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Influence of soil management systems on root parameters in Romanian vineyards

Master Thesis

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Affidavit

I hereby affirm that this Master Thesis represents my own written work and that no assistance other than that which is permitted has been used. Ideas and quotes taken directly or indirectly from other sources are identified as such. The thesis has not yet been submitted in any part.

Vienna, February 2019 ___________________________

Abstract

Soil management in vineyard inter-rows varies depending on pedoclimatic local conditions, management philosophy of wine growers or traditional established practices. In the past, frequent tillage was the standard practice in wine-growing regions. Various management practices in vineyard inter-rows such as permanent vegetation cover, alternating tillage or frequent tillage result in different effects on above and belowground ecosystem service provisions.

This study was embedded in the European BiodivERsA project VineDivers: “Biodiversity based ecosystem services in vineyards: analysing interlinkages between plants, pollinators, soil biota and soil erosion across Europe”. 120 core samples were taken in 15 vineyard inter-rows in the top 10 cm soil to analyse the effect of soil management systems on root parameters of the inter-row vegetation in Romanian vineyards. Roots were extracted from soil samples by washing them out and analysed concerning the most important root parameters: total root length density, total root surface area density, average root diameter and root mass density. Analysis was done in the laboratory with the image analysis system WinRHIZO. From the examined vineyards 7 vineyards were tilled frequently, 3 were treated with an alternating tillage system and on 5 vineyards a permanent vegetation cover was established. Vineyards managed with permanent vegetation cover showed a significantly higher total root length density, higher total surface area density and higher root dry mass density than vineyards managed with alternating tillage or frequent tillage. Furthermore, total organic carbon content was the highest in vineyards with permanent vegetation cover, which in turn can contribute to carbon sequestration, prevention of soil erosion, etc.

The choice of soil management therefore is a key management tool to affect plant root parameter and further contribution to ecosystem services.

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I am greatful for the time at the University of Natural Resources and Life Sciences Vienna which enabled me to expand my expertise of agricultural sciences. My academic study and the acquired knowledge supported me in my decision to found my own farm in 2017.

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1 Introduction

Viticulture dates back hundreds of years in Europe and has had formative influence on landscape, economy and tourism of a region (Dale and Polasky, 2007). Vineyards cover about 7.6 million hectares worldwide (Organisation Internationale de la Vigne et du Vin, 2018) and about 3.2 million hectares in Europe (EUROSTAT, 2017). Romania produces wine on about 183.717 hectares and holds the fifth biggest vineyard area in the European Union (EUROSTAT, 2017).

Each wine grower has his or her own attitude towards vineyard management (Galati et al., 2015) which affects the environment and consequently a wide range of ecosystem services (Dale and Polasky, 2007, Marshall et al., 2010). Ecosystem services are defined as benefits humans obtain from ecosystems such as flood regulation and water purification and can be divided into four groups: supporting, provisioning, regulating and cultural services (Reid et al., 2005). Generally, vineyards are intensively managed permanent crops that undergo a diversification via the introduction of vegetation cover by sowing cover crops or leaving the spontaneous vegetation (Altieri et al., 2010). Different soil-management systems in the inter-rows affect the vegetation composition and thus have major influence on vineyards and associated ecosystem services like soil compaction mitigation or soil water availability (Tilman et al., 2002, Virto et al., 2012, Ruiz-Colmenero et al., 2013, Trigo-Córdoba et al., 2015). Baumgartner et al. (2008) showed in a Californian vineyard the increase of plant diversity in non-tilled inter-rows. At the same time, the abundance/coverage of unfavourable plants such as *Elymus repens* can increase by maintaining permanent vegetation cover (Holzner and Glauninger, 2005). Wine growers´ choice of inter-row soil management system therefore influences the provision of either ecosystem services or disservices of vineyards (Zhang et al., 2007). Nonetheless, the use of soil-management systems with spontaneous vegetation or sown seed mixtures in the inter-rows and their impacts on vines and wine quality is discussed controversially (Virto et al., 2012, Ruiz-Colmenero et al., 2013, Winter et al., 2018). Due to assumed competition for water and nutrients by inter-row vegetation frequent soil tillage is the predominant soil-management system especially in dry climates (Celette et al., 2009, Klodd et al., 2016). Studies investigating water balance and nutrient balance show different results concerning competition for nutrients between vines and inter-row vegetation which is probably related to contrasting pedoclimatic conditions concerning water stress (Trigo-Córdoba et al., 2015). Particularly in warm and dry areas trials showed higher stress for water and nitrogen (Celette and Gary, 2013) and a decrease of grape yield (Tesic et al., 2007). Whereas studies in cooler humid climates showed that the yield and quality of wine is not negatively influenced by vegetation cover (Trigo-Córdoba et al., 2015).

Traditional weed control in the inter-rows of vineyards kept the soil unvegetated during the vegetation period. Whereas the soil was raked by hand before vineyards have been mechanised, rotary tillers became the state of the art (Preuschen et al., 1959). Nowadays, the use of vegetation cover in form of spontaneous vegetation or cover crops is more and more common (Pardini et al., 2002). Agri-environmental schemes that aim to mitigate soil erosion made a major contribution to this development (Pardini et al., 2002).

Besides these controversial views on competition for nutrients and water, farming systems with vegetation cover in the inter-row provide space for beneficial invertebrates and arthropods and can contribute to the provision of ecosystem services in the vineyards (Burgio et al., 2016). Flowering vegetation cover serves as attraction for pollinators by providing pollen and nectar source (Williams et al., 2015), but also bird species number and density increases in less intensively managed vineyards (Verhulst et al., 2004). A trial in Australia showed that native cover crops enhance the abundance of beneficial invertebrates better than non-natives (Danne et al., 2010). In addition, vegetation cover provides nesting sites for below-ground nesting species like wild bees and provides overwintering sites. Furthermore alternative prey/hosts and corridors for beneficial insects which contribute to biological control and pollination services are promoted (Altieri et al., 2010). However, negative effects should be considered too. Danne et al. (2010) showed that apart from positive aspects, native cover crops possibly support the appearance of potential pest species as hosts for pests and deseases (Sébastien et al., 2011).

Keeping the soil open accelerates the mineralization in the top soil (Laudicina et al., 2016) causing several ecosystem disservices such as increasing soil erosion and reduction of soil fertility (Ramos and Martínez-Casasnovas, 2006, Novara et al., 2011, Rodrigo Comino et al., 2016). Several studies have shown a large range of positive effects of cover crops in vineyards such as the prevention of soil erosion (Ruiz-Colmenero et al., 2011, Vršič et al., 2011), increase of soil structure stability, higher content of soil organic carbon (Steenwerth and Belina, 2008, Winter et al., 2018) and the increase of soil organic matter (Morlat and Jacquet, 2003, Zehetner et al., 2015) which leads to higher levels of ecosystem services provision like CO_2 sequestration (Dale and Polasky, 2007, Zhang et al., 2007, Brunori et al., 2016). Therefore, vineyards with low soil-tillage frequency serve as a carbon sink and show how permanent cropping systems could contribute to the mitigation of greenhouse gases like carbon dioxide (Brunori et al., 2016).

Besides these ecological aspects of vineyard inter-row management, there are indications, that the management system influences the chemical composition of the grapes and the must quality (Lopes et al., 2008). Test persons showed at wine tastings a preference for wine produced in vineyards with vegetation cover (Xi et al., 2011). Also economic aspects have to be considered. According to Lisa and Parena (1995), the number of tractor passes per year in the inter-row in Italy can be up to 22 times. This value corresponds to traditionally cultivated vineyards, and number of tractor passes can be decreased by 20% in grass-covered vineyards. Additionally, soil trafficability and workability is improved. Moreover, the aesthetic value of vegetation cover in vineyards should not be underestimated and can contribute to ecotourism (Miglécz et al., 2015).

In general, roots of permanent vegetation cover are not distributed regularly down the soil profile. The largest percentage of roots is located in the upper soil layers. According to Smith (2007) temperate grasslands have shallow rooting profiles with 80-90% of root mass in the top 0.3 m of the profile and grasses have 44% of their root mass in the top 0.1 m soil. Roots of vascular plants are primarily responsible for the acquisition of resources from the soil and the anchorage in the soil. Other functions such as storage or dispersal are seen as secondary functions (Fitter, 2002). Due to their functions, roots simultaneously serve as major pathways for the flow of carbon to the soil and to the soil organisms which in turn influences nitrogen immobilisation, ammonium oxidation and denitrification in the soil (Atkinson, 2000). By input of organic matter to the soil, roots exert an effect on soil structure, enhance aggregate formation and stability, affect associated microorganisms and thus influence cation exchange capacity of the soil (Atkinson, 2000, Kavdir and Smucker, 2005, Ros et al., 2009).

According to Li et al. (1991) the proportion of vegetation cover plays an important role in erosion mitigation, but an increase of root dry mass and root length density (root length in cm/cm^3) in the topsoil is also considered to reduce soil losses by fluvial erosion (Gyssels et al., 2005). Few studies exist about the functions and services of roots of vegetation cover. Most studies on soil erosion mitigation and reduction of water run-off concentrate on the aboveground characteristics of vegetation. Underground properties such as root characteristics are mostly neglected (Morgan and Rickson, 1995) due to the difficult and time consuming sampling methodology (Gyssels and Poesen, 2003). The control of soil erosion and soil retention are part of the regulatory services provided by vegetation (de Groot et al., 2002) achieved by intercepting raindrops, enhanced infiltration, providing additional surface roughness and increase of organic substances to the soil (Morgan and Rickson, 1995, Gyssels and Poesen, 2003). Roots induce macropores and therefore allow rapid rainfall infiltration and percolation to deeper soil layers (Ghestem et al., 2011). With regards to plant root effects on soil hydrology, they increase soil infiltration capacity when thick roots decay and form channels (Archer et al., 2002).

This master thesis is embedded in the European BiodivERsA project VineDivers: “Biodiversity based ecosystem services in vineyards: analysing interlinkages between plants, pollinators, soil biota and soil erosion across Europe”. The overarching objective of the project is the analysis of the implications of different management regimes on above and below-ground biodiversity and the associated ecosystem service in vineyards. The study sites of the project are located in Romania, Austria, France and Spain.

The main objective of the thesis was to analyse and evaluate the influence of different soil management regimes on root parameters of the inter-row vegetation in Romanian vineyards. Furthermore, potential interactions of root characteristics with soil and vegetation parameters provided by partners in the project VineDivers were investigated.

For that purpose, the following research question was formulated:

"How are inter-row vegetation root parameters in Romanian vineyards influenced by the soil management regime, taking into account soil and vegetation characteristics in the examined vineyards?"

It was hypothesized that:

(i) Management systems with permanent vegetation cover show a higher total root length and root surface area than vineyards with alternating tillage or bare soil in the inter-rows.

(ii) Vineyards with higher species numbers in the inter-row vegetation show a higher total root length.

(iii) Vineyards with higher total root mass show a higher total organic carbon content than vineyards with alternating tillage or bare soil.

2 Material and methods

2.1 Study sites

Root samples were taken in vineyards of the Jidvei vinery and in vineyards of small-scale farmers, all located in Târnave wine region in Transylvania (Romania) (see figure 1). The vinery of Jidvei is a company managing more than 2000 hectares of vineyards in that region. The vineyards are rainfed and located in a region with a pronounced continental climate. The average annual temperature is about 9.6 °C and the annual precipitation is about 582 mm (AM Online Projects, n. d.). The regional climate is classified as “Dfb” (D: snow, f: fully humid, b: warm summer) after Köppen-Geiger Climate Classification (Kottek et al., 2006) which signifies a humid continental climate with warm summers. The dominant soil type in the region of Târnave is the Cambisol. Clay, marls and Pannonian gravels are predominant (Marginean et al., 2013).

About 70% of the vineyards are situated in flat areas, whereas 30% of the vineyards are located on slopes (Popescu D., 2016, personal communication). The grape varieties in the surveyed vineyards are: Sauvignon Blanc, Feteasca Regala, Rheinriesling, Muskat Ottonel, Chardonnay and Traminer.

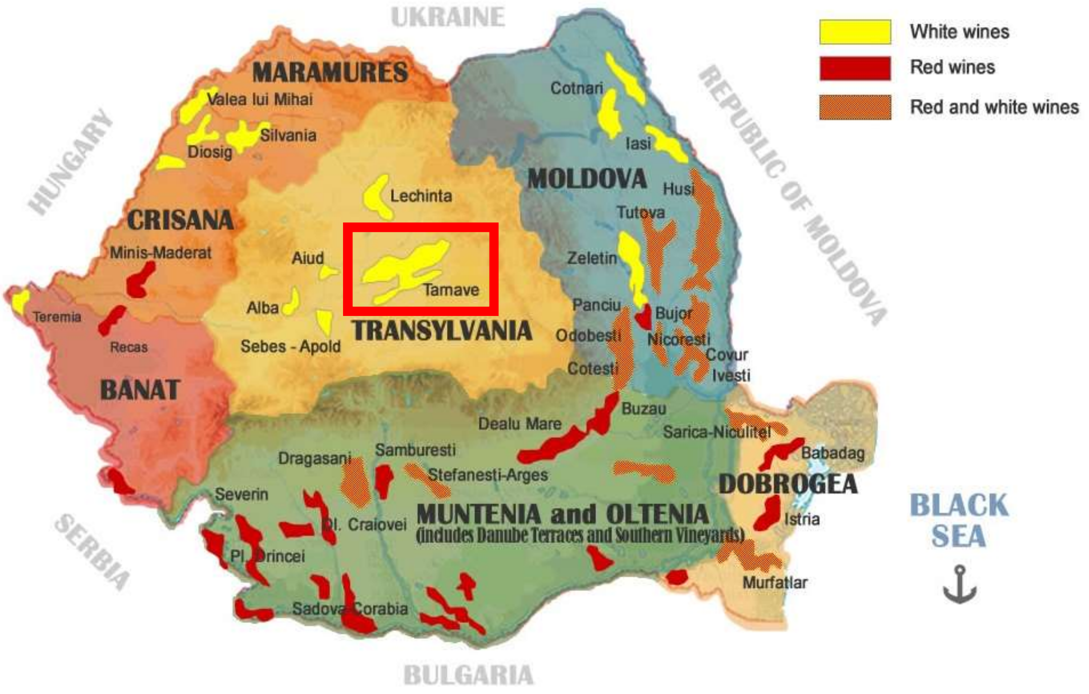


Figure 1: Map of Romania showing the wine-growing region Târnave in the centre of Transylvania (Tulbure, 2012)

The entire study area of the BiodivERsA project VineDivers in Romania encompasses in total 16 landscape circles, designated with the numbers from 1 to 16. The following types of management regimes were chosen in the project:

- Vineyards with permanent vegetation cover (P). Soil in the row is kept open by the application of herbicides or by tilling. The vegetation of inter-rows is mulched regularly. This management type is determined as not tilled for at least 5 years, though the time period varies in the investigated areas from 5 years to more than 10 years (see figure 2a).
- Alternating tillage (A) is defined as management type with annual soil tillage in every second vineyard inter-row. The tilled inter-rows change every year. In the second year of treatment, tilled rows of the first year of management stay untreated (see figure 2b).
- High intensity (HI) managed vineyards that are frequently tilled in the inter-rows and in-rows, which results in bare soil (see figure 2c).

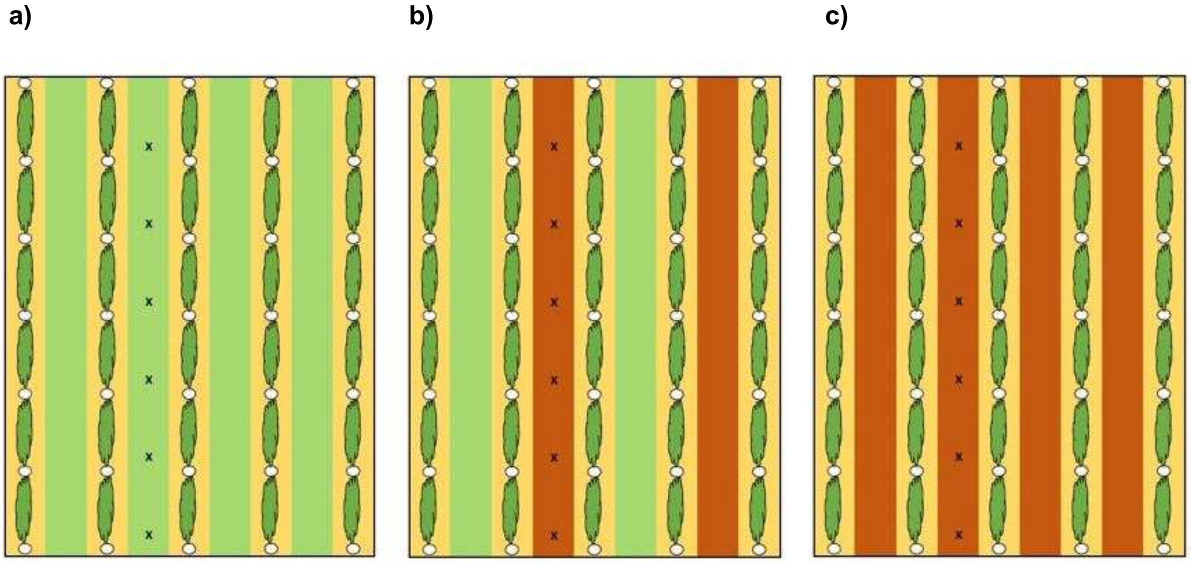


Figure 2: Scheme of vineyard soil management intensities in the inter-rows (O = vineyard poles, X = position of root sample, dark brown area shows the tilled inter-row area, green area vegetation cover, light brown the in-row area): a) management type P, b) management type A and c) management type HI.

Most wine growers use spontaneous vegetation cover in vineyards with alternating tillage or permanent vegetation cover in the inter-rows. Cover crop mixtures were only used in one vineyard in landscape circle 14 (clover-grass mixture, see figure 3). The vineyards are situated in six non-overlapping landscape circles with 750 m radius. Landscape circles contained two to three paired vineyards of different management intensities (see table 1) to minimize heterogeneity due to differences in soil type. In Romania and in the study region, frequent tillage in the inter-rows of vineyards is still the most common soil-management system (Popescu D., 2016, personal communication).

The present thesis analyses root parameters of 15 vineyards in six different landscape circles in the surrounding of the city of Blaj (see figure 3). In total, 5 vineyards with permanent vegetation cover, 3 vineyards with alternating tillage and 7 vineyards that are tilled 4 to 5 times per year in each inter-row (bare soil) were sampled. Table 1 provides an overview of the sampled vineyards and the related information on the vineyards. Within each vineyard inter-row, six root-sample pseudoreplicates (plus two backup samples) were collected. In total, the sampling campaign resulted in 120 soil samples.

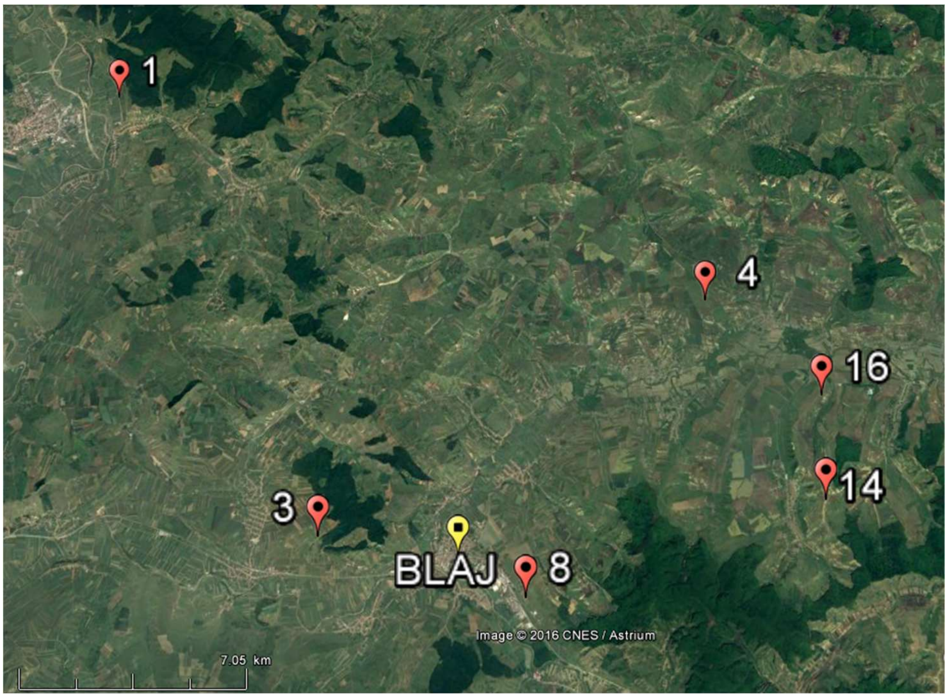


Figure 3: Survey map showing the locations of the six investigated landscape circles. Red marks show the position of the vineyards within the landscape circle and its circle number. The yellow mark shows the city of Blaj in the Alba county (Google Inc., 2017).

Table 1: Overview of investigated vineyards. The sampled vineyards are sorted by their position in the landscape circles and their management type (HI = bare soil, A = alternating tillage, P = permanent vegetation cover).

Landscape circle	**Plot Name**	**Location**	**Coordinates**		**Elevation [m]**	**Management type**			**Availability of soil data**
			Latitude (North)	**Longitude (East)**		**bare soil**	**alternating**	**permanent**	
1	1_P	Ciumbrud	46°19'12.24"	23°45'42.12"	293			×	×
1	1_HI	Ciumbrud	46°19'31.5"	23°45'30.78"	292	×			×
3	3_HI	Crăciunelul de Jos	46°10'57.36"	23°51'51.06"	318	×			
3	3_A	Crăciunelul de Jos	46°11'00.18"	23°51'50.46"	320		×		
4	4_HI	St. Nicolaus	46°15'00.6"	24°01'46.5"	315	×			
4	4_P	St. Nicolaus	46°15'10.74"	24°01'39.6"	344			×	
8	8_HI	Blaj	46°09'56.46"	23°57'01.5"	295	×			×
8	8_HI2	Blaj	46°10'14.52"	23°56'52.74"	292	×			
8	8_P2	Blaj	46°10'14.34"	23°56'57.12"	296			×	×
14	14_HI	Balcaci	46°11'30.72"	24°04'27.9"	437	×			×
14	14_A	Balcaci	46°11'35.22"	24°04'30"	439		×		×
14	14_P	Balcaci	46°11'36.06"	24°04'28.14"	439			×	×
16	16_HI	Jidvei	46°13'23.4"	24°04'33.1"	314	×			×
16	16_A	Jidvei	46°13'26.6"	24°04'34.5"	319		×		×
16	16_P	Jidvei	46°13'28.1"	24°04'33.3"	318			×	×

2.2 Data collection in the vineyards

Soil samples were collected and analysed by the Institute for Land and Water Management Research Federal Agency for Water Management in Petzenkirchen (Austria) in 2015 according to standardized methods. The sampling depth of 10cm was equal to the depth of the cores used for the root sampling. In each vineyard 4 plots were investigated, each plot features four replicates. For estimating dry bulk density, core sampling was conducted according to ISO 11272 (ISO, 1998). Texture was measured by combined wet sieving and sedimentation method (ÖNORM L 1050, 2004, ÖNORM L 1061-1, 2002), water content according to ÖNORM L 1062 (2003), organic carbon content according to ÖNORM L 1081 (2009). Percolation stability of soil aggregates was determined according to Kainz and Weiss (1988) and hydraulic conductivity according to ÖNORM L 1065 (2006). For this, water was percolated through a small tube filled with air-dried aggregates. The amount of water percolating through the aggregates in a predefined time is measured. This rate is then used as a measure for aggregate stability and for erosion prevention (Baize, 1993).

Data of plant diversity was provided by Nicole Penke (Penke, 2017) who investigated four 1 m^2 plots per inter-row in each vineyard twice, in spring and in summer 2016. Within the 1 m × 1 m plots all vascular plant species and their coverage (in %) in addition to overall vegetation cover were recorded. The four pseudoreplicates in each vineyard were established in the inter-rows between two poles and were situated next to four consecutive poles within one inter-row. Cover percentages of individual plant species followed the scale of Londo (1976). A 1 m × 1 m metal frame consisting of 10 cm × 10 cm quadrats was used for sampling.

The procedure of root sampling in a vineyard is shown in figure 4. The distances between the

Figure 4: Root sampling procedure in a Romanian vineyard using a soil corer.

samples were about six meters, resulting from the distance of the consecutive vineyard poles (see figure 2). The outermost 5 m at the beginning or end of the vineyard and positions of changing slopes or slope morphology within one vineyard were excluded from sampling. This was done to avoid distortive factors at the sampling points such as soil dislocation at slopes or compacted soils at the headlands. The soil of the surveyed vineyards was not cultivated previously to root sampling in the year of the investigation. Aboveground plant parts were removed before sampling. The root samples were taken in the middle of the inter-row with a soil corer (see figure 4) according to Böhm (1979). The diameter of the core was 70 mm and the height 100 mm (*i.e.* volumina of ca. 385 cm^3). The core cylinder was completely drilled by hand into the soil and removed with a rotating move (see figure 4). The soil cores were labelled and packed in plastic bags, before being frozen and transported to Vienna for further analysis in the laboratory.

2.3 Laboratory analysis

Washing of root samples

Manual root washing was done according to personal communication (Himmelbauer M., 2016) and methods established in the laboratory at the Institute of Hydraulics and Rural Water Management (Oliveira et al., 2000, Himmelbauer et al., 2004). Sieves with mesh sizes of 0.8 mm, 0.5 mm and 0.25 mm were used. The soil of the samples was dissolved in water (see figure 5) and the suspension emptied into the sieve with mesh size 0.8 mm (see figure 5). The material was sieved using a water hose. The rinsed material was emptied in a porcelain vessel and tap water was added.

Figure 5: Left: Suspension including the dissolved soil sample. Right: Sieving using a water hose.

Organic debris, big mineral constituents, dead roots and other constituent parts were separated manually from the living roots using tweezers (see figure 6). The roots were stored in tubes (of 50 ml content) within an alcoholic solution (50% alcohol diluted with purified water) (see figure 6). Very small root parts and short fragments of roots (shorter than 2 mm in length) could not be extracted and were discarded.

Figure 6: Left: Separating roots from other materials. Right: Storing of roots in tubes in alcoholic solution.

Scanning of roots

To improve the image contrast, roots were stained before the scan with Giemza's solution, a mixture of azure, eosin and methylene blue, diluted 1 to 25 with distilled water according to Himmelbauer et al. (2004). The roots were dipped in the warmed-up solution (about 30 °C) for about 10 minutes. Afterwards, the roots were washed again to drain the methylene-blue solution. For the scanning process, the roots were placed in a transparent plastic tray in a water layer of 2-3 mm depth using de-aerated water. Large root samples were subdivided into smaller sub-samples to avoid a too high scanning density. For this purpose, the sample was placed on a black tray to estimate the size of the sample. Depending on that, one quarter, one third, half of or the whole root sample was scanned. In case of dividing the sample before the scanning process (see figures 7 and 8) the results were multiplied according to the scanned subsample (e.g. if half of the sample was scanned, the results were multiplied by 2 to derive a result for the whole sample).

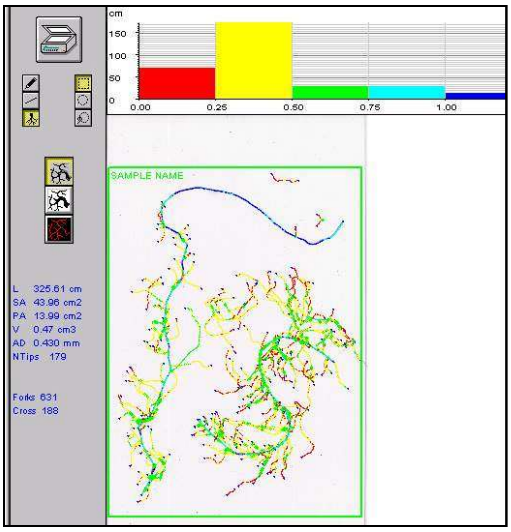
Figure 7: Black tray for estimating the sample size and the generation of sub-samples

Figure 8: Partitioning of a sample into three thirds. The result of the partial scanning was multiplied by the factor 3 in the present case.

The scanner was equipped with an additional lighting system from the top, optimized for root measurements with a scanning resolution of 600 dpi. The software used for the scanning process was WinRHIZO 2003a software (Regent Instruments, 2003) to obtain the root parameters: length (L), surface area (SA) and average diameter (AD) (see figure 9). Additionally, different diameter classes of the roots were classified and measured.

The diameter classes were set as follows:

0-0.2 / > 0.2-0.4 / > 0.4-0.6 / > 0.6-0.8 / > 0.8-1.0 / > 1.0-1.2 / > 1.2-1.4 / > 1.4-1.6 / > 1.6-2 / > 2-3 / > 3-5 / > 5 mm.



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L   325.61 cm
SA  43.96 cm2
PA  13.99 cm2
V   0.47 cm3
AD  0.430 mm
NTips  179

Forks 631
Cross 188
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Figure 9: Scanned root sample showed in WinRHIZO

The distance between the roots in the transparent tray was at least 1 cm. All roots were placed on the tray separately with plastic foreceps. Root pieces that were too big were cut with scissors. After the scanning process, the root samples were stored again in alcoholic solution for further analyses.

Determination of root dry mass

After the scanning process, the root samples were removed from the tubes and washed. Soon after, the roots were oven-dried at 60 °C in porcelain vessels to obtain the root dry mass (RDM). The samples remained in the oven for 48 hours until constant weight.

2.4 Statistical analyses

The data of image analysis and root dry-mass determination was analysed with the statistical software R (R Core Development Team, 2016). Graphic representations were made with the boxplot function and the package RColorBrewer (Neuwirth, 2014).

The statistical model used for analysing interrelations were generalized linear mixed models (GLMM) according to Zuur et al. (2013) since a random factor could be included, enabling to account for the nested sampling design. The sampled pseudoreplicates were nested in the vineyards and in the landscape circles.

The package car (Fox et al., 2016) was used for creating boxplots and the package Coin (Hothorn et al., 2016) was used for performing the Wilcoxon test. Moreover, lme4 (Bates et al., 2015) and AICcmodavg (Mazerolle, 2016) were used for the computation of the GLMMs. Effect plots showing the results of the GLMMs were made with the package effects (Fox, 2003).

The dependent root variables total root length, total root surface area, average root diameter and total root dry mass were analysed in context of soil management, vegetation and soil parameters. Since all root variables were measured for the same soil volume, the terms for root parameters, total root length density, total root surface area density and total root mass density were simplified. They were designated as total root length, total root surface area and total root mass. Data of vegetation, soil parameters and root parameters were averaged for each vineyard before the computations (all plant root parameters are based on the volumina of the collected soil samples i.e. volumina of ca. 385 cm^3). These data were complied in a CSV table for follow-up statistical analyses. The corrected Akaike information criterion (AICc) was used to compare the statistical models according to Motulsky and Christopoulos (2003). The difference of the AICc (corrected AIC for small sample sizes) values between the models should be at least 2, meaning that there is a probability of 73%, that the model with the smaller AIC_C value is more likely to be correct (Motulsky and Christopoulos, 2003). Models were developed according to a stepwise selection. According to this method, variables were consecutively entered into the model ("forward selection"). After the first step of constructing the null-model explanatory variables were included in the models. The complete tables can be found in the appendix. Variables were tested after Pearson before determining the model combinations. Correlating variables were excluded from the models.

The following explanatory variables concerning soil and vegetation management were selected for the statistical models:

- Management type (high intensity managed vineyards, alternating tillage, permanent vegetation cover)
- Soil treatment frequency per year
- Last soil management (in years)
- Duration of current management type (in years)
- Duration of vineyard cultivation (in years)
- Shannon index of vegetation data
- Vegetation cover (in %)
- Species number of vascular plants
- Landscape circle as random variable

Duration of current management type describes the time period of the established management system in years. Duration of vineyard cultivation stands for the time period in years after the vineyard was established. Shannon index accounts for both abundance and evenenness of present species. Here the proportion of species relative to the total number of species is calculated. It was computed according to the description of Oksanen et al. (2016)

by Nicole Penke (Penke, 2017) using the R package vegan (Oksanen et al., 2015). Instead of individual numbers the relative coverage of each plant species was used for calculation.

Since soil data were not available for all investigated vineyards, only 10 vineyards could be analysed (see table 1). Gaussian family was used as statistical distribution form for calculating GLMMs.

The following soil-data parameters were used as explanatory variables in the statistical models:

- Dry bulk density (in g/cm^3)
- Saturated hydraulic conductivity (in m/d)
- pH value
- Carbon content ($CaCO_3$) (in %)
- Total organic carbon content (TOC) (in %)
- Clay content (in %)
- Stone content >2 mm (in %)
- Percolation stability of soil aggregates (in ml/600 s)

3 Results

3.1 Management and vegetation effects on root parameters

3.1.1 Total root length

The distribution of the total root length (in cm) within the different management systems is shown in figure 10. It is obvious that vineyards with permanent vegetation cover show the highest total root length with a mean value of 3995 cm ± 1447 cm (standard deviation).

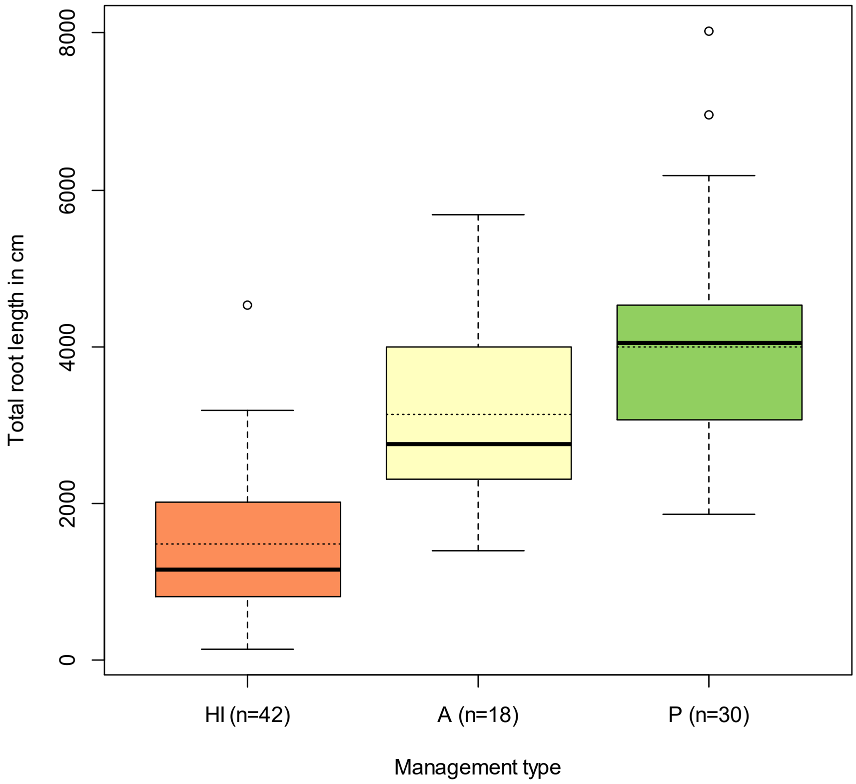

Figure 10: Total root length of different management systems. The lines in the boxplots show the mean value (dotted line) and the median (bold line) (HI = high management intensity, A = alternating tillage, P = permanent vegetation cover).

The total root length increases with decrease of management intensity. The mean value of the alternating management treatment is 3133 ± 1178 cm and the lowest value, of high management intensity treatments, accounts 1490 ± 935.

Distribution of total root length by diameter classes

The distribution of total root length from fine to coarse root diameter classes is shown in figure 11. Measurements show a generally high proportion of roots in the three classes 0-0.2 mm, > 0.2-0.4 mm and > 0.4-0.6 mm. Therefore, the majority of the roots in the different management systems can be assigned to the fine root classes. High management intensity shows clearly a lower total root length of fine roots than the management types with alternating management treatments and permanent vegetation cover.

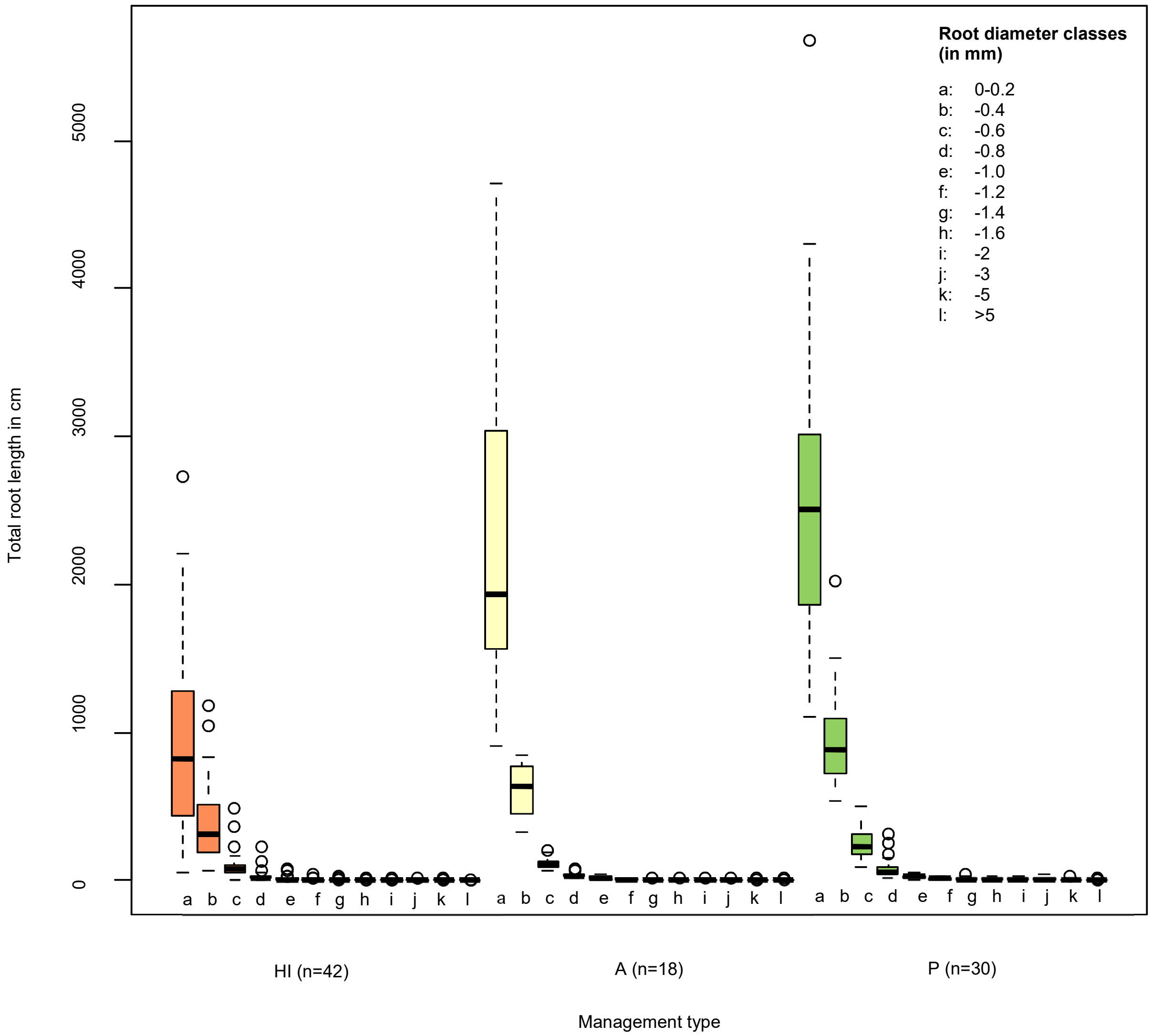

Figure 11: Distribution of total root length by diameter classes (0-0.2 / -0.4 / -0.6 / -0.8 / -1.0 / -1.2 / -1.4 / -1.6 / -2 / -3 / -5 / >5 mm) and management type (HI = high management intensity, A = alternating tillage, P = permanent vegetation cover). The bold lines in the boxplots show the median.

For the two variables total root length and last soil management a correlation was computed (see figure 12) showing an increase of total root length with longer time interval between the last soil managements.

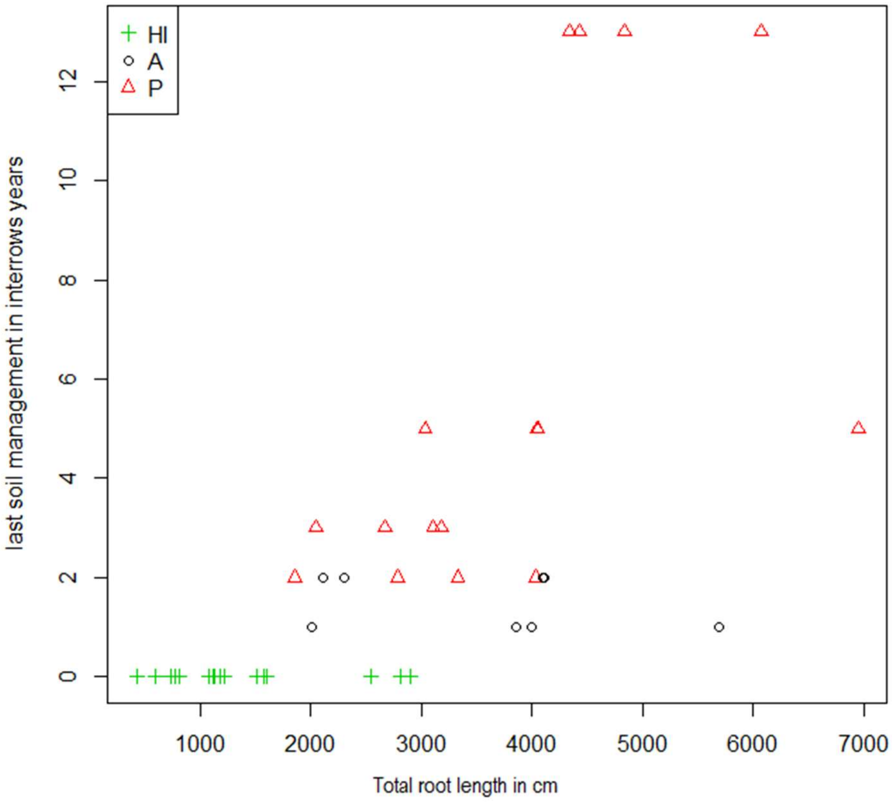

Figure 12: Correlation of root length and last soil management in the inter-rows in years (r = 0.65)

For the two variables total root length and plant species number a correlation was computed (see figure 13) showing no significant correlation between those parameters.

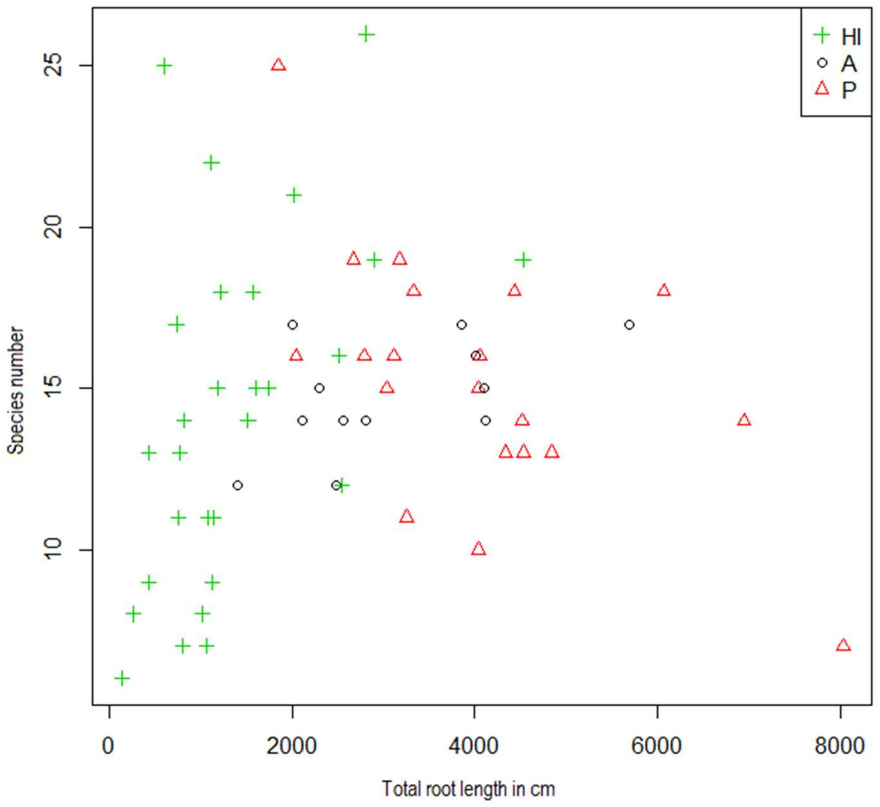

Figure 13: Correlation of total root length and species number (r = 0.11)

Also for the variables total root length and vegetation cover (see figure 14) and total root length and Shannon index (see figure 15) correlations were computed showing no significant correlation between those parameters.

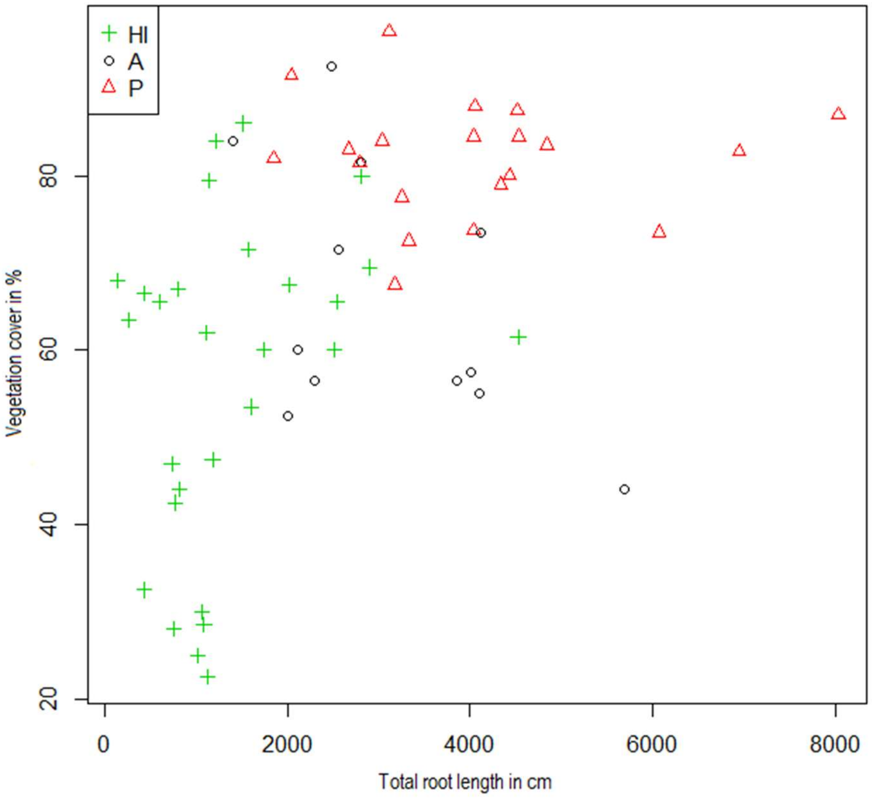

Figure 14: Correlation of total root length and plant cover in the inter-rows (r = 0.44)

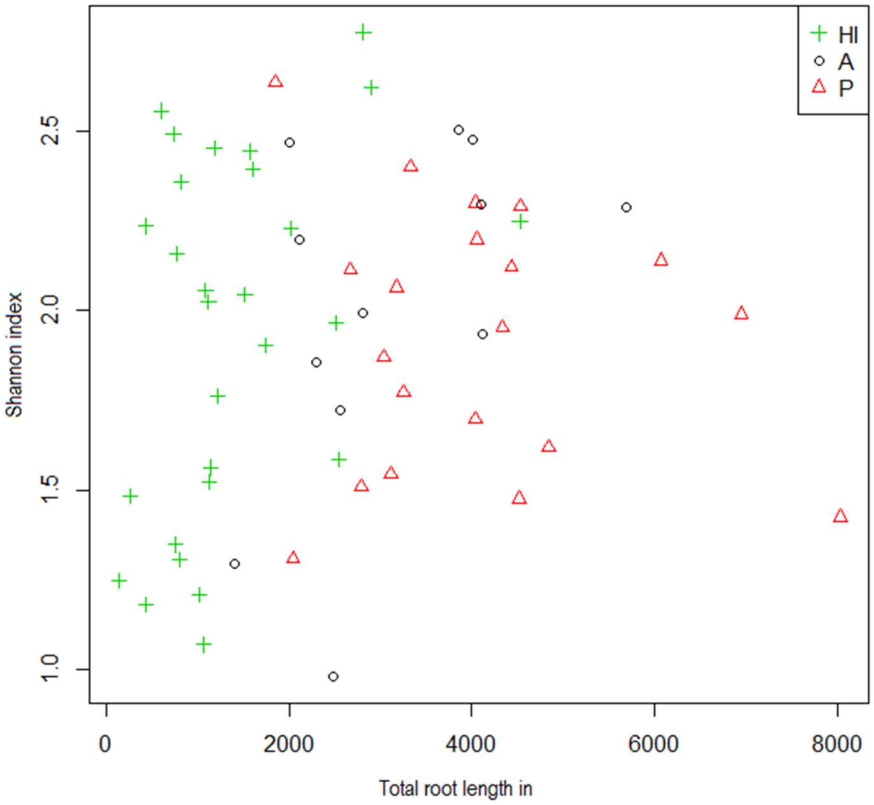

Figure 15: Correlation of total root length and Shannon index in the inter-rows (r = 0.15)

3.1.2 Total root length – GLMM

An overview of the four best models for the response variable total root length concerning the influence of management and vegetation is shown in table 2. After the construction of the null-model and adding one explanatory variable, subsequently management was used as an additional explanatory variable. The complete table can be found in the appendix. Models with more than two explanatory variables were calculated, but did not improve the AICc values.

The parameter total root length can not be explained best by only one explanatory variable. Three of the four best models show a similar result with ΔAICc ≤ 2. The best model includes the explanatory variables last soil management and management type. The second best model includes management type and Shannon index and the third only management type.

Table 2: Overview of best models (lowest AICc and ∆AICc ≥ 2) for the parameter root length. Best models are marked in bold.

Compared models	AICc
root length ~ 1 [null variant] + circle/plot	167.73
root length ~ management type + circle/plot	**142.55**
root length ~ last soil management + management type + circle/plot	**140.36**
root length ~ soil-treatment frequency + management type + circle/plot	144.98
root length ~ Shannon index + management type + circle/plot	**141.11**

The effect plot (see figure 16) of the best model demonstrates the increase of total root length the longer ago soil management was applied.

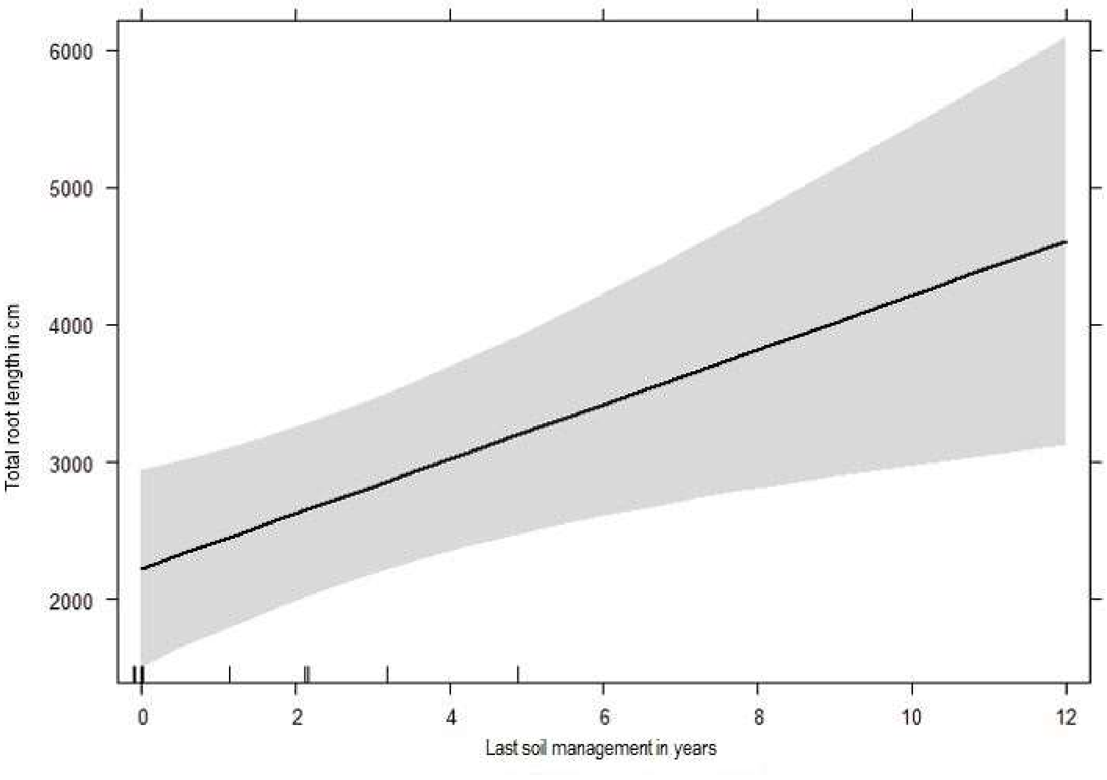

Figure 16: Effect plot of root length depending on last soil management in the inter-rows. (n=15).

The effect plot in figure 17 shows that the total root length differs in the soil management systems. Total root length increases with the decrease of soil management intensity whereas vineyards with alternating soil management systems showed the highest amount of total root length.

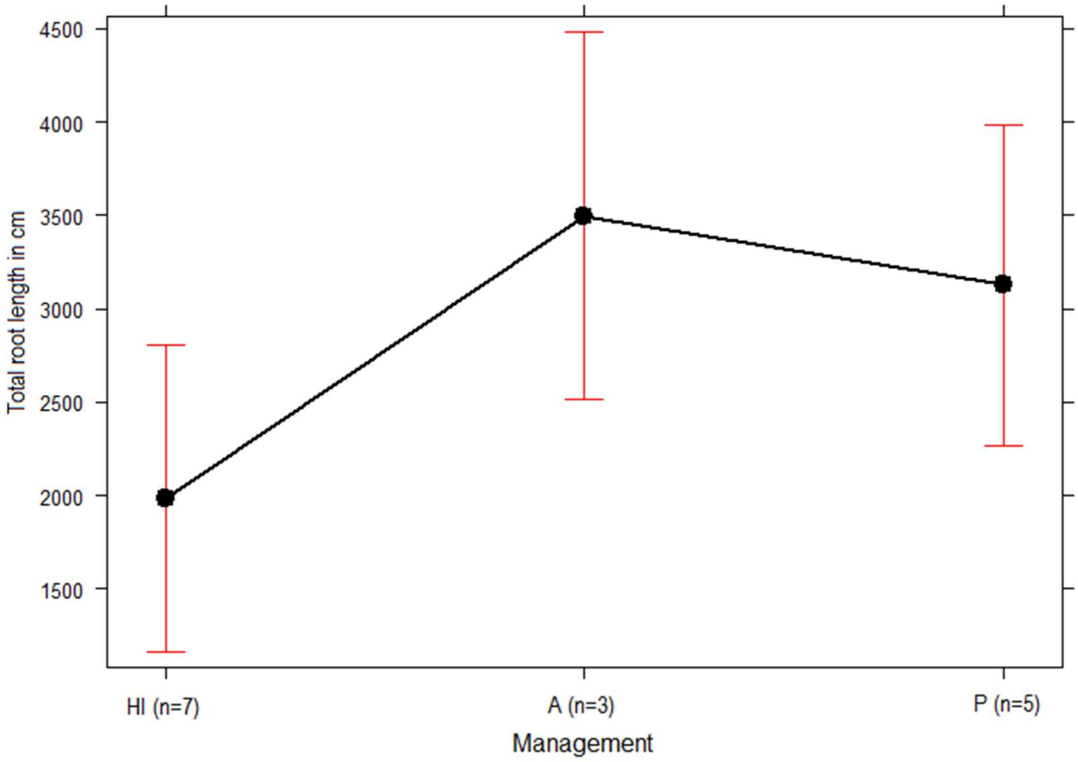

Figure 17: Effect plot of total root length depending on the type of management in the inter-rows (HI = high management intensity, A = alternating tillage, P = permanent vegetation cover) (n=15).

3.1.3 Total root surface area

The total surface area of roots (in cm^2) is shown in figure 18. The highest mean value of 328.0 ± 114.10 cm^2 is again reached by vineyards with permanent vegetation cover. The mean value of alternating management treatments is 212.1 ± 69.25 cm^2 and high management intensity vineyards show the lowest mean value of 114.9 ± 77.23 cm^2. The decrease of management intensity leads to an increase of total surface area of the roots.

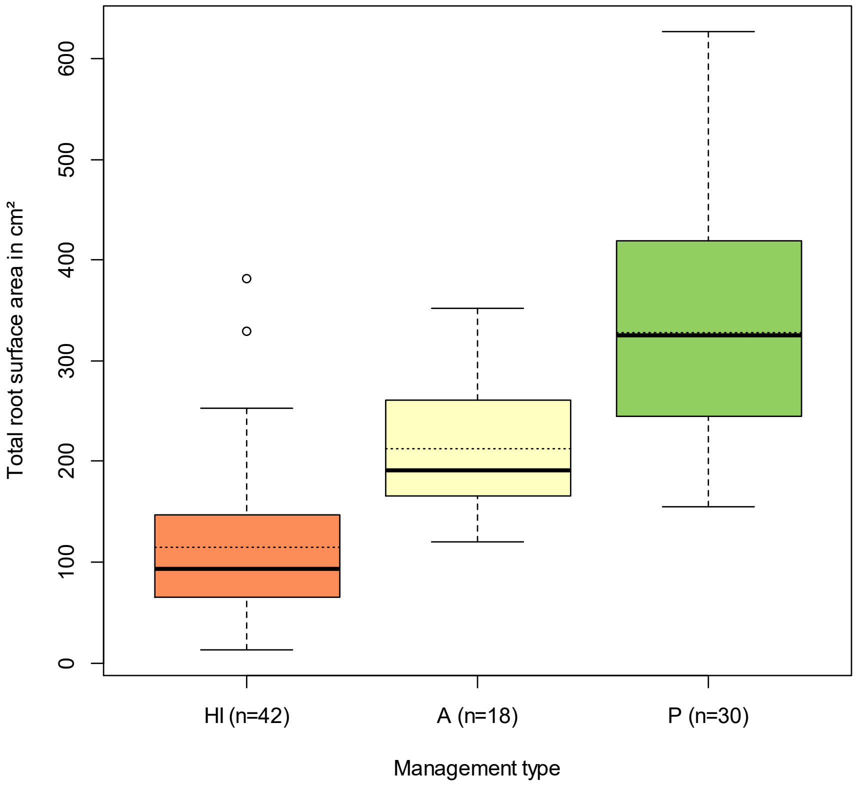

Figure 18: Total root surface area of the different management intensities. The lines in the boxplots show the mean value (dotted line) and the median (bold line) (HI = high management intensity, A = alternating tillage, P = permanent vegetation cover).

Distribution of total root surface area by diameter classes

The distribution of total root surface area (in cm^2) by average diameter classes is shown in figure 19. Root area measurements show corresponding results to the total root length having high proportion in the fine diameter classes of 0-0.2 mm, > 0.2-0.4 mm and > 0.4-0.6 mm. High management intensities result in lower root surface area than the alternating management and the permanent vegetation cover treatments. Notable is a higher proportion of total surface area in the diameter class of > 2-3 mm in all three management types. This tendency is most pronounced in the management with permanent vegetation cover.

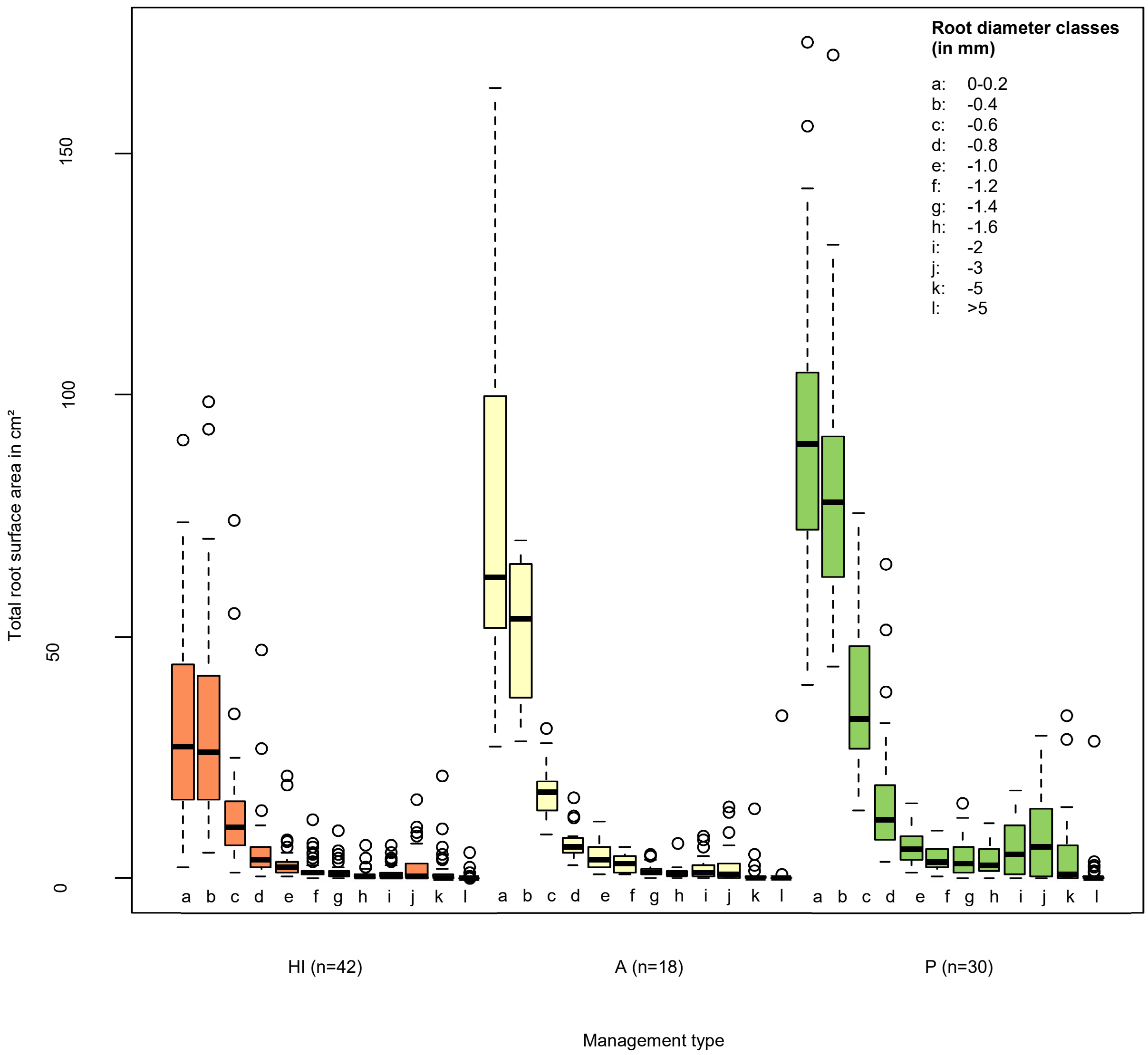

Figure 19: Distribution of total root surface area by diameter classes (0-0.2 / -0.4 / -0.6 / -0.8 / -1.0 / -1.2 / -1.4 / -1.6 / -2 / -3 / -5 / > 5 mm) and management type (HI = high management intensity, A = alternating tillage, P = permanent vegetation cover). The bold lines in the boxplots show the median.

For the two variables total root surface area and last soil management a correlation was computed (see figure 20) showing an increase of total root surface area with a longer time interval between the last soil management treatments.

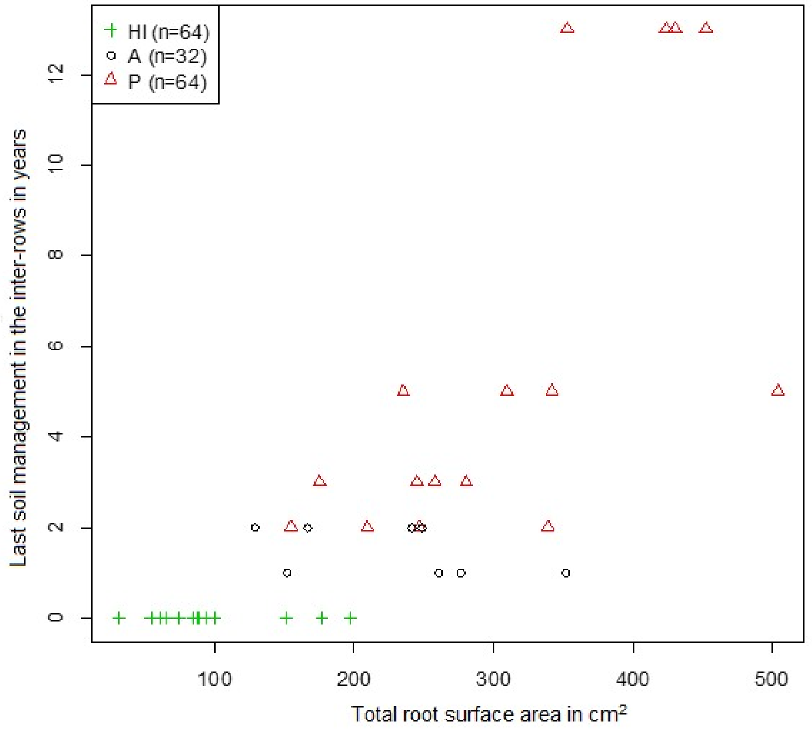

Figure 20: Correlation between root surface area and last soil management (r = 0.77)

3.1.4 Total root surface area – GLMM

Root parameter surface area was best explained by the model including the variable management type (see table 3). ΔAIC$_C$ is ≥ 2 in relation to the other tested models.

Table 3: Overview of best models (lowest AICc and ΔAICc ≥ 2) for the parameter surface area. Best model is marked in bold.

Compared models	AICc
surface area ~ 1 [null variant] + circle/plot	122.70
surface area ~ management type + circle/plot	**107.11**
surface area ~ last soil management + circle/plot	111.20
surface area ~ last soil management + management type + circle/plot	109.43
surface area ~ Shannon index + management type + circle/plot	110.66

The effect plot (see figure 21) shows that the total root surface area varies with the type of management. The highest amount of root surface area can be seen in the management type with permanent vegetation cover.

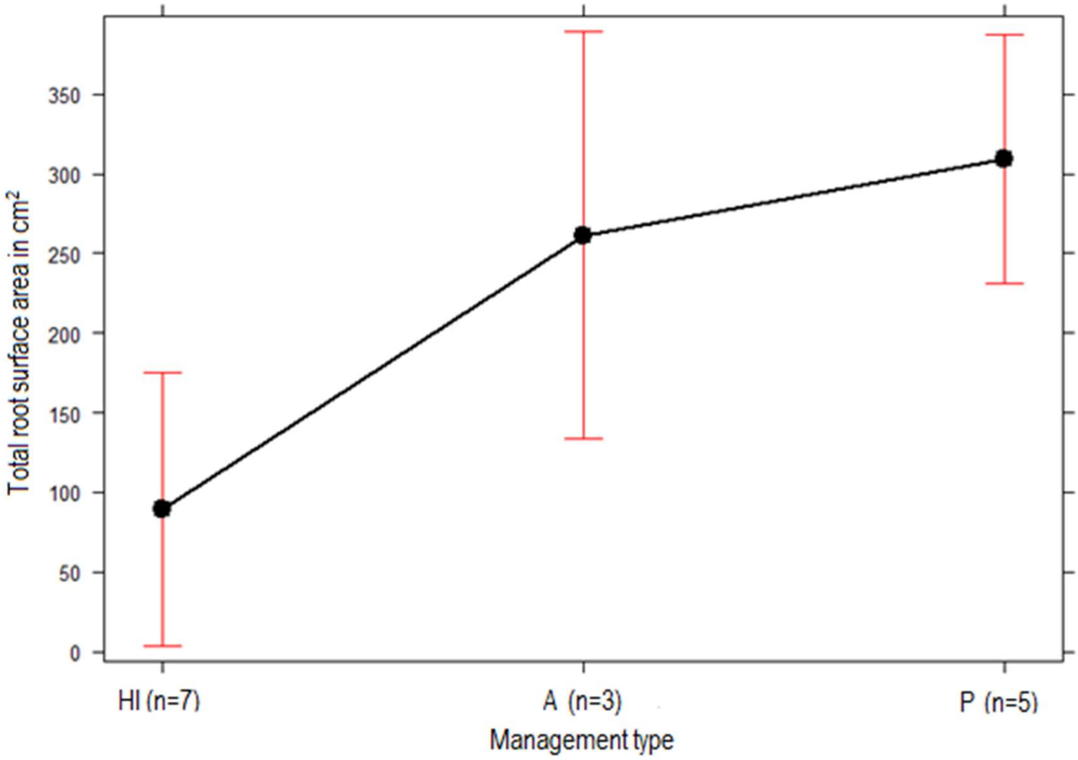

Figure 21: Effect plot of total root surface area depending on the type of management in the inter-rows (HI = high management intensity, A = alternating tillage, P = permanent vegetation cover) (n=15).

3.1.5 Average root diameter

The results of the average root diameter (in mm) for the different management systems is shown in figure 22. The differences between the treatments are not very pronounced. The highest mean value occurred in vineyards with permanent vegetation cover with 0.2631 ± 0.0235 mm. Vineyards with high management intensities reached a similar mean value of 0.2519 ± 0.0562 mm, while alternating management treatments had the lowest mean value of 0.2206 ± 0.0313 mm.

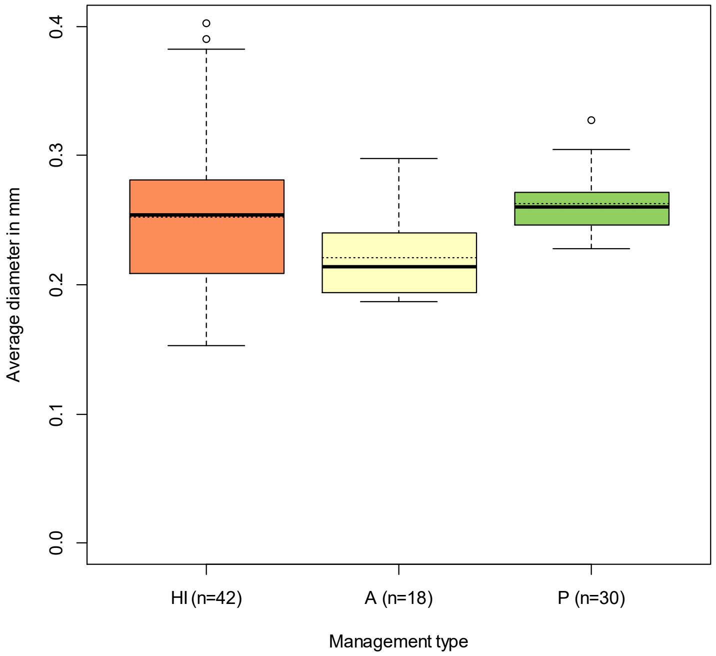

Figure 22: Results of average root diameter for the different management systems. The lines in the boxplots show the mean value (dotted line) and the median (bold line) (HI = high management intensity, A = alternating tillage, P = permanent vegetation cover).

3.1.6 Average root diameter – GLMM

The basic model without any explanatory variable showed the best AICc value for the response variable average root diameter (see table 4). The second best AICc value showed the model including the explanatory variable Shannon index.

Table 4: Overview of best models (lowest AICc and ∆AICc ≥ 2) for the parameter average root diameter. Best model is marked in bold.

Compared models	AICc
average root diameter ~ 1 [null variant] + circle/plot	**-21.50**
average root diameter ~ last soil management + circle/plot	-9.28
average root diameter ~ species number + circle/plot	-10.13
average root diameter ~ shannon index + circle/plot	-11.23

3.1.7 Total root dry mass

Results of total root dry mass for the different soil management intensities are shown in figure 23. The highest root dry mass is reached in vineyards with permanent vegetation cover having mean value of 0.61 ± 0.35 g. Alternating tillage shows mean value of 0.19 g ± 0.12 g, while the lowest value of 0.12 g ± 0.16 g is found in high management intensity plots. As for total root length and surface area data, the decrease of management intensity leads to an increase of total root dry mass.

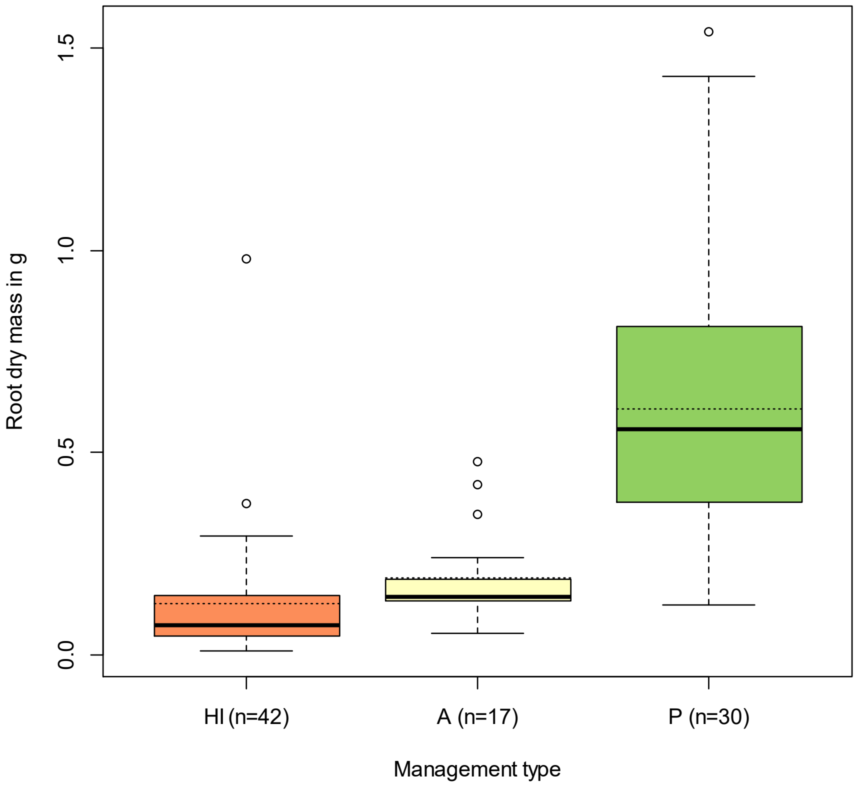

Figure 23: Total root dry mass of root samples (in g) in the different management intensities. The lines in the boxplots show the mean value (dotted line) and the median (bold line) (HI = high management intensity, A = alternating tillage, P = permanent vegetation cover).

For the two variables total root dry mass and last soil management, a correlation was computed (see figure 24) showing an increase of total root dry mass with longer time intervals between the last soil management treatment and date of survey.

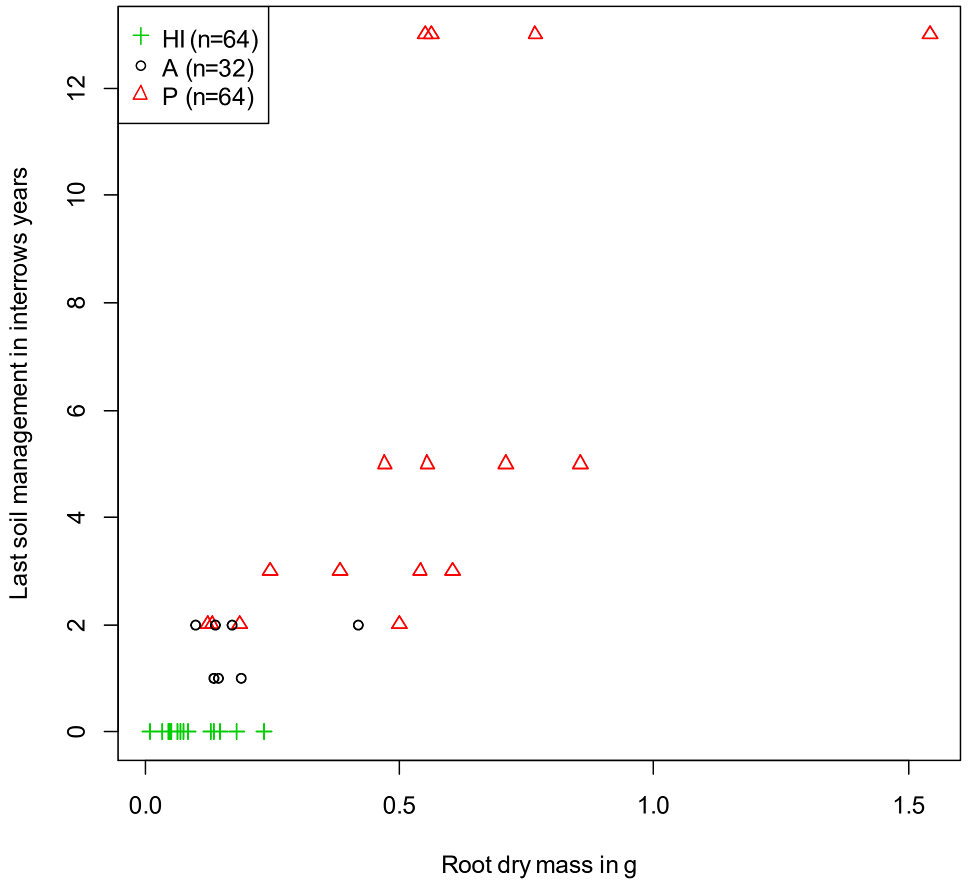

Figure 24: Correlation of total root dry mass and last soil management (r = 0.80)

3.1.8 Total root dry mass – GLMM

For the response variable root dry mass, the model including the variable last soil management was the best one (see table 5). Though, the difference to the null-model was not larger than 2.

Table 5: Overview of best models (lowest AIC$_C$ and ΔAIC$_C \geq 2$) for the parameter total root dry mass. Best models are marked in bold.

Compared models	AICc
total root dry mass ~ 1 [null variant] + circle/plot	**14.93**
root dry mass ~ last soil management + circle/plot	**13.35**
root dry mass ~ soil-treatment frequency + circle/plot	22.88
root dry mass ~ Shannon index + circle/plot	18.21

The effect plot of the best model in figure 25 shows the correlation of last soil management and total root dry mass. Total root dry mass increases the longer ago the last soil management was applied.

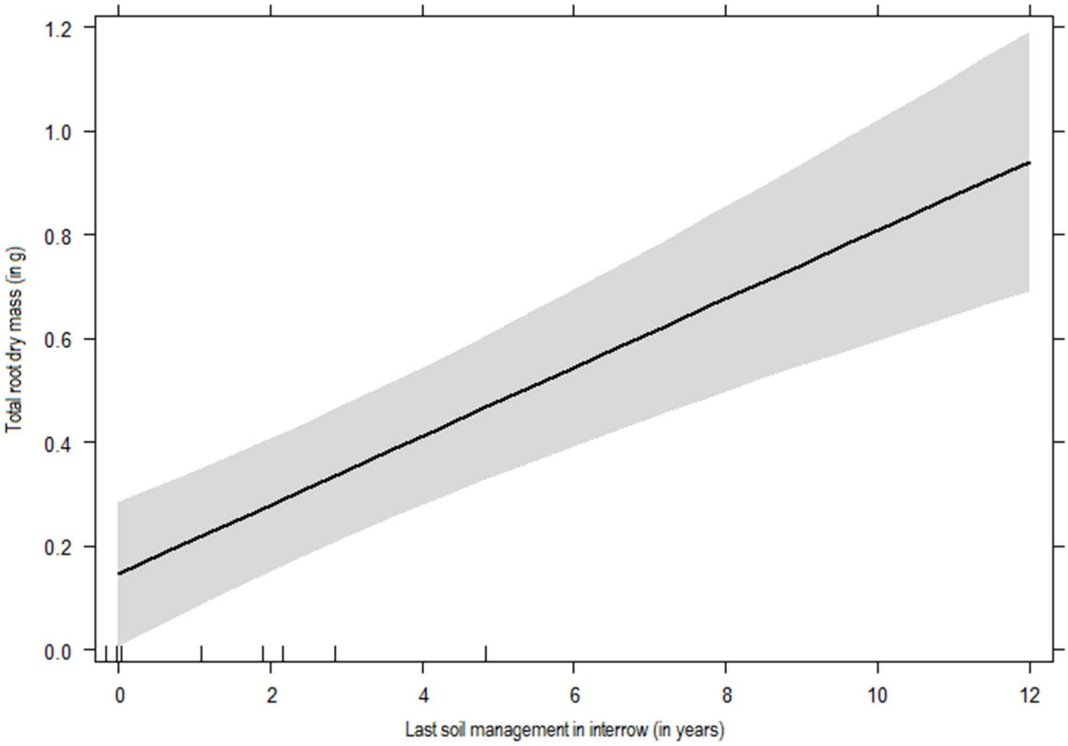

Figure 25: Effect plot showing the total root dry mass depending on the last soil management in the inter-rows in years (n=15)

3.2 Soil parameter effects on root variables

GLMMs including soil parameters were calculated for ten vineyards where soil data were available. The design of the models was done analogous to management and vegetation effects.

3.2.1 Total root length – GLMM

The total root length is best explained by the model including the explanatory variable stone content together with the type of management in the vineyard inter-row (see table 6).

Table 6: Overview of best models (lowest AICc and △AICc ≥ 2) for the parameter total root length. Best model is marked in bold.

Compared models	AIC_C
root length ~ 1 [null variant] + circle/plot	167.73
root length ~ dry bulk density + management type + circle/plot	139.00
root length ~ pH + management type + circle/plot	142.76
root length ~ TOC + management type + circle/plot	142.93
root length ~ stone content + management type + circle/plot	**136.22**

The effect plot shows a decrease of total root length with increasing stone content in the soil (see figure 26).

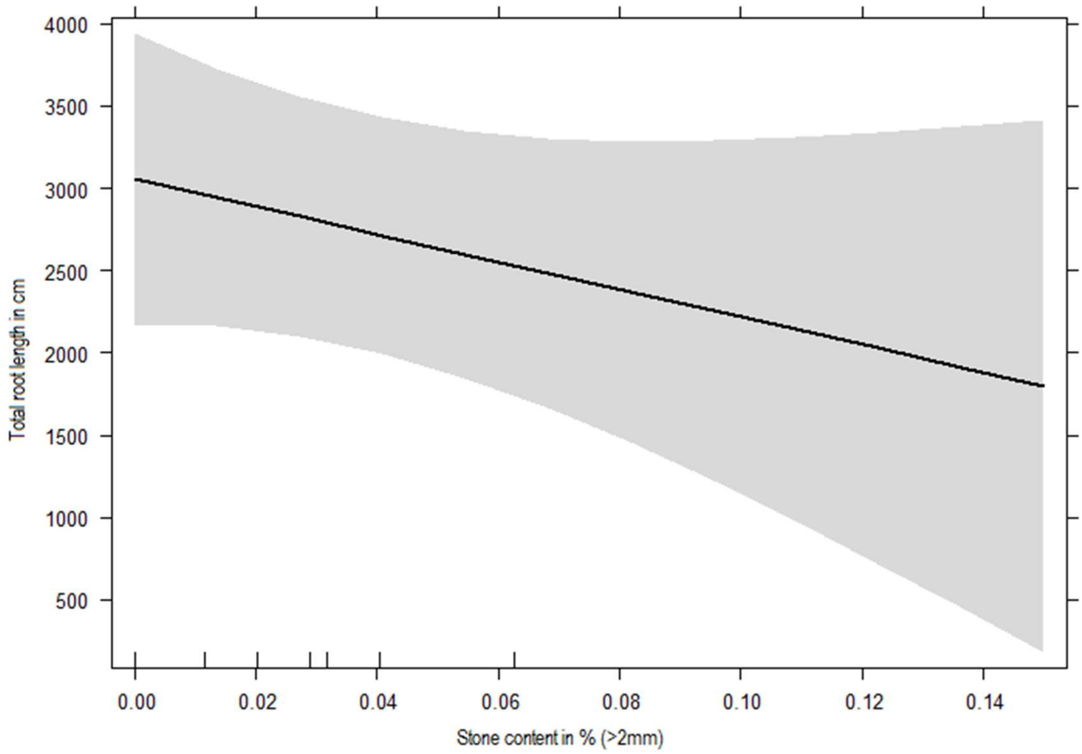

Figure 26: Effect plot showing the total root length depending on the stone content (n=10)

The effect plot in figure 27 shows that the total root length differs according to the soil management system. Total root length increases with the decrease of soil management intensity. Vineyards with alternating soil management systems and permanent vegetation cover showed quite similar results for total root length.

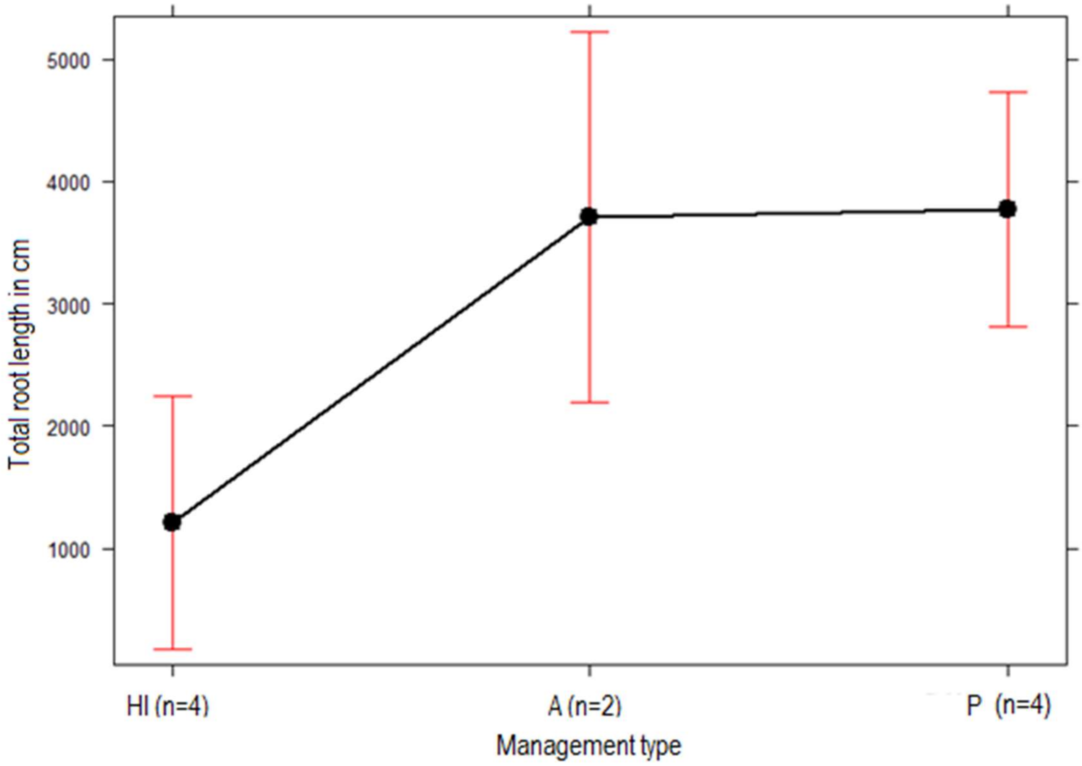

Figure 27: Effect plot of total root length depending on the type of management in the inter-rows (HI = high management intensity, A = alternating tillage, P = permanent vegetation cover) (n=10).

3.2.2 Total root surface area – GLMM

The variable surface area is also best explained by the model including stone content together with the type of management in the vineyard inter-row (see table 7).

Table 7: Overview of best models (lowest AICc and ∆AICc ≥ 2) for the parameter total root surface area. Best model is marked in bold.

Compared models	AICc
surface area ~ 1 [null variant] + circle/plot	122.70
surface area ~ dry bulk density + management type + circle/plot	109.54
surface area ~ pH + management type + circle/plot	112.31
surface area ~ stone content + management type + circle/plot	**106.41**
surface area ~ percolation stability + management type + circle/plot	109.99

The effect plot shows a decrease of total root surface area with increasing stone content in the soil (see figure 28).

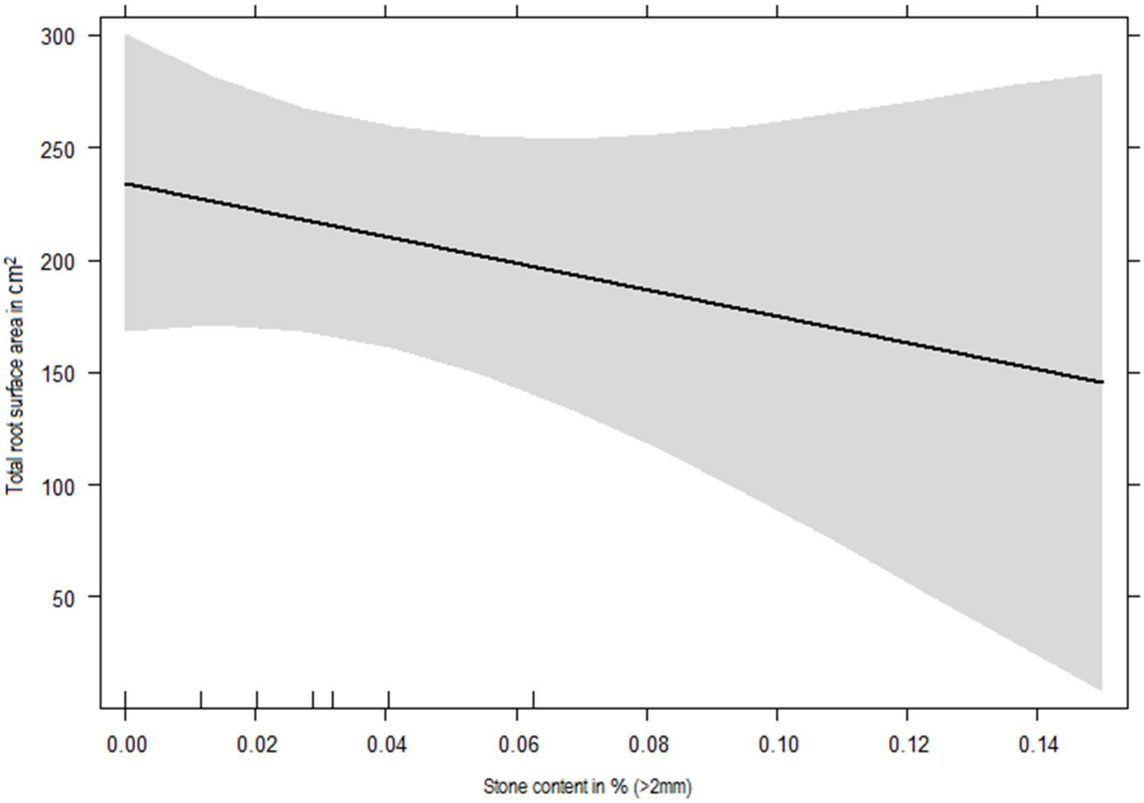

Figure 28: Effect plot showing the total root surface area depending on the stone content (n=10)

The effect plot (see figure 29) shows that the total root surface area varies with the type of management. The highest amount of root surface area can be seen in the management type with permanent vegetation cover.

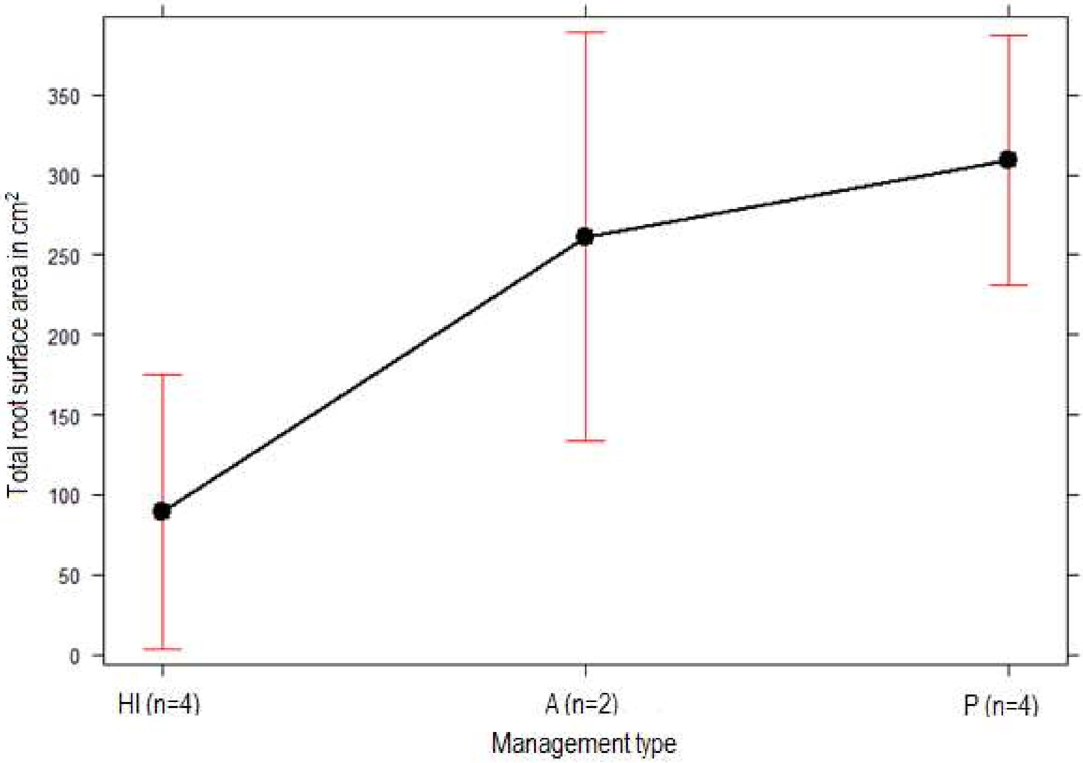

Figure 29: Effect plot of total root surface area depending on the type of management in the inter-rows (HI = high management intensity, A = alternating tillage, P = permanent vegetation cover) (n=10).

3.2.3 Average root diameter – GLMM

The basic model for average root diameter was not improved by adding explanatory variables (see table 8). The null-model showed the best AICc value. Second best was the model including the stone content though, the difference to the other models was not larger than 2.

Table 8: Overview of best models (lowest AICc and ∆AICc ≥ 2) for the parameter average root diameter. Best model is marked in bold.

Compared models	AIC_C
average diameter ~ 1 [null variant] + circle/plot	**-21.50**
average diameter ~ dry bulk density + circle/plot	-12.65
average diameter ~ TOC + circle/plot	-10.79
average diameter ~ stone content + circle/plot	-14.25

3.2.4 Total root dry mass – GLMM

The basic model for root dry mass was not improved by adding explanatory variables (see table 9). The null-model showed the best AICc value. Second best was the model including the total organic carbon.

Table 9: Overview of best models (lowest AIC_C and $\Delta AIC_C \geq 2$) for the parameter total root dry mass. Best model is marked in bold.

Compared models	AIC_C
root dry mass ~ 1 [null variant] + circle/plot	**14.93**
root dry mass ~ dry bulk density + circle/plot	18.67
root dry mass ~ TOC + circle/plot	17.48
root dry mass ~ stone content + circle/plot	18.00

4 Discussion

The effects of different soil management systems on root parameters in the inter-row of the vineyards were studied and evaluated. The investigation showed that an increase of soil-management intensity (with high intensity management being the most intense) causes a decrease of total root length of inter-row vegetation. Simultaneously, the results for surface area and root dry mass showed the same trend. The statistical models showed that management intensity considerably improved the model fit for total root length and surface area. The explanatory variable management type was always included in the best models for the two parameters. For root dry mass the time of the last soil management was included in the best model. Interestingly, vegetation parameters like vegetation cover or plant diversity did not improve the model fit of various dependent root parameters. Models including the soil parameters were less conclusive than the full set of vineyards. Solely for total root length and total root surface area management and stone content best explained the data.

Intensity of soil management controls the presence of roots in the topsoil in the inter-rows. Total root length and total root surface area were always highest in vineyard inter-rows with permanent vegetation cover which is in accordance to the **first hypothesis**. That was also confirmed by Celette et al. (2008) who examined Mediterranean vineyards with different management regimes with regard to water erosion. In their study, vineyards with permanent vegetation covers showed also higher root length densities (root length in cm/cm3 soil) than vineyards with higher tillage frequencies. This was also confirmed by Garcia et al. (2018). However, Celette et al. (2008) found that cover crops with higher root length densities dried out the soil compartements more intensively in the inter-row compared to bare soil treatments and annual cover crops. Besides, root surface area which is linked to root length is seen as an indicator for water and nutrient uptake by plants (Tachibana and Ohta, 1983). Higher root surface area as found in the Romanian vineyards with permanent vegetation cover therefore suggests higher uptake of water and nutrients by inter-row vegetation. Morlat and Jacquet (2003), Celette et al. (2005) and Klodd et al. (2016) showed that permanent vegetation cover in vineyards influences the root system of the grapevines owing to more competition in the inter-row. Those studies showed that more roots of the grapevines were formed in-row and less in the inter-row compared to bare soil management, which influences their uptake of water and nutrients. The use of vegetation cover in the inter-row caused a downward shift in vertical distribution of grapevine fine roots and reduction in absorptive grapevine root lengths (Morlat and Jacquet, 2003, Klodd et al., 2016). The study of Klodd et al. (2016) showed that aboveground vegetative growth of grapevines remained rather constant thanks to little influence on uptake of water and nitrogen. However, the uptake of phosphorus of grapevines was reduced and contributed to a modest reduction of fruit biomass (by 17%) showing that grapevine root systems are partially capable of adapting to vegetation cover (Klodd et al., 2016). Low intensity management systems with permanent vegetation cover and their higher amount of root length and surface area will therefore affect vineyards and their grapevines with regard to water and nutrient uptake as observed in other studies.

The potential of **soil erosion prevention** is most likely provided in the examined vineyards with permanent vegetation cover. The proportion of roots with an diameter of less than 1 mm is crucial for a high soil erosion resistance (Li et al., 1991). A look on the parameter average root diameter in the investigated vineyards and its comparison between the management regimes showed quite similar results. The statistical model did not show a clear effect for the influence on average root diameter. Analysis of root diameter classes however showed that management systems with permanent vegetation cover had the highest amount of total root length in the class smaller than 1 mm compared to the other management systems. This is an indication for a more effective soil erosion mitigation compared to the other management systems. On average, the results for total root length for low intensity management vineyards were more than twice as high compared to high intensity vineyards. Soil tillage during the vegetation period is problematic and fosters soil erosion due to higher precipitation rates during the summer period in most humid climates. Typical soil management in Romania takes place from the beginning of the vegetation period in April till autumn and therefore increases the potential of erosion. A trial in France using different cover crops in vineyard inter-rows showed that root mean diameter and root mass density showed positive correlations with aggregate stability (Garcia et al., 2018). They emphasized that soil aggregate stability is the result of interactions between soil management strategies, soil characteristics and plant root traits. The effect of soil management strategies in their study was significant for root average diameter and specific root length density. The importance of the influence of different cover crops on soil erosion was also underlined by Yu et al. (2016). They showed that high rooting density effectively reduced surface runoff by enhancing soil hydraulic conductivity. Apart from that, Biddoccu et al. (2017) compared vineyards in Italy with tilled and grass covered inter-rows. They showed that conventional tillage systems with high management intensities resulted in higher loss of soil and water run-off after rainfall events.

In the **second hypothesis** it was claimed that higher plant diversity in the inter-row increases total root length. Differences in plant diversity between the management sytems in Romania were not significant (Penke, 2017). Nonetheless, alternating management showed the highest, whereas high intensity vineyards resulted in the lowest plant species diversity. Correlations of plant cover and total root length, correlation of species number and total root length and as well the correlation of shannon index and total root length did not show a significant interrelation. Though the correlation of plant cover and total root length showed a tendency of increasing total root length with higer vegetation cover. Also model fit of the GLMM could not be improved by species diversity. As the low intensity management system showed the highest total root length and vineyards with alternating management showed the highest species diversity, no evidence for an influence of species diversity on total root length could be derived. However, Berendse et al. (2015) found that plant species diversity increased total root length and root mass in the upper 40 cm of the soil. This could be related to the difference in the soil sampling depth. A study in the Czech Republic showed the increase of plant species richness through mulching of permanent vegetation cover compared with frequently tilled vineyards (Lososová et al., 2003). Impacts on root parameters were not examined in that study. With regard to total root dry mass a survey in Germany showed, that there was no significant correlation of plant diversity or functional group diversity and total root mass in temperate grasslands (Gastine et al., 2003). Root dry mass in Romania was highest in vineyards with permanent vegetation cover. This was also revealed by a study carried out in Spain. Root dry mass was 2 to 4 times higher than the root dry mass in tilled vineyard inter-rows (Ruiz-Colmenero et al., 2013). On average, the root dry mass in Romania was 5 times higher in vineyards with permanent vegetation cover compared to frequently tilled vineyards.

Permanent vegetation cover did not only increase total root mass but also showed higher amounts of TOC in less intense soil management systems which is in accordance to the **third hypothesis.** Agnelli et al. (2014), Morlat and Jacquet (2003) and Virto et al. (2012) found an increase of organic material in the topsoil of vineyards in less intensively managed inter-rows in comparison with high intensive soil management systems without vegetation cover. Vineyard inter-row soil management systems influence the carbon storage in the soil, thereby vineyards can act as carbon sinks (Brunori et al., 2016). The proportion of organic carbon is increased by less frequent tillage in the inter-row by decaying plant parts and roots in low intensity tillage systems (Morlat and Venin, 1981, Agnelli et al., 2014). Fine roots have faster turnover rates and degrade more quickly to soil organic matter which supports soil aggregate stability (Li et al., 1991). This in turn modifies several properties of upper soil layers which are responsible for the increase of TOC, nitrogen or exchangeable K_2O (Morlat and Jacquet, 2003). The total amount of fine roots in the survey was clearly higher in less intensive management systems.

The results of the statistical models including **soil parameters** were less clear than the larger sample size including only management and vegetation variables. Besides the type of management, stone content was included in two of the best models for the parameters total root length and total root surface are. The proportion of stones larger than 2 mm did not exceed 0.19 % in any vineyard. Consequently, the influence of the stone content on total root length and total root surface area seems questionable due to the small proportion of stones in the soil.

The results concerning root parameters influenced by different soil management regimes confirm impacts of ground-cover manipulation. The effects of management intensities show that it is important to recognise that the choice of soil management regime does not only affect the roots of inter-row vegetation but also the roots of grapevines with all its mentioned possible consequences. In addition, higher **biodiversity of permanent vegetation cover** is not always related to a higher total root length of permanent vegetation cover. Though **ecosystem service** provision like soil erosion prevention is assumed to be highest in vineyards with permanent vegetation cover, competiton for resources has to be considered especially in rainfed vineyards under dry climates (Winter et al., 2018). Apart from the mentioned aspects, permanent vegetation covers offer other ecosystem services which are controlled by inter-row management (Altieri et al., 2010). Management is seen as the key instrument influencing plant communities contributing to higher biodiversity (Wilmanns, 1993). It cannot be stated that higher taxonomic plant diversity will automatically lead to a higher ecosystem service provision in vineyards. Even if alternating soil management regimes show a higher plant diversity, few species can have strong ecosystem effects indicating the importance of functional diversity of plant communities (Chapin et al., 2000). Species could be classified according to their impact on ecosystem processes and functions (Lavorel and Garnier, 2002). Thus, it would be beneficial to link root traits of inter-row plant species with related ecosystem services. The functional characterisation of plant communities and their response to management regimes was studied by Kazakou et al. (2016). They showed in French Mediterranen vineyardshow the understanding of the impact of soil management on plant community helps to apply appropriate vineyard management for a more sustainabe grapevine system. Crucial is to understand how plant communities respond on soil management practices or rather on changes of management practices and how these can affect ecosystem services (Suding et al., 2008). Finally, one has to take into account that measures taken in the vineyards aiming for higher ecosystem provision are strongly influenced by **geographical, climatic, political and economic aspects** (Delucchi, 1997). In fact, the choice of the optimal cover crop is seen as a core issue requiring appropriate consideration referred to the local conditions (Burgio et al., 2016).

It should be noted that the number of investigated vineyards with associated soil data should be increased for future studies (in this study: 10 vineyards with 4 pseudoreplicates per vineyard). Further it would be interesting to observe **different cover crop mixtures** in various management intensites and their impact on root parameters. Especially the interrelation of plant species diversity and its effects on root parameters seems inconclusive. Moreover, investigation of **roots in deeper soil layers** than 10 cm with regard to distribution and root parameter characteristics will be interesting in future analysis. Besides, v**ineyard margin size** differences and margin type could influence inter-row flora (Mania et al., 2015) and subsequently potentially the root parameters of the vegetation. They showed in north-west Italy that plant species diversity and composition depends on grass coverage management and that more complex margins may improve the composition of the flora. Furthermore, the **duration of management** varied within management types, a challenging aspect for statistical analysis and evaluation of possible impacts.

The choice of adequate soil management and optimal cover crops is a challenging aspect and has to be solved in the world´s various wine growing areas under inclusion of the prevailing conditions. Interrelations of vegetation cover and its root characteristics and their impact on ecosystem services in vineyards are currently sparsley investigated and closer investigation may help to understand functions and dynamics of soil management intensities.

5 Conclusion

The investigations of this study showed a clear influence of management intensities on root parameters of inter-row permanent vegetation cover. Total root length, total root surface area and total root dry mass increased with decreasing management intensity. There was also a tendency for higher total root length with increasing plant vegetation cover. Although the relations between soil and root parameters did not improve the statistical model, TOC was highest in vineyards with permanent vegetation cover.

Soil management in the vineyard inter-row influenced plant communities and associated root parameters affecting ecosystem services provision. It could not be shown that higher plant diversity significantly increased total root length. Generally, it would be interesting to test cover crop mixtures for their suitability for different wine-regions and their root characteristics. Optimal seed mixtures should be adapted to precipitation, climate and soil type. Further investigations have to consider the functional role of different root morphological and architectural characteristics and identify management processes that support favourable plant species for ecosystem service provision. Additional root investigations and examination of deeper soil layers are needed to gain new insights into root distributions in deeper soil layers under different soil management regimes. Moreover, repeated sampling of roots during the vegetation period would be interesting to analyse the temporal effects of management.

Vineyards can contribute to nature conservation and provide space for natural vegetation in the inter-rows. While permanent vegetation cover and alternating tillage are already a fixed part of the management in vineyard inter-rows in countries with humid climate, Romanian vineyards are still predominantly managed by intensive soil tillage which is prone to soil erosion. Agri-environmental schemes supporting soil erosion control in the inter-rows can contribute to sustainable management of vineyards. In this regard, agricultural policies are appropriate measures to encourage new soil management approaches.

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Table 10: Model selection for total root length. Models are selected by comparing the AIC_C values (minimum difference of 2). Best models are marked in bold.

Compared models	AIC_C
root length ~ 1 [null variant] + circle/plot	167.73
root length ~ management type + circle/plot	**142.55**
root length ~ last soil management + circle/plot	154.35
root length ~ soil-treatment frequency + circle/plot	157.65
root length ~ duration of management + circle/plot	163.95
root length ~ duration of vineyard cultivation + circle/plot	163.49
root length ~ vegetation cover + circle/plot	163.08
root length ~ species number + circle/plot	161.58
root length ~ Shannon index + circle/plot	155.97
root length ~ last soil management + management type + circle/plot	**140.36**
root length ~ soil-treatment frequency + management type + circle/plot	144.98
root length ~ duration of management + management type + circle/plot	149.46
root length ~ duration of vineyard cultivation + management type + circle/plot	146.51
root length ~ vegetation cover + management type + circle/plot	149.04
root length ~ species number + management type + circle/plot	146.48
root length ~ Shannon index + management type + circle/plot	**141.11**

Table 11: Model selection for root surface area. Models are selected by comparing the AIC_C values (minimum difference of 2). The best model is marked in bold.

Compared models	AIC_C
surface area ~ 1 [null variant] + circle/plot	122.70
surface area ~ management type + circle/plot	**107.11**
surface area ~ last soil management + circle/plot	111.20
surface area ~ soil-treatment frequency + circle/plot	117.35
surface area ~ duration of management + circle/plot	124.24
surface area ~ duration of vineyard cultivation + circle/plot	124.39
surface area ~ vegetation cover + circle/plot	121.92
surface area ~ species number + circle/plot	121.71
surface area ~ Shannon index + circle/plot	115.47
surface area ~ last soil management + management type + circle/plot	109.43
surface area ~ soil-treatment frequency + management type + circle/plot	114.58
surface area ~ duration of management + management type + circle/plot	119.01
surface area ~ duration of vineyard cultivation + management type + circle/plot	117.85
surface area ~ vegetation cover + management type + circle/plot	118.56
surface area ~ species number + management type + circle/plot	116.11
surface area ~ Shannon index + management type + circle/plot	110.66

Table 12: Model selection for plant root average diameter. Models are selected by comparing the AIC_C values (minimum difference of 2). The best model is marked in bold.

Compared models	AIC_C
average root diameter ~ 1 [null variant] + circle/plot	**-21.50**
average root diameter ~ management type + circle/plot	2.77
average root diameter ~ last soil management + circle/plot	-9.28
average root diameter ~ soil-treatment frequency + circle/plot	-8.43
average root diameter ~ duration of management + circle/plot	-3.38
average root diameter ~ duration of vineyard cultivation + circle/plot	-4.24
average root diameter ~ vegetation cover + circle/plot	-4.14
average root diameter ~ species number + circle/plot	-10.13
average root diameter ~ Shannon index + circle/plot	-11.23
average root diameter ~ last soil management + management type + circle/plot	26.04
average root diameter ~ soil-treatment frequency + management type + circle/plot	24.52
average root diameter ~ duration of management + management type + circle/plot	29.57
average root diameter ~ duration of vineyard cultivation + management type + circle/plot	29.08
average root diameter ~ vegetation cover + management type + circle/plot	29.32
average root diameter ~ species number + management type + circle/plot	22.15
average root diameter ~ Shannon index + management type + circle/plot	21.20

Table 13: Model selection for root dry mass. Models are selected by comparing the AIC_C values (minimum difference of 2). Best models are marked in bold.

Compared models	AIC_C
root dry mass ~ 1 [null variant] + circle/plot	**14.93**
root dry mass ~ management type + circle/plot	26.01
root dry mass ~ last soil management + circle/plot	**13.35**
root dry mass ~ soil-treatment frequency + circle/plot	22.88
root dry mass ~ duration of management + circle/plot	28.86
root dry mass ~ duration of vineyard cultivation + circle/plot	29.19
root dry mass ~ vegetation cover + circle/plot	24.76
root dry mass ~ species number + circle/plot	25.91
root dry mass ~ Shannon index + circle/plot	18.21
root dry mass ~ last soil management + management type + circle/plot	40.60
root dry mass ~ soil-treatment frequency + management type + circle/plot	44.99
root dry mass ~ duration of management + management type + circle/plot	49.46
root dry mass ~ duration of vineyard cultivation + management type + circle/plot	49.45
root dry mass ~ vegetation cover + management type + circle/plot	48.91
root dry mass ~ species number + management type + circle/plot	46.60
root dry mass ~ Shannon index + management type + circle/plot	40.99

Table 14: Calculated GLMMs for root length. Models are selected by comparing the AIC$_C$ values (minimum difference of 2). Best models are marked in bold.

Compared models	AIC$_C$
root length ~ 1 [null variant] + circle/plot	167.73
root length ~ dry bulk density + circle/plot	155.38
root length ~ saturated hydraulic conductivity + circle/plot	162.62
root length ~ pH + circle/plot	157.98
root length ~ $CaCO_3$ + circle/plot	162.59
root length ~ TOC + circle/plot	157.28
root length ~ clay + circle/plot	163.81
root length ~ stone content + circle/plot	153.72
root length ~ percolation stability + circle/plot	162.04
root length ~ dry bulk density + management type + circle/plot	139.00
root length ~ saturated hydraulic conductivity + management type + circle/plot	144.93
root length ~ pH + management type + circle/plot	142.76
root length ~ $CaCO_3$ + management type + circle/plot	147.75
root length ~ TOC + management type + circle/plot	142.93
root length ~ clay + management type + circle/plot	148.46
root length ~ stone content + management type + circle/plot	**136.22**
root length ~ percolation stability + management type + circle/plot	148.29

Table 15: Calculated GLMMs for surface area. Models are selected by comparing the AIC_C values (minimum difference of 2). Best models are marked in bold.

Compared models	AIC_C
surface area ~ 1 [null variant] + circle/plot	122.70
surface area ~ dry bulk density + circle/plot	115.34
surface area ~ saturated hydraulic conductivity + circle/plot	122.65
surface area ~ pH + circle/plot	117.93
surface area ~ $CaCO_3$ + circle/plot	122.00
surface area ~ TOC + circle/plot	116.33
surface area ~ clay + circle/plot	123.73
surface area ~ stone content + circle/plot	113.76
surface area ~ percolation stability + circle/plot	120.30
surface area ~ dry bulk density + management type + circle/plot	109.54
surface area ~ saturated hydraulic conductivity + management type + circle/plot	115.28
surface area ~ pH + management type + circle/plot	112.31
surface area ~ $CaCO_3$ + management type + circle/plot	117.29
surface area ~ TOC + management type + circle/plot	112.42
surface area ~ clay + management type + circle/plot	118.00
surface area ~ stone content + management type + circle/plot	**106.41**
surface area ~ percolation stability + management type + circle/plot	109.99

Table 16: Calculated GLMMs for average diamter. Models are selected by comparing the AIC_C values (minimum difference of 2). Best models are marked in bold.

Compared models	AIC_C
average diameter ~ 1 [null variant] + circle/plot	**-21.50**
average diameter ~ dry bulk density + circle/plot	-12.65
average diameter ~ saturated hydraulic conductivity + circle/plot	-5.46
average diameter ~ pH + circle/plot	-9.86
average diameter ~ $CaCO_3$ + circle/plot	-5.78
average diameter ~ TOC + circle/plot	-10.79
average diameter ~ clay + circle/plot	-4.89
average diameter ~ stone content + circle/plot	-14.25
average diameter ~ percolation stability + circle/plot	-6.61
average diameter ~ dry bulk density + management type + circle/plot	19.88
average diameter ~ saturated hydraulic conductivity + management type + circle/plot	26.13
average diameter ~ pH + management type + circle/plot	21.44
average diameter ~ $CaCO_3$ + management type + circle/plot	27.91
average diameter ~ TOC + management type + circle/plot	23.16
average diameter ~ clay + management type + circle/plot	28.49
average diameter ~ stone content + management type + circle/plot	18.50
average diameter ~ percolation stability + management type + circle/plot	24.34

Table 17: Calculated GLMMs for root dry mass. Models are selected by comparing the AIC_C values (minimum difference of 2). Best models are marked in bold.

Compared models	AIC_C
root dry mass ~ 1 [null variant] + circle/plot	**14.93**
root dry mass ~ dry bulk density + circle/plot	18.67
root dry mass ~ saturated hydraulic conductivity + circle/plot	26.72
root dry mass ~ pH + circle/plot	22.24
root dry mass ~ $CaCO_3$ + circle/plot	26.14
root dry mass ~ TOC + circle/plot	17.48
root dry mass ~ clay + circle/plot	27.01
root dry mass ~ stone content + circle/plot	18.00
root dry mass ~ percolation stability + circle/plot	22.35
root dry mass ~ dry bulk density + management type + circle/plot	39.85
root dry mass ~ saturated hydraulic conductivity + management type + circle/plot	46.87
root dry mass ~ pH + management type + circle/plot	42.27
root dry mass ~ $CaCO_3$ + management type + circle/plot	47.78
root dry mass ~ TOC + management type + circle/plot	42.00
root dry mass ~ clay + management type + circle/plot	46.83
root dry mass ~ stone content + management type + circle/plot	38.29
root dry mass ~ percolation stability + management type + circle/plot	47.92