a more thorough RMMF model validation.

6.8 Extension and policy recommendations

Apart from the scientific relevance, the results of this PhD study are important for small-scale rural hillside farmers, soil conservationists, and policy makers. *M. aquifolium* is a viable, marketable crop that can assist in stabilizing mountain agro-ecosystems, while it could also provide economic stability to these rural communities. However, *M. aquifolium* is not a cure to all rural problems in mountainous areas, because of many other socio-economic problems that put the farming systems under pressure.

The results of the study provide a compelling argument to policy makers regarding the restoration of government subsidies for growing *M. aquifolium*. The environmental benefits are clear but perhaps a more detailed study could be made concerning the socio-economic benefits of *M. aquifolium* plantations. Soil conservation on hillslopes is already part of national policy although farmers' opportunities will of course differ on the basis of their individual site conditions, financial background, knowledge and available resources. Additional incentives should be provided to farmers who are willing to use soil conservation strategies, e.g. replacing their crops with plants which have greater soil protective properties or built in soil conservation techniques, use of *M. aquifolium* strips or mulching. Education on agricultural production technology of *M. aquifolium* would enable farmers to maximise their productivity and minimise input costs. It would therefore be good that knowledge of the opportunities and practices surrounding *M. aquifolium* cultivation were disseminated to farmers and relevant organizations through workshops to provide all necessary information on the land use management techniques involved (i.e. sowing dates, cultivation strategies, tillage and harvesting techniques), as well as aspects of market supply and demand.

References

Abe, K.., Ziemer, R.R., 1991. Effect of tree roots on a shear zone: modeling reinforced shear stress. Canadian Journal of Forest Research 21, 1012–1019.

Abernethy, B., Rutherfurd, I.D., 2001. The distribution and strength of riparian tree roots in relation to riverbank reinforcement. Hydrological processes 15, 63–79.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56. FAO, Rome.

Anderson, E.W., 1986. A guide for estimating cover. Rangelands 8, 236.

Andreu, V., Rubio, J.L, Gimeno-Garcia E, Linares J.V., 1998. Testing three Mediterranean shrub species in runoff reduction and sediment transport. Soil and Tillage Research 45, 441–454.

Ang, A.H.S., Tang, W.H., 1975. Probability concepts in engineering planning and design, Vol. 2, John Wiley & Sons, Inc., New York, pp. 562.

Angers, D.A., Caron, J., 1998. Plant-induced changes in soil structure: processes and feedbacks. Biogeochemistry 42, 55–72.

Anonymous, 2004. A termőföld rendeltetésszerű hasznosításra alkalmassá tételével összefüggő feladatok végrehajtásának támogatása. MezőHír Független Agrárinformációs Szaklap 4 (in Hungarian).

Antoine, P., Giraud, A., Meunier, M., Van Asch, T., 1995. Geological and geotechnical properties of the "Terres noires" in southeastern France: weathering, erosion, solid transport and instability. Engineering Geology 40, 223–234.

Apáti, F., 2009. A meggytermesztés jelene és kilátásai a gazdaságosság tükrében (1.) A magyar meggytermesztés költség- és jövedelemviszonyai. Agrofórum Extra 28, 34-38.

Auge, H., Brandl, R., 1997. Seedling recruitment in the invasive clonal shrub, Mahonia aquifolium Pursh (Nutt.) Oecologia 110, 205-211.

Augustin, M., Andrees, U., Grimme, H., Schopf, E., Simon, J., 1999. Effects of Mahonia aquifolium ointment on the expression of adhesion, proliferation, and activation markers in the skin of patients with psoriasis Forschende Komplementarmedizin 6 (SUPPL. 2), 19-21.

Avar, L., 2013. Korszerű alma biztos védelem. Kertészet és szőlészet 16.

Bacsó, N., 1973. Bevezetés az agrometeorológiába. Mezőgazdasági Kiadó, Budapest (in Hungarian).

Barrouillet, J., 1982. La revégétalisation dans les Alpes du Sud: choix et emploi des espèces herbacées et arbustives. Cemagref, Grenoble, pp. 143.

Basayigit, L., Dinc, U., 2010. Prediction of soil loss in lake watershed using GIS: A case study of Egirdir Lake, Turkey. Journal of Natural and Environmental Sciences 1, 1-11.

Baxter, C., Rowan, J.S., McKenzie, B.M., and Neilson, R., 2013. Understanding soil erosion impacts in temperate agro-ecosystems: bridging the gap between geomorphology and soil ecology. Biogeosciences Discuss. 10, 7491-7520. doi:10.5194/bgd-10-7491-2013, 2013.

Biamah, E.K., Gichuki, F.N., Kaumbutho, P.G., 1993. Tillage methods and soil and water conservation in eastern Africa. Soil and Tillage Research 27, 105-123.

Bischetti, G.B., Bonfanti, F., Greppi, M., 2003. Root tensile strength measurement: testing device and protocol. Quad. Idron. Mont. 21, 349–360.

Bischetti, G.B., Chiaradia, E.A., Simonato, T., Speziali, B., Vitali, B., Vullo, P., Zocco, A., 2005. Root strength and root area ratio of forest species in Lombardy (Northern Italy). Plant and Soil 278, 11–22.

Bouma, J., Varallyay, G., Batjes, N.H., 1998. Principal land use changes anticipated in Europe. Agriculture, Ecosystems and Environment 67, 103– 119.

Böhm, W., 1979. Methods of studying root systems. Ecological Series No. 33. Springer-Verlag, Berlin, pp. 188.

Brandt, C.J., 1990. Simulation of the size distribution and erosivity of raindrops and through fall drops. Earth Surface Processes and Landforms 15, 687-698.

Brezová, V., Dvoranová, D., Kostálová, D., 2004. Oxygen activation by photoexcited protoberberinium alkaloids from Mahonia aquifolium. Phytotherapy Research 18, 640-646.

Burger, A., Szép, K., 2007. The economic situation of individual (family) farms in Hungary. Combined elaboration of the first and second parts of papers prepared for presentation at the IAMO FORUM, Halle.

Burylo, M., Rey, F., Delcros, P., 2007. Abiotic and biotic factors influencing the early stages of vegetation colonization in restored marly gullies (Southern Alps, France). Ecological Engineering 30, 231–239.

Burylo, M., Rey, F., Roumet, C., Buisson, E., Dutoit, T., 2009. Linking plant morphological traits to uprooting resistance in eroded marly lands (Southern Alps, France). Plant and Soil 324, 31–42.

Cammeraat, E., Kooijman, A., Van Beek, R., 2005. Vegetation succession and its consequences for slope stability in SE Spain. Plant and Soil 278, 135–147.

CAP, 1997. Council Regulation (EEC) no.950/97, Official Journal of European Communities, L142/1, 2.6.97, Commision of European Comunities, Brussels.

Centeri, C., Pataki, R., Barczi, A., 2001. Soil erosion, soil loss tolerance and sustainability in Hungary. 3rd International Conference on Land Degradation and Meeting of the IUSS Subcommission C – Soil and Water Conservation. Rio de Janeiro, Brazil.

Centeri, C., Barta, K., Jakab, G., Szalai, Z., Bíró, Z., 2009. Comparison of EUROSEM, WEPP, and MEDRUSH model calculations with measured runoff and soil-loss data from rainfall simulations in Hungary. Journal of Plant Nutrition and Soil Science 172, 789-797.

Coppin, N., Stiles, R., 1995. Ecological principles for vegetation establishment and maintenance. In: Morgan, R.P.C., Rickson, R.J., (Eds.), Slope stabilization and erosion control: A bioengineering approach. E and FN Spon, London, pp. 59–94.

Coutts, M.P., Nielsen, C.C.N., Nicoll, B.C., 1999. The development of symmetry, rigidity and anchorage in the structural root system of conifers. Plant and Soil 217, 1–15.

Craine, J., 2006. Competition for nutrients and optimal root allocation. Plant and Soil 285, 171–185.

De Baets, S., Poesen, J., Knapen, A., Galindo, P., 2007. Impact of root architecture on the erosion-reducing potential of roots during concentrated flow. Earth Surface Processes and Landforms 32, 1323–1345.

De Baets, S., Poesen, J., Knapen, A., Barbera, G.G., Navarro, J.A., 2007. Root characteristics of representative Mediterranean plant species and their erosion-reducing potential during concentrated runoff. Plant and Soil 294, 169–183.

De Baets, S., Torri, D., Poesen, J., Meersmans, J., 2008. Modelling increased soil cohesion due to roots with EUROSEM. Earth Surface Processes and Landforms 33, 1948–1963.

De Baets, S., Poesen, J., Reubens, B., Wemans, K., De Baerdemaeker, J., Muys, B., 2008. Root tensile strength and root distribution of typical Mediterranean plant species and their contribution to soil shear strength. Plant and Soil 305, 207–226.

De Baets, S., Poesen, J., Reubens, B., Muys, B., De Baerdemaeker, J., 2009. Methodological framework to select plant species for controlling rill and gully erosion: application to a Mediterranean ecosystem. Earth Surface Processes and Landforms 34, 1374–1392.

De Baets, S., Poesen, J., 2010. Empirical models for predicting the erosion-reducing effects of plant roots during concentrated flow erosion. Geomorphology 118, 425-432.

Descroix, L., 1994. L'érosion actuelle dans la partie occidentale des Alpes du Sud. Ph.D. Thesis, Lyon, France.

Dhandar, D.G., Singh, R., 1989. Root studies in grapefruit (Citrus paradisi Macf.) using radiotracer technique. Scientia Horticulturae 40, 113–118.

Dingman, S.L., 2002. Physical Hydrology, second ed. Prentice Hall, New York, pp. 312-324.

Dunjó, G., Pardini, G., Gispert, M., 2003. Land use change effects on abandoned terraced soils in a Mediterranean catchment, NE Spain. Catena 52, 23–37.

Dupuy, L., Fourcaud, T., Stokes, A., 2005. A numerical investigation into the influence of soil type and root architecture on tree anchorage. Plant and Soil 278, 119–134.

Durán, Z.V.H., Francia, M.J.R., Rodríguez, P.C.R., Martínez, R.A., Carce´les, R.B., 2006. Soil-erosion and runoff prevention by plant covers in a mountainous area (SE Spain): implications for sustainable agriculture. Environmentalist 26, 309–319.

Durán, Z.V.H., Rodríguez, P. C.R., Francia, M.J.R., Raya, A.M., Panadero, L.A., Rodríguez, B.C., Navarro, M.M.C., 2008. Benefits of plant strips for sustainable mountain agriculture. Agronomy for Sustainable Development 28, 497-505. http://dx.doi.org/10.1051/agro:2008020

Eswaran, H., Lal, R., Reich, P.F., 2001. Land degradation: an overview. In: Bridges, E.M., Hannam, I.D., Oldeman, L.R., Pening de Vries, F.W.T., Scherr, S.J., Sompatpanit, S., (Eds.), Responses to land degradation. Proc. 2nd. International Conference on Land Degradation and Desertification, Khon Kaen, Thailand. Oxford Press, New Delhi, India.

FAO., 2008. What is conservation agriculture? Agriculture and Consumer Protection Department, Conservation Agriculture. http://www.fao.org/ag/ca/1a.html

Fitter, A.H., Stickland, T.R., 1991. Architectural analysis of plant root systems 2. Influence of nutrient supply on architecture in contrasting plant species. New Phytologist 118, 383–389.

Flora of North America Editorial Committee, Eds., 1997. Flora of North America North of Mexico. Vol. 3, New York and Oxford.

Francis, J.K., (Eds.), 2003. Wide land shrubs of the United States and its territories, Thamnic descriptions. General technical report IITF-WB-1, U.S. Department of Agriculture, Forest Service. http://www.fs.fed.us/global/iitf/pdf/shrubs/Mahonia%20aquifolium.pdf.

Gábris, Gy., Kertész, Á., Zámbo, L., 2003. Land use change and gully formation over the last 200 years in a hilly catchment. Catena 50, 151–164.

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

Gieler, U., Von der Weth, A., Heger, M., 1995. Mahonia aquifolium - A new type of topical treatment for psoriasis. Journal of Dermatological Treatment 6, 31-34.

Gimeno-Garcia, E., Andreu, V., Rubio, J.L., 2007. Influence of vegetation recovery on water erosion at short and medium-term after experimental fires in a Mediterranean shrubland. Catena 69, 150-160.

Glawe, A., D., 2003. First report of Powdery mildew of Mahonia aquifolium caused by *Microsphaera berberidis* (*Erysiphe berberidis*) in North America. Plant Management Network. DOI:10.1094/PHP-2003-0206-01-HN

Glits, M., and Folk, G., 1993. Kertészeti növénykórtan. 2., javított kiadás. Mezőgazda kiadó. Budapest.
Goodman, A.M., Ennos, A.R., 1999. The effects of soil bulk density on the morphology and anchorage mechanics of the root systems of sunflower and maize. Annals of Botany 83, 293–302.
Grae, I., 1974. Nature's colors: Dyes from Plants. MacMillan, New York, pp. 229.
Gray, P.H.H., and Lachance, R.A., 1957. Assimilation of Berberine and Chelidoxanthine by bacteria. Plant and Soil 8, 354-366.
Gray, D.H., 1995. Influence of vegetation on the stability of slopes. In: Proceedings of International Conference on Vegetation and Slopes Stabilization, Protection and Ecology, Institution of Civil Engineers, London, pp. 2–25.
Gray, D.H., Sotir, R.B., 1996. Biotechnical and soil bioengineering slope stabilization. In: A practical guide for erosion control. Wiley, John & Sons, New York, pp. 1–105.
Greenway, D.R., 1987. Vegetation and slope stability. In: Anderson, M.G., Richards, K.S., (Eds.), Slope stability. John Wiley and Sons, New York, pp. 187–230.
Greenwood, J.R., 2006. SLIP4EX — a program for routine slope stability analysis to include the effects of vegetation, reinforcement and hydrological changes. Geotechnical and Geological Engineering 24, 449–465.
Grimm, M., Jones, R., Montanarella, L., 2002. Soil erosion risk in Europe. The European Soil Bureau Institute for Environment and Sustainability, JRC, Ispra Italy.
Győri, D., Palkovics, M., Matusné, S.K., 1998. Helyszini és laboratóriumi talajvizsgálatok. Egyetemi jegyzet. Agrártudományi Egyetem, Keszthelyi Mezőgazdaságtudomanyi Kar Talajtani és Agrokémiai Tanszék. (in Hungarian)
Gyssels, G., Poesen, J., Bochet, E., Li, Y., 2005. Impact of plant roots on the resistance of soils to erosion by water: a review. Progress in Physical Geography, 29, 189-217.
Gyúró, F., 1974. A gyümölcstermesztés alapjai. Mezőgazdasági Kiadó, Budapest, pp. 220–239 (in Hungarian).
Hamza, M.A., Anderson, W.K., 2005. Soil compaction in cropping systems: a review of the nature, causes and possible solutions. Soil and Tillage Research 82, 121–145.
Hancock, M., 1997. Potential for colourants from plant sources in England and Wales, ST0106, Arable crops and Horticulture division. ADAS Boxworth Boxworth, Cambridge. http://www.defra.gov.uk/farm/crops/industrial/research/reports/RDREP01.pdf
Hathaway, R.L., Penny, D., 1975. Root strength in some Populus and Salix clones. New Zealand Journal of Botany 13, 333–344.
Heuser, L.I., 2010. History and ethics of European (& international) soil protection law, in: Zlatic, M., (Eds.), Global change: challenges for soil management, Advances in Geoecology 41. Catena Verlag, Germany, pp. 334-354.
Hodge, A., 2004. The plastic plant: root responses to heterogeneous supplies of nutrients. New Phytologist 162, 9–24.
Hopkins, A., 2011. Mountainous farming in Europe. Grassland Science in Europe, 16, 3-12.
Hudek, C., 2005. A sokoldalu kerti mahonia Mahonia aquifolium (Pursh) Nutt. Kertgazdaság 37, 63-65.
Hudek, C., Burylo, M., Rey, F., 2007. Root density distribution and root tensile strength of typical forest species on Marly gullies in the French Southern Alps. In: Proceedings of the International Symposium on Erosion and Torrent Control as a Factor in Sustainable River Basin Management, Belgrade.

Hudek, C., Rey, F., 2009. Studying the effects of Mahonia aquifolium populations on small-scale mountain agro-ecosystems in Hungary with the view to minimise land degradation. Land Degradation and Development 20, 252–260.

Hudek, C., Burylo, M., Rey, F., 2010. Root system traits of Mahonia aquifolium and its potential use in soil reinforcement in mountain horticultural practices. Scientia Horticulturae 125, 504-511.

IFAD, 2008. The Role of High-Value Crops in Rural Poverty Reduction in the Near East and North Africa. International Fund for Agricultural Development, Near East and North Africa Division Programme Management Department, Rome.

Jordan, G., Van Rompaey, A., Szilassi, P., Csillag, G., Mannaerts, C.,Woldai, T., 2005. Historical land use changes and their impact on sediment fluxes in the Balaton basin (Hungary). Agriculture, Ecosystems and Environment 108, 119–133.

Karátson, D., Németh, K., Székely, B., Ruszkiczay-Rüdiger, Zs., Pécskai, Z., 2006. Incision of a river curvature due to exhumed Miocene volcanic landforms: Danube Bend, Hungary. International Journal of Earth Sciences (Geol Rundsch) 95, 929–944.

Karsai, G., 1999. A Magyar gazdaság folyamatai 1990–98. (Helyzetkép a TEP makro-forgatókönyveihez). Nemzeti Kutatási és Technológiai Hivatal: Budapest (in Hungarian).

Keddy, P., 1992. Assembly and response rules: two goals for predictive community ecology. Journal of Vegetation Science 3, 157–164.

Kertész, Á., 2004. Az egyik legfontosabb recens felszínalakító folyamat, a talajpusztulás Magyarországon. – in: Dövényi, Z., – Schweitzer, F., (Eds.), Táj és környezet: tiszteletkötet a 75 éves Marosi Sándornak. MTA FKI, Budapest, pp. 203–212.

Kertész, Á., 2009. Environmental conditions of gully erosion in Hungary. Hungarian Geographical Bulletin 58, 79–89.

Kertész, Á., Loczy, D., 1996. Soil erosion control in Hungary, in: Krecek, J., Rajwar, G.S., Haigh, M.J., (Eds.), Hydrological problems and environmental management in the highlands and headwaters. A.A. Balkema, Brookfield.

Kim, Y.D., Kim, S.H., Landrum, L.R., 2004. Taxonomic and phytogeographic implications from ITS phylogeny in Berberis (Berberidaceae). Journal of Plant Research 117, 175-182.

Kostálová, D., Kardosová, A., Hajnická, V., 2001. Effect of Mahonia aquifolium stem bark crude extract and one of its polysaccharide components on production of IL-8. Fitoterapia 72, 802-806.

KSH, 2009. Agricultural long time series and censuses—Number of employed persons, 1990–2007. Hungarian Central Statistical Office, Budapest.

KSH, 2011. Agricultural long time series and censuses—Land area of Hungary by land use categories, 1853-2010. Hungarian Central Statistical Office, Budapest.

Lal, R., 1998. Soil erosion impact on agronomic productivity and environment quality. Critical Reviews in Plant Sciences, 17, 319–464.

Lampert, M.L., Andenmatten, C., Schaffner, W., 1998. Mahonia aquifolium | [MAHONIA AQUIFOLIUM (PURSH) NUTT.] Zeitschrift fur Phytotherapie 19, 107-118.

Lans, C., Turner, N., Khan, T., Brauer, G., Boepple, W., 2007. Ethnoveterinary medicines used for ruminants in British Columbia, Canada. Journal of Ethnobiology and Ethnomedicine 3, 11. DOI: 10.1186/1746–4269–3–11

Lecompte, M., Lhenaff, R., Marre, A., 1998. Huit ans de mesures du ravinement des marnes dans les Baronnies méridionales (Préalpes françaises du sud). Géomorphologie: relief, processus, environnement 4, 351–374.

Lipecki, J., Berbec, S., 1997. Soil management in perennial crops: orchards and hop gardens. Soil and Tillage Research 43, 169–184.
Loades, K.W., Bengough, A.G., Bransby, M.F., Hallett, P.D., 2010. Planting density influence on fibrous root reinforcement of soil. Ecological Engineering 36, 276–284.
Lopez-Vicente, M., Navas, A., Machın, J., 2008. Modelling soil detachment rates in rainfed agrosystems in the south-central Pyrenees. Agricultural Water Management 95, 1079-1089.
MacDonald, D., Crabtree, J.R., Wiesinger, G., Dax, T., Stamou, N., Fleury, P., Gutierrez Lazpita, J., Gibon, A., 2000. Agricultural abandonment in mountain areas of Europe: Environmental consequences and policy response. Journal of Environmental Management 59, 47–69.
Maquaire, O., Ritzenthaler, A., Fabre, D., Ambroise, B., Thiery, Y., Truchet, E., Malet, J.P., Monnet, J., 2002. Caractérisation des profiles de formations superficielles par pénétrométrie dynamique à énergie variable: application aux marnes noires de Draix (Alpes-de-Haute-Provence, France). C.R. Géosciences 334, 835–841.
Maquaire, O., Malet, J.P., Remaître, A., Locat, J., Klotz, S., Guillon, J., 2003. Instability conditions of marly hillslopes: towards landsliding or gullying? The case of the Barcelonnette basin, South East France. Engineering Geology 70, 109–130.
Marler, T.E., Discekici, H.M., 1997. Root development of 'Red Lady' papaya plants grown on a hillside. Plant and Soil 195, 37–42.
Maskey, S., Guinot, V., 2003. Improved first-order second moment method for uncertainty estimation in flood forecasting. Hydrological Sciences Journal 48, 183-196.
Mathys, N., Brochot, S., Meunier, M., Richard, D., 2003. Erosion quantification in the small marly experimental catchments of Draix (Alpes de Haute Provence, France). Calibration of the ETC rainfall–runoff-erosion model. Catena 50, 527–548.
Mattia, C., Bischetti, G.B., Gentile, F., 2005. Biotechnical characteristics of root systems of typical Mediterranean species. Plant and Soil 278, 23–32.
Mayor, A.G., Bautista, S., Llovet, J., Bellot, J., 2007. Post-fire hydrological and erosional responses of a Mediterranean landscape: Seven years of catchment-scale dynamics. Catena 71, 68–75.
McCutcheon, A.R., Ellis, S.M., Hancock, R.E.W., Towers, G.H.N., 1994. Antifungal screening of medicinal plants of British Columbian native peoples Journal of Ethnopharmacology 44, 157-169.
Micheli, E., 2009. Soil classification of Hungary in: Krasilnikov, P.V., Marti, J.I., Arnold, R., Shoba, S., (Eds.), A handbook of soil terminology, correlation and classification. Earthscan, UK, pp. 173.
Mickovski, S.B., Van Beek, L.P.H., Salin, F., 2005. Uprooting resistance of vetiver grass (Vetiveria zizanioides). Plant and Soil 278, 33–41.
Mickovski, S.B., Bengough, A.G., Bransby, M.F., Davies, M.C.R., Hallett, P.D., 2007. Material stiffness, branching pattern and soil matric potential affect the pullout resistance of model root systems. European Journal of Soil Science 58, 1471–1481.
Mickovski, S.B., Van Beek, L.P.H., 2009. Root morphology and effects on soil reinforcement and slope stability of young vetiver (Vetiveria zizanioides) plants grown in semi-arid climate. Plant and Soil 324, 43–56.
Mickovski, S.B., Hallett, P.D., Bransby, M.F., Davies, M.C.R., Sonnenberg, R., Bengough, A.G., 2009. Mechanical reinforcement of soil by willow roots: impacts of root properties and root failuremechanism. Soil Science Society of America Journal 73, 1276–1285.

Mitsch, W.J., Jørgensen, S.E., 2003. Ecological engineering: a field whose time has come. Ecological Engineering 20, 363–377.

Moehansyah, H., Maheshwari, B.L., Armstrong, J., 2004. Field evaluation of selected soil erosion models for catchment management in Indonesia. Biosystems Engineering 88, 491–506.

Moerman, D.E., 1998. Native American ethnobotany. Timber press Inc. Portland, Oregon, USA pp. 15.

Morgan, R.P.C., Morgan, D.D.V., Finney, H.J., 1984. A predictive model for the assessment of erosion risk. Journal of Agricultural Engineering Research 30, 245-253.

Morgan, R.P.C., 1995. Soil erosion and conservation, Second edition. Longman, Harlow, UK.

Morgan, R.P.C., Rickson, R.J., 1995. Water and erosion control. In: Morgan, R.P.C., Rickson, R.J., (Eds.), Slope stabilization and erosion control: A bioengineering approach. E and FN Spon, London, pp. 191-220.

Morgan, R.P.C., 1996. Soil erosion and conservation. Second edition. Longman, Harlow, UK.

Morgan, R.P.C., 2001. A simple approach to soil loss prediction: a revised Morgan-Morgan-Finney model. Catena 44, 305-322.

Morgan, R.P.C., 2005. Soil erosion and conservation, Third edition. Blackwell, Oxford.

Morgan, R.P.C., 2007. Vegetative-based technologies for erosion control. In: Stokes, A., Spanos, I., Norris, J., and Cammeraat, E., (Eds), Eco- and Ground Bio-Engineering: The Use of Vegetation to Improve Slope Stability, Springer, Dordrecht, pp. 265–272.

Morgan, R.P.C., Duzant, J.H., 2008. Modified MMF (Morgan-Morgan-Finney) model for evaluating effects of crop and vegetation cover on soil erosion. Earth Surface Processes and Landforms 32, 90-106.

Muller, K., Ziereis, K., Gawlik, I., 1995. The antipsoriatic Mahonia aquifolium and its active constituents; II. Antiproliferative activity against cell growth of human keratinocytes. Planta Medica 61, 74-75.

Mussulman, J., 2003. Discovering Lewis & Clark. VIAs Inc. USA http://www.lewis-clark.org/content/content-article.asp?ArticleID=1347

Myers, J.L, Wagger, M.G., 1996. Runoff and sediment loss from three tillage systems under simulated rainfall. Soil and Tillage Research 39, 115–129.

Németh, T., Stefanovits, P., Várallyay, Gy., 2005. Talajvédelem. Országos Talajvédelmi Stratégia tudományos háttere, Kármentesítési tájékoztató. Környezetvédelmi és Vízügyi Minisztérium, Budapest (in Hungarian).

Nilaweera, N.S., Nutalaya, P., 1999. Role of tree roots in slope stabilization. Bulletin on Engineering Geology and the Environment 57, 337–342.

Norris, J.E., 2005. Root reinforcement by hawthorn and oak roots on a highway cutslope in Southern England. Plant and Soil 278, 43–53.

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

Odum, H.T., Odum, B., 2003. Concepts and methods of ecological engineering. Ecological Engineering 20, 339–361.

Oldeman, L.R., 2000. Impact of soil degradation: a global scenario. International conference on managing natural resources for sustainable agricultural production in the 21st Century, New Delhi, 14-18 February 2000.

Oostwoud Wijdenes, D.J., Ergenzinger, P., 1998. Erosion and sediment transport on steep marly hillslopes, Draix, Haute-Provence, France: an experimental field study. Catena 33, 179–200.

Operstein, V., Frydman, S., 2000. The influence of vegetation on soil strength. Ground Improvement 4, 81–89.

Orfila, L., Rodríguez, M., Colman, T., Hasegawa, M., Merentes, E., Arvelo, F., 2000. Structural modification of berberine alkaloids in relation to cytotoxic activity in vitro. Journal of Ethnopharmacology 71, 449-456.

Pardini, G., Gispert, M., Dunjo,´ G., 2003. Runoff erosion and nutrient depletion in five Mediterranean soils of NE Spain under different land use. Science of the Total Environment 309, 213–224.

Peng, Y., Chen, S.B., Liu, Y., Chen, S.L., Xiao, P.G., 2006. A pharmacophylogenetic study of the Berberidaceae (s.l.) Acta Phytotaxonomica Sinica 44, 241-257.

Poesen, J., Nachtergaele, J., Verstraeten, G., Valentin, C., 2003. Gully erosion and environmental change: importance and research needs. Catena 50, 91–133.

Pollen, N., Simon, A., 2005. Estimating the mechanical effects of riparian vegetation on streambank stability using a fiber bundle model. Water Resources Research 41, 1–11.

Quine, C.P., Burnand, A.C., Coutts, M.P., Reynard, B.R., 1991. Effects of mounds and stumps on the root architecture of Sitka spruce on a peaty gley restocking site. Forestry 64, 385–401.

Rackova, L., Oblozinsky, M., Kostalova, D., Kettmann, V., Bezakova, L., 2007. Free radical scavenging activity and lipoxygenase inhibition of Mahonia aquifolium extract and isoquinoline alkaloids. Journal of Inflammation 4, 15.

Rameau, J.C., Mansion, D., Dumé, G., 1993. Flore forestière française (guide écologique illustré), tome 2 : Montagnes. Institut pour le Développement Forestier.

Reubens, B., Poesen, J., Danjon, F., Geudens, G., Muys, B., 2007. The role of fine and coarse roots in shallow slope stability and soil erosion control with a focus on root system architecture: a review. Trees 21, 385–402.

Rey, F., 2002. Influence de la distribution spatiale de la vegetation sur la production sédimentaire de ravines marneuses dans les Alpes du sud. Ph.D. Thesis, Cemagref, Grenoble, France.

Rey, F., Isselin-Nondedeu, F., Bédécarrats, A., 2005. Vegetation dynamics on sediment deposits upstream of bioengineering works in mountainous marly gullies in a Mediterranean climate (Southern Alps, France). Plant and Soil 278, 149–158.

Rey, F., 2009. A strategy for fine sediment retention with bioengineering works in eroded marly catchments in a mountainous Mediterranean climate (Southern Alps, France). Land Degradation and Development 20, 1–7.

Rickson, R.J., 1995. Simulated vegetation and geotextiles. In: Morgan, R.P.C., Rickson, R.J., (Eds.), Slope stabilization and erosion control: A bioengineering approach. E and FN Spon, London, pp. 95.

Roering, J.J., Schmidt, K.M., Stock, J.D., Dietrich, W.E., Montgomery, D.R., 2003. Shallow landsliding, root reinforcement and the spatial distribution of trees in the Oregon Coast Range. Canadian Geotechnical Journal 40, 237–253.

Samecka-Cymerman, A., Kempers, A.J., 1999. Bioindication of heavy metals in the town Wroclaw (Poland) with evergreen plants. Atmospheric Environment 33, 419-430.

Schmid, I., Kazda, M., 2002. Root distribution of Norway spruce in monospecific and mixed stands on different soils. Forest Ecology and Management 159, 37–47.

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

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

Seidemann, J., 1998. Die Mahonie (Mahonia aquifolium/Pursh/Nutt.), eine brauchbare Obstpflanze? Deutsche Lebensmittel-Rundschau 94, 217-220.

Shrestha, D.P., Zinck, J.A., Van Ranst, E., 2004. Modelling land degradation in the Nepalese Himalaya. Catena 57, 135-156.

Siepel, A.C., Steenhuis, T.S., Rose, C.W., Parlange, J.Y., McIsaac, G.F., 2002. A simplified hillslope erosion model with vegetation elements for practical applications, Journal of Hydrology 258, 111-121.

Slobodníková, L., Rasochova, E., Kostalova, D., Kotulova, D., Sochorova, R., 2000. Bacteria isolated from skin lesions of patients with ache and their in vitro sensitivity to standardized extract from Mahonia aquifolium (pursh) nutt | [Bakterialne osidlenie koznych lezii pacientov s akne a jeho citlivost' in vitro na standardizovany extrakt z Mahonia aquifolium (pursh) nutt]. Cesko-Slovenska Dermatologie 75, 99-103.

Slobodníková, L., Kostálová, D., Labudová, D., Kotulová, D., Kettmann, V., 2004. Antimicrobial activity of Mahonia aquifolium crude extract and its major isolated alkaloids. Phytotherapy Research 18, 674-676.

STATISTICA 1984. STATISTICA Version 7.1 for Windows, Statsoft Inc.

STATISTICA 2007. STATISTICA Version 8.0 for Windows. Statsoft Inc.

Stefanovits, P., 1966. Mezőgazdasági Mérnöktovábbképző Intézet talajvédelmi tanfolyama. Egyetemi jegyzet. pp. 15-35 (in Hungarian).

Stermitz, F.R., Beeson, T.D., Mueller, P.J., Hsiang, J.F., Lewis, K., 2001. Staphylococcus aureus MDR efflux pump inhibitors from a Berberis and a Mahonia (sensu strictu) species. Biochemical Systematics and Ecology 29, 793-798.

Stokes, A., Ball, J., Fitter, A.H., Brain, P., Coutts, M.P., 1996. An experimental investigation of the resistance of model root systems to uprooting. Annals of Botany 78, 415–421.

Stokes, A., Atger, C., Glyn Bengough, A., Fourcaud, T., Sidle, R.C., 2009. Desirable plant root traits for protecting natural and engineered slopes against landslides. Plant and Soil 324, 1–30.

Styczen, M.E., Morgan, R.P.C., 1995. Engineering properties of vegetation. In: Morgan, R.P.C., Rickson, R.J., (Eds.), Slope stabilization and erosion control: A bioengineering approach. E and FN SPON, London, pp. 5–58.

Sudhishri, S., Dass, A., Lenka, N.K., 2008. Efficacy of vegetative barriers for rehabilitation of degraded hill slopes in eastern India. Soil and Tillage Research 99, 98–107.

Szabó, G., 2007. Changes in the structure of agricultural production, farm structure and income in Hungary in the period of 2004-2006. 104th (joint) EAAE-IAAE Seminar Agricultural Economics and Transition: "What was expected, what we observed, the lessons learned." Budapest, Hungary.

Taub, D.R., Goldberg, D., 1996. Root system topology of plants form habitats differing in soil resource availability. Functional Ecology 10, 258–264.

Taylor, N., (Edit) 1956. Taylor's Encyclopedia of gardening: Horticulture and Landscape design. American Garden Guild, Inc and Houghton Mifflin Co, Boston.

Terpó, A., Grusz, E., 1976. A Magyarországon termesztett Mahonia állomány rendszertani vizsgálata. Kertészeti Egyetem Közleményei 40, 333–349 (in Hungarian).

Thierfelder, C., Amezquita, C.E., Stahr, K., 2005. Effects of intensifying organic manuring and tillage practices on penetration resistance and infiltration rate. Soil and Tillage Research 82, 211-226.

Thornes, J.B., 1990. Vegetation and erosion, processes and environments. John Wiley & Sons.

Thyll, S., (Eds.), 1992. Talajvédelem és vízrendezés dombvidéken (2nd edn). Mezőgazdasági Kiadó, Budapest (in Hungarian).

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

Tóth, I., 1969. Díszfák, díszcserjék. Mezőgazdasági Kiadó, Budapest, pp. 80–82 (in Hungarian).

Tsukamoto, Y., Kusakabe, O., 1984. Vegetative influences on debris slide occurrences on steep slopes in Japan. In: Proceedings of Symposium on Effects Forest Land Use on Erosion and Slope Stability, Environment and Policy Institute, Honolulu, Hawaii.

Turner, N., 2000. Plant technology of the first peoples in British Columbia, (Reprint of Plants in British Columbian Indian Technology, 1998). Royal British Columbia Museum and First Peoples' Cultural Foundation, University of British Columbia Press. Victoria,Vancouver, Canada, pp. 256.

Udvardi, L., (Edited) 2000. A kertészeti növénytan növényismereti kompendiuma 2.32. Szent István Egyetem Kertészettudományi Kar Növénytani Tanszék, Soroksári Botanikus Kert. Budapest.

Valkó, G,. 2012. Magyarország mezőgazdasága, 2010, Általános mezőgazdasági összeírás. Központi Statisztikai Hivatal, Budapest.

Vallauri, D., 1997. Dynamique de la restauration forestière des substrats marneux avec Pinus nigra J.F. Arnold ssp. nigra dans le secteur haut-provençal. PhD thesis, Cemagref, Grenoble, France.

Vallauri, D.R., Aronson, J., Barbero, M., 2002. An analysis of forest restoration 120 years after reforestation on badlands in the South-western Alps. Restoration Ecology 10, 16–26.

Van der Knijff, J.M., Jones, R.J.A., Montanarella, L., 2000. Soil erosion risk assessment in Europe. European Soil Bureau, Joint Research Center of the European Commission.

Van Dijk, P.M., Kwaad, F.J.P.M., and Klapwijk, M., 1996. Retention of water and sediment by grass strips. Hydrological Processes 10, 1069–1080.

Vaughan, M., and Black, H.S., 2006. Improving forage for native bee crop pollinators. USDA AF Note-33.

Vidal, H., 1966. La terre armée. Annales Institut Technique Batim., Paris, No. 223-229, 888-939.

Vigiak, O., Okoba, B.O., Sterk, G., Groenenberg, S., 2005. Modelling catchment-scale erosion patterns in the East African Highlands. Earth Surface Processes and Landforms 30, 183-196.

Vigiak, O., Sterk, G., Romanowicz, R.J., Beven, K.J., 2006. A semi-empirical model to assess uncertainty of spatial patterns of erosion. Catena 66, 198-210.

Volleková, A., Kostálová, D., Sochorová, R., 2001. Isoquinoline alkaloids from Mahonia aquifolium stem bark are active against Malassezia spp. Folia Microbiologica 46, 107-111.

Waldron, L.J., 1977. The shear resistance of root-permeated homogeneous and stratified soils. Soil Science Society of America Journal 41, 843–849.

Waldron, L.J., Dakessian, S., 1981. Soil reinforcement by roots: calculation of increased soil shear resistance from root properties. Soil Science 132, 427–435.

Watson, L., and Dallwitz, M.J., 1992. The families of flowering plants: descriptions, illustrations, identification, and information retrieval. CD-ROM, Version 1.0 for MS-DOS. CSIRO Publications Melbourne.

Wertán, Z., 1962. A Mahonia: fajai, tulajdonságai, termesztése, és felhasználása, Szakdolgozat, Kertészeti és Szőlészeti Főiskola, Budapest, pp. 29. (in Hungarian)

Wischmeier, W.H., Smith, D.D., 1978. Predicting rainfall erosion losses: A guide to conservation planning. Agriculture Handbook No. 537. USDA-Science and Education Administration, US. Government Printing Office, Washington DC, pp. 58.

Withers, P.J.A., Hodgkinson, R.A., Bates, A., Withers, C.L., 2007. Soil cultivation effects on sediment and phosphorus mobilization in surface runoff from three contrasting soil types in England. Soil and Tillage Research 93, 438–451.

Wu, J.Y., Huang, D., Teng, W.J., Sardo, V.I., 2010. Grass hedges to reduce overland flow and soil erosion. Agronomy for Sustainable Development 30, 481-485.

Wu, T.H., 1976. Investigation of landslides on Prince of Wales Island, Alaska. Geotechnical Engineering Reports 5. Ohio State University, Department of Civil Engineering.

Wu, T.H., McKinnell III, W.P., Swantson, D.N., 1979. Strength of tree roots and landslides on Prince of Wales Island, Alaska. Canadian Geotechnical Journal 16, 19–33.

Wu, T.H., 1995. Slope stabilization. In: Morgan, R.P.C., Rickson, R.J., (Eds.), Slope stabilization and erosion control: A bioengineering approach. E and FNSpon, London, pp. 221–263.

Yarnell, E., Abascal, K., 2004. Botanical treatment and prevention of malaria: Part 2 - Selected botanicals. Alternative & Complementary Therapies 10, 277-284.

Zámbó, A., 1995. A kötészeti célra termesztett mahónia gyomviszonyai és gyomírtása. Diplomamunka Kertészeti és Élelmiszeripari Egyetem, Kertészeti Kar, Budapest (in Hungarian).

Ziemer, R.R., 1981. Roots and the stability of forested slopes. Erosion and sediment transport in Pacific rim steeplands. International Associated Hydrological Science Publications 132, 343–361.

Summary

Agriculture is an essential component of a settled, structured society as it provides a dependable source of food and various other by-products. Due to the ever increasing demands of a growing population, agriculture cannot always be conducted under ideal environmental conditions. Farming on hillsides is an example of necessity pushing agriculture into potentially undesirable conditions. Extreme site conditions necessitate selecting the appropriate vegetation and cultivation methods to ensure the long term stability of top soil through sustainable farming practices, particularly when extreme site conditions and small farm size combine as small-scale farms greatly depend on short-term output. Both the above and below ground biomass play an important role in soil erosion prevention. When the above ground biomass is absent the root system provides the only protection to the soil. Therefore it is important to identify root system traits and to determine their potential function in soil erosion control, particularly in the case of perennial crops under which root reinforcement can have a long term effect. The aim of this study was to develop and test solutions that can reduce soil loss and prevent environmental damage to small-scale mountain-agro ecosystems.

The research began with the study of root traits and morphology of three different plant groups (tree, shrub and herbaceous) to evaluate and compare their suitability for soil reinforcement. Examples of two species were taken from each group. Root distribution, root area ratio and root tensile strength measurements together with the additional soil shear strength provided by roots in terms of the computed root cohesion were used to compare species' efficiency in soil reinforcement. All tested plants had their highest root biomass in the upper soil layer while root area ratio measurements significantly decreased with depth. Even though there were differences in root area ratio between the plant groups it was not considered significant. The root tensile strength measurements showed significant differences between the tested species and plant groups. With increasing root diameter the tensile strength results decreased. The study concluded that grass and shrub roots provided a greater increase in soil shear strength in the topsoil than tree roots in the early stages of their development. However root reinforcement decreased quickly with increasing soil depth for all species.

The root system of *Mahonia aquifolium* was studied to determine its suitability for hilly areas with the intention of determining its effectiveness as soil erosion control. *M. aquifolium* can be cultivated for a wide range of purposes which makes the plant a marketable option for small-scale farmers. Furthermore, it has a high abiotic tolerance, is extremely hardy and adaptable to cultivation under various conditions. Therefore, it was of interest to determine the differences, if any, between cultivated and non cultivated *M. aquifolium*; paying particular attention to their root system to determine the plant's potential implications in horticultural engineering for slope stabilization.

Root distribution, root area ratio and root tensile strength measurements together with the root-induced cohesion derived from computations were used to determine *M. aquifolium's* efficiency as soil reinforcement. Cultivated plants showed a higher mean root count with well developed lateral and sinker roots while non-cultivated samples had a deeper penetrating tap root with weaker lateral and sinker roots. Even though cultivated *M. aquifolium* had significantly higher root area ratio results, both cultivated and non-cultivated plants had their highest root area ratio

results in the upper soil layer which then decreased with increasing soil depth. The root tensile strength measurements showed no significant difference between cultivated and non-cultivated *M. aquifolium*. Thin roots were most resistant to tension and with increasing root diameter the root tensile strength decreased. Cultivated *M. aquifolium* showed significantly higher soil shear strength from roots than the non cultivated plant due to its dense root system near the soil surface.

A field study was conducted with different ages of *M. aquifolium* populations to determine their effectiveness as erosion control. Soil loss and runoff results were collected from four different age groups (4, 12, 20 and 25) of cultivated *M. aquifolium*. A grass and bare soil plot represented the control. The highest cumulative runoff results were collected from the two control plots, bare soil and grass plots, followed by the cultivated *M. aquifolium* plots with increasing population age. Two years after setting up a new *M. aquifolium* plantation (the four year old group) *M. aquifolium* cultivation can decrease the cumulative runoff by 69% compared to bare soil. The lowest cumulative soil loss result was collected from the control grass plot followed by the cultivated *M. aquifolium* plots from oldest to youngest. Overall *M. aquifolium* plantations have a significant influence on the quantity of surface runoff and the yield of sediment.

Finally, *M. aquifolium's* potential as a strip crop under various bio-physical conditions with different agricultural crops was investigated. This was done by predicting the surface runoff and soil loss results using the Revised Morgan-Morgan and Finney model (RMMF), an empirical soil erosion model. First the soil erosion model was calibrated using measured runoff and soil loss data from a field experiment (Chapter 4) by tuning the effective hydrological depth and the soil detachability index. The calibrated effective hydrological depth values varied with the age of the *M. aquifolium* plantations. The lowest value was obtained by the bare soil plot followed by the *M. aquifolium* plantations from youngest to oldest. The soil detachability index had to be adjusted for the control bare plot due to the higher amount of rocks in the soil. After model calibration the model was able to predict runoff and soil loss values with almost universally accurate predictions for all studied plots. Both the surface runoff and soil loss results indicated the effectiveness of the *M. aquifolium* strips on hillsides. The model predictions also indicate that agricultural or horticultural cultivations can succeed on even steeper slopes if *M. aquifolium* strips are applied and that these strips can reduce surface runoff and soil loss from both small-scale and large-scale agricultural hillsides.

Samenvatting

De landbouw is een onmisbaar onderdeel van onze maatschappij en een essentiële en betrouwbare bron van voedsel en grondstoffen. Echter, de toenemende vraag naar voedsel en grondstoffen ten gevolge van bevolkingsgroei en toenemende welvaart, maakt het niet altijd eenvoudig om de landbouwactiviteiten op een volledig milieuvriendelijke wijze uit te voeren. De bewerking van glooiende of reliëfrijke landschappen is een goed voorbeeld, waar, door de fysische omstandigheden, landbouw kan leiden tot ongewenste bijeffecten zoals bodemerosie. De keuze van het juiste gewas in combinatie met de juiste bodembeschermende maatregelen is dan essentieel voor duurzame landbouw. Bodembeschermende maatregelen zijn noodzakelijk om de bodemvruchtbaarheid op lange termijn te waarborgen en de 'off-site' effecten te beheersen. De plantaardige biomassa onder en boven het grondoppervlak speelt een belangrijke rol in de bescherming van de bodem en in het voorkomen van bodemerosie. In geval van ontbrekende vegetatiedek boven het grondoppervlak, neemt het wortelsysteem een deel van de beschermende functie over. Daarom is het heel belangrijk het wortelsysteem van de plant te leren kennen, om zo de invloed van de wortels op de bodemerosie te kunnen definiëren. Dit wordt des te belangrijker in geval van overwinterende planten. Immers, bij deze planten komen de uitwerkingen van het wortelsysteem op de lange termijn tot zijn recht. De bedoeling van deze studie is het volgende: Het tot stand brengen en het testen van oplossingen die geschikt zijn om de grondverliezen te reduceren, en het kunnen voorkomen van de nadelinge effectenop het milieu van landbouw op kleine percelen binnen een ecosysteem in een agrarische bergstreek.

Ik ben de studie begonnen met de analyse van het wortelsysteem en met een morfologisch onderzoek van drie verschillende groepen (bomen, struiken en kruiden), met de bedoeling om hun geschiktheid in grondversteviging te analyseren en te vergelijken. Ik heb twee plantsoorten van iedere groep onderzocht. Om de uitwerking van de plantsoorten op de grondversteviging te vergelijken, heb ik het volgende gemeten en de berekende waarden onderzocht: verdeling van de wortel, quotiënt van het wortel-gebied, trekvastheid van de wortel. Het wortelsysteem verhoogt de trekvastheid van de grond door het creëren van een toegevoegde cohesie, daarom is het bepalen van de waarde van wortelcohesie ook onderdeel van het onderzoek geweest. De resultaten van het onderzoek tonen dat bij zowel de gecultiveerde als de niet-gecultiveerde planten de wortel dichtheid het grootst is nabij het oppervlak. De wortelsterkte toont geen significant vershcil tussen gecultiveerde en niet-gecultiveerde planten. De waarden van het quotiënt van het wortel-gebied bij verschillende plantengroepen wijken wel van elkaar af, maar deze zijn niet significant. De resultaten van de metingen van de wortel trekvastheid daarentegen, vertoonden significante afwijkingen tussen zowel de plantsoorten als tussen de plantengroepen. Bovendien werd het feit bevestigd dat de toename van de worteldiameter evenredig is met de sterkte en trekvastheid van de wortel. De conclusie van dit deel van de studie is dat wortelsystemen van grassen en struiken zorgen voor een grotere toename van de bodemsterkte nabij het oppervlak dan de wortelsystemen van bomen. De toename van de bodemsterkte door wortels neemt echter snel af met bodemdiepte voor alle groepen.

Als volgende stap heb ik het wortelsysteem van de *Mahonia aquifolium* onderzocht. Dit met de bedoeling om te bepalen of deze plant geschikt is om bodemerosie te reduceren in reliefrijke gebieden. *M. aquifolium* is een multi-funtionele plant en wordt daarom veel verbouwd in het studiegebied veelal op kleine percelen en door kleinere landbouwbedrijven. *M. aquifolium*kan zich

goed aanpassen aan lokale condities, heeft een groot bladoppervlak en een goede wortelstructuur en is daardoor erg geschikt voor bodembeschermende maatregelen.Ik heb onderzocht of er een verschil bestaat tussen gecultiveerde en niet-gecultiveerde wortelsystemen van *M. aquifolium*en ik heb de effectiviteit van erosiereductie onderzocht van *M. aquifolium*van verschillende leeftijden (4, 12, 20 en 25 jaar). De invloed van de *M. aquifolium* op de grondversteviging heb ik met volgende gemeten- en berekende waarden onderzocht: verdeling van de wortel, quotiënt van het wortel-gebied, trekvastheid van de wortel en de wortelcohesie. De onderzoeksresultaten laten een hoger aantal gemiddelde wortelen met goed ontwikkelde zijwortelen zien bij gekweekte *M. aquifolium* planten, terwijl de in de landbouw niet gebruikte wortelmonsters van *M. aquifolium* planten over een meer diepgaand hoofd- en minder ontwikkeld zijwortel-systeem beschikken. Ondanks het feit dat de gecultiveerde *M. aquifolium* planten een aantoonbaar groter quotiënt van het wortel-gebied waarde hadden in vergelijking met de niet-gecultiveerde *M. aquifolium* planten, waren de hoogste quotiënt van wortel-gebied waarden bij beide plantengroepen dicht bij het grondoppervlak te vinden, en deze waarde nam voor beiden af met toenemende diepte. De resultaten van de wortel trekvastheidsmetingen vertoonden geen significante verschillen tussen de beide *M. aquifolium* groepen. Over het algemeen kan gezegd worden dat de wortelen met een kleine diameter (dun) de relatief grootste trekvastheid hadden, en dat deze evenredig afnam met de toename van de worteldiameter.

De volgende stap in mijn onderzoek richtte zich op het bepalen van de effectiviteit van bodemverlies door erosie van *M. aquifolium*. Ik heb het bodemverlies door erosie en de oppervlakkge afstroming van water onderzocht voor verschillende plots met *M. aquifolium* planten van verschillende leeftijden (4, 12, 20 en 25 jaar) en deze vergeleken met gemeten waarden op een plot met grasland en een plot met kale bodem. De hoogste waarden voor oppervlakkige afstroming werden respectievelijk gemeten op de kale bodem plot, de gras plot en de *M. aquifolium*met toenemende leeftijd. De resultaten tonen dat oppervlakkige afstroming sterk afneemt, tot wel 69%, bij twee-jarige *M. aquifolium*ten opzichte van de kale bodemplot.Bodemverlies door erosie was het laagst op de referentie grasplot. Bodemverlies was verder het laagst voor de plots met de oudste *M. aquifolium*planten. De conclusie van deze studie is dat *M. aquifolium*een belangrijk reducerend effect heeft op oppervalkkige afstroming van water en op de bodemerosie van de plots.

Als laatste stap heb ik onderzocht, wat de geschiktheid is van *M. aquifolium* voor de bestrijding van bodemerosie als stripgewas voor verschillende natuurlijke omstandigheden en toegepast tussen verschillende landbouwgewassen. Hiervoor heb ik het Revised Morgan-Morgan & Finney (RMMF) empirisch bodemerosiemodel gebruikt. Met behulp van dit model kon ik de bodemverlies- en oppervalkkige afstroming van water simuleren. Eerst heb ik het model gecalibreerd met behulp van de in het veld gemeten bodemerosie en oppervlakkige afstromingswaarden (hoofdstuk 4). Calibratie is voornamelijke gedaan met twee parameters: de effectieve hydrologische diepte (EHD) en de erodibiliteitsfator (K). De gecalibreerde EHD waarden vertoonden een verandering, evenredig aan de leeftijd van het *M. aquifolium* bestand. De laagste EHD waarde kwam voor op het gebied van het kale bodem perceel, deze werden gevolgd door de gecultiveerde *M. aquifolium*plots, met toenemende bestandsleeftijd. De K waarden vertoonde alleen bij het kale bodem perceel een afwijking in vergelijking met de resultaten van de plots. Het grotere aantal stenen aan het oppervalk ten opzichte van de andere plots speelt hierbij waarschijnlijk een rol. Calibratie van het RMMF werd daarom alleen voor dit perceel toegepast.

Het gecalibreerde model werd gebruikt om voor alle plots erosie en oppervlakkige afstroming te simuleren. Modelresultaten tonen aan dat *M. aquifolium*een effectief gewas is om oppervlakkige afstroming en bodemverlies te reduceren. De modelresultaten tonen ook aan dat *M. aquifolium*een effectief stripgewas is om te worden gebruikt tussen andere landbouwgewassen op hellingen om bodemerosie en afstroming te reduceren.

Összefoglalás

A mezőgazdaság, nélkülözhetetlen eleme egy berendezkedett, strukturált társadalomnak. Képes megbízható élelemforrást valamint egyéb területeken is felhasználható nyersanyagot biztosítani. Azonban a népességnövekedés következtében fellépő növekvő kereslet, nem mindig teszi lehetővé, hogy a mezőgazdasági tevékenységek ideális környezeti feltételek mellett valósuljanak meg.
A leejtős területek művelése egy példa arra, amikor a kényszerűség vezeti a mezőgazdasági tevékenységet nem kívánt kondíciók közé. Egy fenntartható gazdálkodási forma mellett a szélsőséges termőhelyi adottságok szükségessé teszik a termeszteni kívánt növényfaj és az alkalmazni kívánt agrotechnika megfelelő módon történő megválasztását, ahhoz hogy hosszú távon is biztosítani lehessen a talaj termékenységét. Kiváltképpen igaz ez akkor, amikor a szélsőséges termőhelyi adottságok mellett a kis tábla méret is nehezíti a talajvédelem feladatait.
Mind a talajfelszín alatt mind a talajfelszín fölött megtalálható növényi biomassza fontos szerepet játszik a talaj védelmében, a talajerózió megelőzésében.
Abban az esetben, amikor a talajfelszín fölötti növényi biomassza hiányzik a gyökérrendszer veszi át a teljes védelmi funkció szerepét. Ezért fontos hogy minél alaposabban megismerjük a növény gyökérrendszerét, hogy minél pontosabban meghatározhassuk a gyökérzet talajerózióra gyakorolt hatását, Ez az évelő növények esetében talán még hangsúlyosabb szerepet kap hiszen ezeknél a növényeknél a gyökérrendszer hosszú távú hatásai érvényesülnek.
A jelen tanulmány célja az volt hogy létrehozzak és teszteljek olyan megoldásokat melyek képesek csökkenteni a talajveszteséget és képesek megelőzni a környezet károsítást a kisparcellás hegyvidéki agrár ökoszisztémákban.

A tanulmányt három különböző növénycsoport (fa, bokor és lágyszárú) gyökér- jellemzőinek és morfológiai vizsgálatainak elemzésével kezdtem meg azon célból, hogy kielemezhessem és összehasonlíthassam alkalmasságukat a talajerősítésében.
Két-két növényfajt vizsgáltam minden növénycsoportból. A növényfajok talajerősítésre gyakorolt hatásának összehasonlítására a következő mért és számított értékeket vizsgáltam: gyökér eloszlás, gyökér-terület hányados, gyökér szakítószilárdság. A gyökér-rendszer a talaj nyírószilárdságát egy hozzáadott kohézió létrehozásával növeli ezért a gyökér kohéziós érték meghatározása szintén a vizsgálat tárgyát képezte.
A vizsgálati eredmények a legnagyobb mennyiségű gyökér biomasszát a talajfelszínhez közel mutatták ki az összes vizsgált növény esetében. A gyökér-terület hányados értékek szignifikáns csökkenést mutattak a talaj mélység növekedésével. A különböző növénycsoportok gyökér-terület hányados értékei eltértek ugyan egymástól de ezek az eltérések nem mutatkoztak szignifikánsnak. Ezzel ellentétben a gyökér szakítószilárdság mérésének eredményei szignifikáns eltérést mutattak mind a növényfajok mind a növénycsoportok között. Valamint megerősítésre került az a tény is hogy a gyökérátmérő növekedésével a gyökér-szakítószilárdsága csökken.
Végeredményképpen elmondható hogy a füvek és a bokrok gyökérrendszere nagyobb talaj nyírószilárdság növekedést eredményezett a talaj felső rétegeiben, mint a vizsgált fa fajok gyökérrendszere.
Valamint az hogy a gyökér kohézió határozott csökkenést mutatott a talaj mélység növekedésével az összes vizsgált növényfaj esetében.

Következő lépésben a *Mahonia aquifolium* gyökérrendszerét vizsgáltam azon célból, hogy meghatározzam megfelel-e a növény a hegyvidéki viszonyok közötti termesztésnek, valamint hogy meghatározzam alkalmasságát a talajerózió elleni védekezésben.
A termesztett *M. aquifolium*-nak számos felhasználási területe ismert mely több területen is értékesíthető növénnyé teszi a kisparcellás hegyvidéki gazdaságok számára.
Ezen túlmenően tág abiotikus tűrőképességgel rendelkezik és képes alkalmazkodni különféle termesztési feltételekhez.
Első lépésben megvizsgáltam hogy van e különbség a termesztett és termesztésbe nem vont *M. aquifolium* gyökérrendszere között, különös tekintettel annak lejtőstabilitásra gyakorolt hatására és a lehetséges későbbi alkalmazási területére.

A *M. aquifolium* talajerősítésre gyakorolt hatását a következő mért és számított értékekkel vizsgáltam: gyökér eloszlás, gyökér-terület hányados, gyökér szakítószilárdság és gyökér kohézió.
A vizsgálati eredmények a termesztett *M. aquifolium* növények esetében magasabb átlag gyökérszámot mutattak, jól fejlett oldalgyökerekkel, míg a termesztésbe nem vont *M. aquifolium* növények gyökérmintái egy mélyebbre hatoló fő- és egy gyengébben fejlődött oldalgyökér-rendszerrel rendelkeztek.
Annak ellenére, hogy a termesztésbe vont *M. aquifolium* növényeknek szignifikánsan nagyobb gyökér-terület hányados értékük volt kimutatható, mint a nem termesztésbe vont *M. aquifolium* növényeknek, a legmagasabb gyökér-terület hányados értékek mindkét vizsgált növénycsoport esetében a talajfelszínhez közel voltak megtalálhatók majd a talaj mélység növekedésével fokozatosan csökkenő értéket mutattak.
A gyökér szakítószilárdság méréseinek eredményei nem mutattak szignifikáns különbséget a két vizsgált *M. aquifolium* csoport között. Általánosságban elmondható azonban hogy a kis átmérőjű (vékony) gyökereknek volt a legnagyobb a szakítószilárdsága mely a gyökér átmérő növekedésével fokozatosan csökkent.
A termesztésbe vont *M. aquifolium* szignifikánsan nagyobb mértékben növelte a talaj nyírószilárdságát, köszönhetően a magasabb gyökérsűrűségének a felső talajrétegben, mint a művelésbe nem vont *M. aquifolium*.

Következő lépésben a szabadföldi kísérletek arra irányultak, hogy meghatározzam milyen hatékonysággal képesek a különböző korú *M. aquifolium* ültetvények eredményesen részt venni a talajerózió elleni védekezésben. A négy különböző korú (4, 12, 20 és 25 éves) termesztésbe vont *M. aquifolium* ültetvény talajveszteség és lefolyás értékeit vizsgáltam és hasonlítottam össze a mért kontroll gyep és csupasz talaj parcellák értékeivel. A legmagasabb összesített lefolyás értékek a két kontroll parcella területéről kerültek összegyűjtésre melyet a termesztésbe vont *M. aquifolium* állományok követtek növekvő állomány korral. Az eredmények alapján elmondható hogy a *M. aquifolium* állomány telepítését követő második évben már 69%-os csökkenés volt kimutatható az összesített lefolyás értékekben a csupasz talaj parcellákhoz viszonyítva.
A legalacsonyabb összesített talajveszteség érték a gyeppel borított kontroll parcella területéről került összegyűjtésre. Ezt követte a termesztésbe vont *M. aquifolium* állomány csökkenő állomány korral.
Összességében elmondható hogy a *M. aquifolium* állományoknak szignifikáns hatásuk van a terület lefolyás és a talajveszteség mennyiségi értékeire.

Utolsó lépésként azt vizsgáltam, hogy milyen hatást gyakorol a *M. aquifolium* mint strip crop (sáv növény) különböző biofizikai kondíciók mellett különböző mezőgazdasági termesztésű növényállományokban a talaj erózió elleni védekezés szempontjából. Ennek megállapítására a Revised Morgan-Morgan és Finney (RMMF) empirikus talajeróziós modellt használtam fel mely segítségével a talajveszteség és lefolyás értékeket tudtam szimulálni.
Elsőként a modell kalibrálását végeztem el a negyedik fejezetben szabadföldi kísérletek során nyert talajveszteség és lefolyás értékeinek felhasználásával.
Mivel előzetesen az EHD és a talaj erodálhatóságát kifejező értékek (K) érzékenynek bizonyultak ezen értékeket finomítani kellett. A kalibrált EHD értékek változást mutattak a *M. aquifolium* állomány korának változásával. A legalacsonyabb EHD érték a csupasz talaj kontroll parcellán volt melyet a termesztésbe vont *M. aquifolium* állomány növekvő állomány korral követett. A K érték egyedül a csupasz talaj esetében mutatott eltérést a szabadföldi kísérletek értékeihez viszonyítva ezért annak kalibrálása csupán erre a parcellára terjedt ki. Ennek az oka a nagyobb számban előforduló kődarabok jelenlétével magyarázható a parcellán. A modell a kalibrálását követően képes volt pontos talajlehordás és lefolyás értékeket szimulálni az összes vizsgált parcella esetében.
A talajeróziós folyamatok szimulációját követően mind a talajveszteség mind a lefolyás értékek alátámasztottak a *M. aquifolium* mint strip crop hatékonyságát a leejtős területeken. Továbbá, hogy mind a mezőgazdasági mind a kertészeti művelése a meredek leejtőknek sikeresen megvalósítható, ha *M. aquifolium* strip kerül alkalmazásra a művelt területeken.
Mindemellett a *M. aquifolium* strip képes a talajlehordást és a lefolyás mértékét mind a kisparcellás mind a nagyparcellás hegyvidéki agrárterületeken csökkenteni.

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About the author

Csilla Hudek was born on the 18th of May in 1977 in Szentendre, Hungary. Csilla attended primary school in her home town and high school in Budapest as well as one year at Juniata High School in Mifflintown, Pennsylvania, USA. In 1997 she started her Horticultural Engineering studies at the St. Stephen University in Budapest, Hungary. She followed courses in Ecological Agriculture at the The Royal Veterinary and Agricultural University in Copenhagen, Denmark and in Wildlife Management at the St. Stephen University Institute for Wildlife Conservation, Gödöllő, Hungary. During her studies Csilla was a horticultural trainee with the L'Ecole Superieure d'Agriculture d'Angers in France and with Aarstiderne, Organic and Biodynamic farm in Humlebak, Denmark. At the end of her Master thesis in 2003 she obtained a MSc. Diploma in Horticultural Engineering, specialising in Ecological and Sustainable Development. Following her diploma studies, Csilla carried out an internship on ecological monitoring at the University of South Bohemia, Department of Ecology in Ceske Budejovice, Czech Republic and on modelling and monitoring of harvest dates and the shelf life of stock at Greenmount Campus College of Agriculture Food and Rural Enterprise Development Centre in Antrim, Northern Ireland.

Following her master study Csilla joined the Department of Soil Science and Water Management at the Corvinus University of Budapest in Hungary to work on research focusing on sustainable horticultural use of terrain under extreme conditions. During this research period she was involved not only in the monitoring of natural ecosystems but also discussions on the socio-economic aspects and public issues affecting rural mountain areas. During this time Csilla attended international conferences and published her findings in peer-reviewed journals.

In 2006 she moved to Grenoble, France and took part in research activities at Cemagref Grenoble (now Irstea). These research activities brought her into close contact with typical Alpine species and the detailed study thereof. The research activities involved the study of soil reinforcement by typical forest species on marly soils in the French Southern Alps as well as bioengineering works and restoration ecology issues. Csilla attended international conferences and published research results in various international peer-reviewed journals.

She also had the privilege of being selected for the Third ALTER-Net Summer School on "Biodiversity and Ecosystem Services" which made her even more enthusiastic about sustaining our ecological well being. The workshop promoted interdisciplinary approaches to topics such as state of the art biodiversity in Europe, monitoring and assessment, critical ecosystem properties to sustain ecosystem services, resilience of social and natural systems, ecological and socio-economic modelling and linking biodiversity research with policy and the public. The workshop provided an opportunity to work on a case study which was formulated as though it were an EU-project in the 7th Framework Programme. This gave her the chance of working together with people from different countries and professional backgrounds on conservation issues.

Following her research at Cemagref, Csilla joined the Department of Physical Geography, at Utrecht University in The Netherlands to work on her Ph.D. research focusing on improving the knowledge on the efficiency of vegetation for protection against water erosion in mountain ecosystems. It aimed to highlight the importance of plant community behaviour in both long and short term environmental management.

List of Publications

Scientific papers

Hudek, C., Sterk, G., Van Beek, R., De Jong, S.M., (submitted) Modelling soil erosion reduction by Mahonia aquifolium on hillslopes in Hungary: the impact on soil reinforcement by roots. Catena

Burylo, M., **Hudek, C**., Rey, F., 2011. Soil reinforcement by the roots of six dominant species on eroded mountainous marly slopes (Southern Alps, France). Catena 84, 70-78.

Hudek, C., 2010. Improving Soil and Water Conservation with Mahonia aquifolium horticulture in the Hills of Hungary, in: Zlatic, M., (Eds.), Global change - challenges for soil management. Advances in GeoEcology 41, Catena Verlag, pp. 269-277.

Hudek, C., Burylo, M., Rey F., 2010. Root system traits of Mahonia aquifolium and its potential use in soil reinforcement in mountain horticultural practices. Scientia Horticulturae 125, 504-511.

Hudek, C., Rey F., 2009. Studying the effects of Mahonia aquifolium populations on small-scale mountain agro-ecosystems in Hungary with the view to minimise land degradation. Land Degradation & Development 20, 252–260.

Hudek, C., 2005. A sokszínű Kerti Mahónia. Kertgazdaság 37, 63-65 (in Hungarian).

International conference papers

Hudek, C., Rey, F., Molnar, E., 2008. Influence of Mahonia aquifolium population on erosion control in a mountainous area in Hungary. 15th International Congress of the ISCO, "Soil and Water Conservation, Climate Change and Environmental Sensitivity" 18th - 23rd of May, 2008, Budapest, Hungary.

Hudek, C., Burylo, M., Rey F., 2007. Root density distribution and root tensile strength of typical forest species on marly soils in the French Southern Alps. International Conference Erosion and Torrent Control as a Factor in Sustainable River Basin Management (25-28 September 2007), Belgrade, Serbia.

Hudek, C., Forro E., 2006. Our Peatlands Future. 2nd International Conference on Environmental Research and Assessment - ICERA2006. 5th - 8th of October, 2006, Bucharest, Romania, CD ROM.

Hudek, C., 2006. Sustainable Use of Peatlands. International Environmental Conference: Sustainable Management and Development of Mountainous and Island Areas 29th of September, 2006 to 1st of October, 2006, Island of Naxos, Greece, pp. 148-154.

Hudek, C., 2004. Sustainable use of extreme areas. Agro Environ 2004 Congress Role of Multi-purpose Agriculture in Sustaining Global Environment, 20-24 October, 2004, Udine, Italy, pp. 331-333.

Posters

Hudek, C., Sterk, G., Van Beek, R., De Jong, S.M., 2012. Modelling the impact of Mahonia aquifolium strips on hillslope erosion. International Conference: Land Conservation – LANDCON 1209, (17^{th} – 21^{st} September 2012), Danube Region, Republic of Serbia.

Hudek, C., Rey, F., Molnar, E., 2009. Efficiency of plants for protection against surface water erosion in mountainous areas: the case of Mahonia aquifolium. International Conference: Land Conservation – LANDCON 0905, (26^{th} - 30^{th} May 2009), Tara Mountain, Republic of Serbia.

Hudek, C., 2008. Ecological rehabilitation of small size abandoned mountain agro-ecosystems in Hungary. 3rd ALTER-Net Summer School: Biodiversity and Ecosystem Services, (2^{nd} - 14^{th} September, 2008), Peyresq, Alpes de Haute-Provence, France.

Hudek, C., 2004. Mahonia aquifolium in Sustainable Agriculture. International Conference on Horticulture Post-graduate (Ph.D.) Study System and Conditions in Europe, (16^{th} - 19^{th} November, 2004), Lednice, Czech Republic.

Harun, R., **Hudek, C**., Davidson, D., Kidd, S., 2004. Improving the shelf life of stock. Flower Focus (22^{nd} September, 2004), Greenmount Campus College of Agriculture Food and Rural Enterprise Development Centre, Antrim, (Northern Ireland).

Other Research Reports

Den Uyl R., Garcia-Llorente, M., Goldin S.R., **Hudek, C**., Ónodi, G., Prior, G., Zimmermann, P., 2008. Managing the human environment system to provide and sustain ecosystem services for all users safeguarding human wellbeing and biodiversity (MEDUSA) - developing strategies to adapt to future changes. 3rd ALTER-Net Summer School: Biodiversity and Ecosystem Services, (2-14 September, 2008), Peyresq, Alpes de Haute-Provence, France.

Brandao, M., Hansen, L., **Hudek, C**., Pallottino, F., 2001: The potential use of allelopathy in agriculture. SOCRATES European Common Curriculum, KVL (The Royal Veterinary and Agricultural University), Department of Agricultural Sciences, Copenhagen, Denmark.

Hudek, C., Czibolya J., 2004. Sustainable Agriculture in Hungary year 2004. 3rd ENOAS (European Network of Organic Agriculture Students) International meeting and workshop, (19th –23rd July, 2004), Ancona, Italy.

Hudek, C., Meszaros B., 2003. Sustainable Agriculture in Hungary year 2003. 2nd ENOAS (European Network of Organic Agriculture Students) International meeting and workshop, (July, 2003), Kassel, Germany.