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Topographic Position, Land Use and Soil Management Effects on Soil Organic Carbon (Vineyard Region of Niš, Serbia)

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Abstract: Spatial distribution of soil organic carbon (SOC) is the result of a combination of various factors related to both the natural environment and anthropogenic activities. The aim of this study was to examine (i) the state of SOC in topsoil and subsoil of vineyards compared to the nearest forest, (ii) the influence of soil management on SOC, (iii) the variation in SOC content with topographic position, (iv) the intensity of soil erosion in order to estimate the leaching of SOC from upper to lower topographic positions, and (v) the significance of SOC for the reduction of soil's susceptibility to compaction. The study area was the vineyard region of Niš, which represents a medium-sized vineyard region in Serbia. About 32% of the total land area is affected, to some degree, by soil erosion. However, according to the mean annual soil loss rate, the total area is classified as having tolerable erosion risk. Land use was shown to be an important factor that controls SOC content. The vineyards contained less SOC than forest land. The SOC content was affected by topographic position. The interactive effect of topographic position and land use on SOC was significant. The SOC of forest land was significantly higher at the upper position than at the middle and lower positions. Spatial distribution of organic carbon in vineyards was not influenced by altitude, but occurred as a consequence of different soil management practices. The deep tillage at 60–80 cm, along with application of organic amendments, showed the potential to preserve SOC in the subsoil and prevent carbon loss from the surface layer. Penetrometric resistance values indicated optimum soil compaction in the surface layer of the soil, while low permeability was observed in deeper layers. Increases in SOC content reduce soil compaction and thus the risk of erosion and landslides. Knowledge of soil carbon distribution as a function of topographic position, land use and soil management is important for sustainable production and climate change mitigation.

Keywords: soil organic carbon; viticulture; topography; land use; management

1. Introduction

Soil organic carbon (SOC) is key constituent of soil organic matter (SOM), which is an essential component of soils as it supports soil structure, fertility and a range of physical and chemical properties. Soil organic carbon stocks comprise the largest carbon pool in terrestrial ecosystems and act as a major source or sink for atmospheric CO_2 [1,2]. SOC sequestration is regarded as an option to mitigate climate change and is based on positive

SOC budgets for specific land use and management systems, whereby the input of C into soils exceeds the losses of SOC through erosion, mineralization/volatilization and leaching [3]. Small changes in the SOC stock impact the carbon cycle and may significantly increase or decrease the carbon concentrations in the atmosphere [4]. Batjes [5] estimated the global SOC stock up to a 2 m depth to be 2060 ± 215 Pg. C. Scharlemann et al. [6] reviewed the SOC estimations published in 27 studies from 1951 to 2014 and pointed out that there was a very considerable range of variation, between 504 and 3000 Pg. Responding to the current capacities for soil carbon sequestration, the initiative "4 per Thousand" (4 p1000) was formed in Paris in 2015, with the aim of increasing awareness about land use responsibility and climate change [7].

Spatial distribution of SOC is the result of a combination of various factors related to both the natural environment and human activities, with heterogeneity observed at different spatial scales [8].

Land use is one of the main factors that control the distribution of SOC [9]. Changes in land use are the second most important source of greenhouse gas (GHG) emissions into the atmosphere after fossil fuel burning [10,11]. The replacement of forest and natural grassland by cropland may cause a reduction of SOC [12]. SOC loss after deforestation is between 30% and 42% and conversion from grassland to cropland caused a decline of 24–59% of total SOC [13,14]. Deng et al. [15] stated that cropland has lower SOC content compared to undisturbed natural soil due to the continual harvest of aboveground biomass. In contrast, improved soil management, like conversion from cropland into grassland and afforested land, can reduce emissions through SOC sequestration, since plant residues and roots are accumulated in the soil as soil organic matter [13].

Soil management can change the content and distribution of SOC. Tillage operations strongly control the soil environment. These effects influence many physical, chemical and biological properties of soil [16]. Conventional tillage has been shown to enhance short-term CO_2 evolution and microbial biomass turnover, as well as accelerate organic C oxidation to CO_2, not only by improving soil aeration but also by increasing contact between soil and crop residues and by exposing aggregate-protected organic matter to microbial attack [17].

Topographic position influences accumulation of SOC mainly by altering the input and output of carbon via hydrological processes [18,19], and it affects soil erosion and sediment deposition [20], temperature regime, vegetation distribution, and soil processes [14]. Surface SOC concentration has been found to correlate negatively with annual mean temperature and correlate positively with annual mean precipitation and altitude [21]. However, in soils located on steeper terrain, organic matter accumulation often occurs at the bottom of the slope. There are two reasons for this accumulation: conditions are wetter, and organic matter is transported to the lowest point in the landscape through runoff and erosion [22]. Increases in SOM content at mid- or upper-slope positions may decrease soil erodibility and reduce risks of soil erosion [23].

Soil loss caused by erosion, with various categories of degradation, is a serious problem in the Republic of Serbia [24]. In the Niš region, which mainly belongs to the hilly, mountainous area of the country, a part of the surface is under the influence of high and severe intensity erosion, which requires the application of protective measures. Some of the measures include no-till farming, reduced tillage, terrace construction and maintenance, cover crops, continuous plant cover and crop rotation and shelterbelts. Also, in recent years, the trend for soil use changes has been very pronounced, especially the replacement of perennial crops with annual ones, which brings an additional risk of soil erosion and loss of organic matter. However, perennial plants are also endangered by these processes. In vineyards, erosion processes can be very pronounced because vineyards are usually based on steep and hilly terrain, as well as on mountains with southern exposure due to the better quality of grapes obtained [25,26]. Besides, due to specific soil properties in vineyards, such as limited soil development, coarse texture and low capacity to protect SOM binding to soil minerals, these soils are sensitive to degradation [27–29] and lose potentially more SOC than other agricultural soils.

To ensure sustainable land management and to protect the land from degradation, it is necessary to achieve a satisfactory level of SOC and maintain it. Thus, understanding soil carbon distribution as a function of topographic position, land use, soil management and their interaction is important for designing sustainable production and climate change mitigation that also contribute to food security [30,31]. These effects have not been studied enough in the soils of Serbia, especially not with regard to multiannual plantations like vineyards. This study represents a continuation of soil examination in vineyards. Previous research covered the vineyard region of Tri Morava in Serbia, examining the state of SOC and the impact of soil type and fertilization strategy on the organic carbon content of the soil [32].

The aim of this study was to examine (i) the state of SOC in topsoil and subsoil of vineyards compared to the nearest forest, (ii) the influence of soil management on SOC, (iii) the variation of SOC content with topographic position, (iv) soil erosion intensity in order to estimate the significance of SOC leaching from upper to lower topographic positions, (v) the significance of SOC for reducing the susceptibility of soil to compaction.

2. Materials and Methods

2.1. Study Area

The study area was the vineyard region of Niš (Figure 1), which represents a medium-sized vineyard region in Serbia with a surface area of 1040.84 km^2. This region is located between 43°41′ N and 43°13′ N.

The Niš region includes vineyards located in the valley of the lower Nisava river basin and the lower basins of the Južna Morava and Moravica rivers. Although in previous periods the areas used for vineyards in the Niš region were much larger, currently there are 13.12 km^2 of vineyards [33].

There are six vine growing districts in this region (Figure 1a): Sokobanja, Aleksinac, Žitkovac, Čegar, Kutina and Svrljig [34]. The relief characteristics of the region are visible at three general altitudes (Figure 1b): (1) plains around the rivers in the southeast/northwest directions—lower level; (2) areas with hills and ridges on both sides of the valleys (except in the southwestern part of the region)—higher level; and (3) the ends of the mentioned mountains in the northeast and a small part in the west (near the mountain Jastrebac)—the highest mountain level. Most of the plots (48.11%) are located at altitudes between 200 and 300 m; 28.11% are located at altitudes of 300 to 400 m, while 13.02% are located at altitudes of 400 to 500 m. At other altitudes, there are significantly lower shares of the plots.

Viticultural plots in the Niš region are mostly located on flat and slightly steep terrains: 43.39% of the plots are located on terrain with a slope greater than 0 to 5° (Figure 1c). The share of vineyard plots in the Niš region on slopes greater than 5 to 10° is 26.42%, while 16.04% of plots are located on very steep terrain (slopes greater than 10 to 15°) [34].

Figure 1d shows that the plots in the Niš region are mostly located in the south (S) (31.5%), southwest (SW) (19.16%) and southeast (SE) (14.04%) and in western (W) (11.95%) and eastern (I) exposures (7.40%) [34].

Significant pedological diversity, i.e., the diversity of soil types, is expressed in the Niš viticultural region (Figure 2). The Niš wine-growing region consists of fourteen different types of soil represented by larger or smaller areas, and the most common soil types are vertisol, eutric cambisol and luvisol.

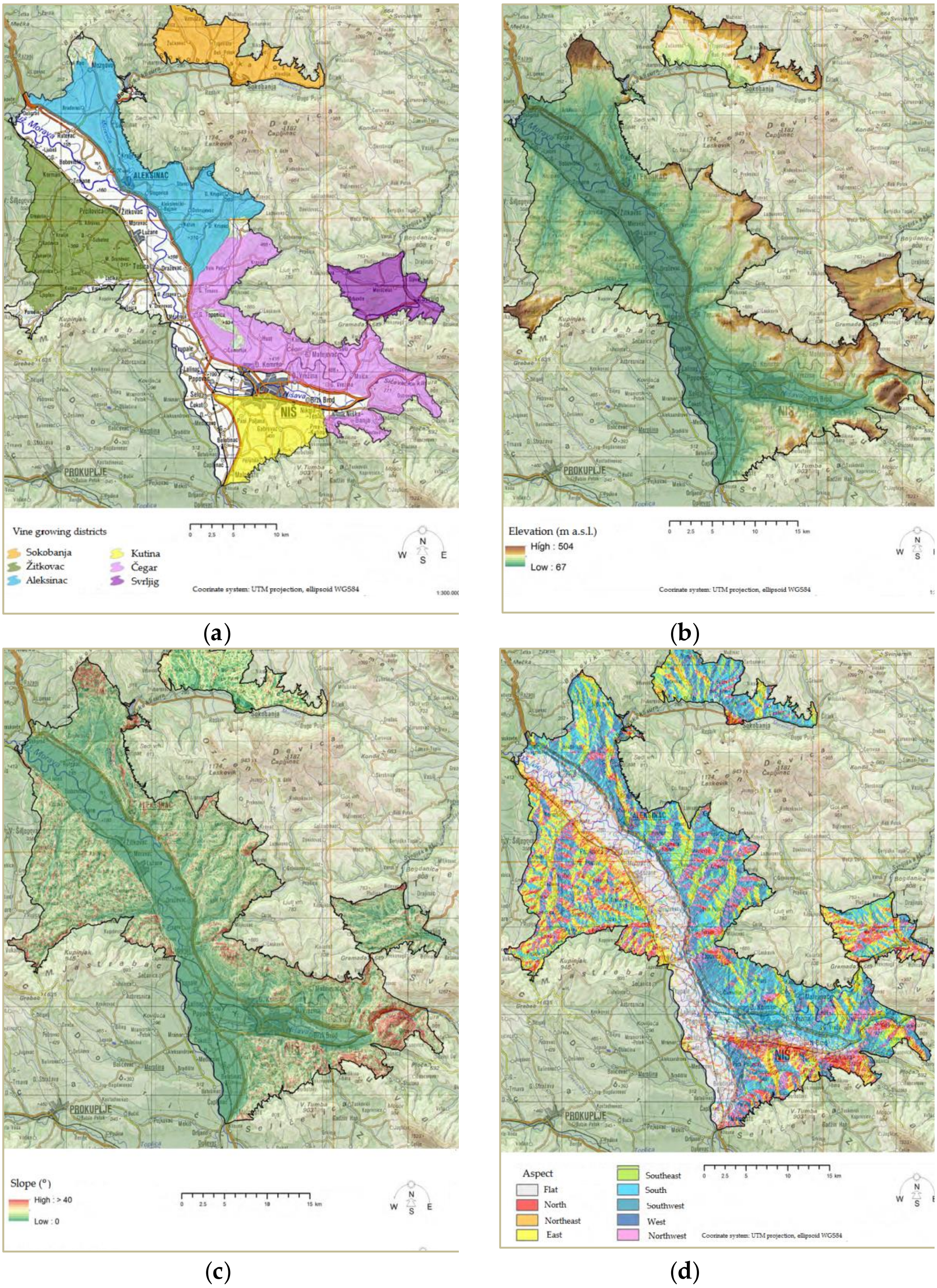


Figure 1. The vineyard region of Niš, Serbia: (**a**) vine-growing districts; (**b**) elevation (m.a.s.l.); (**c**) slope (°); (**d**) aspect ([33], modified by the authors).

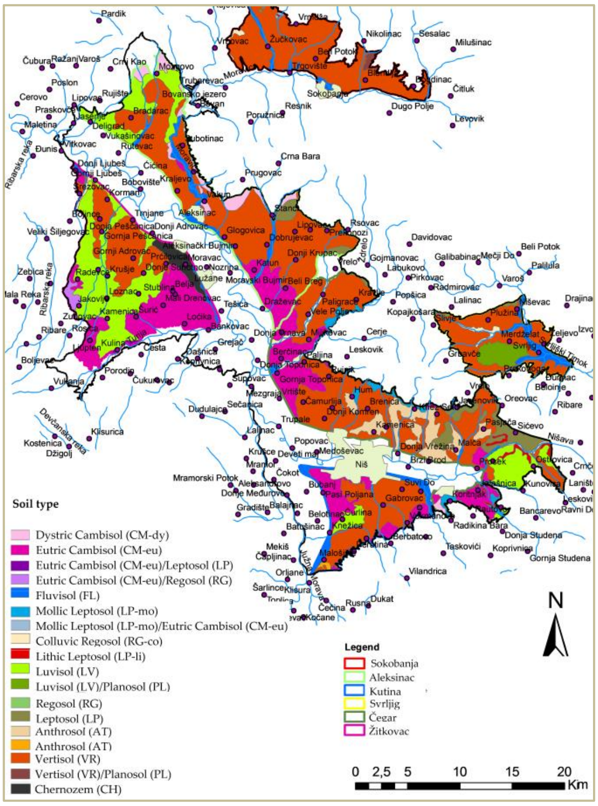


Figure 2. Pedological map of the wine-growing region of Niš and borders of vine-growing districts, according to the World Reference Base (WRB) soil classification; based on a digitalized primary pedological map of the Republic of Serbia, 1:50,000.

2.2. Climate Characteristics

Climatological data were obtained from four meteorological stations: Niš (Jasenovik, Malča, Sićevo and Gornji Barbeš localities), Aleksinac (Jasenje, Šurić, Beli Breg and Vele Polje localities), Sokobanja (Beli Potok locality) and RC Niš (Svrljig locality).

For the last 20 years, the mean annual air temperatures were 12.4, 9.3, 13 and 11.2 °C at the Niš (204 m.a.s.l.), RC Niš (807 m.a.s.l.), Aleksinac (180 m.a.s.l.) and Sokobanja (300 m.a.s.l.) meteorological stations, respectively (Figure 3). The heat summation period (April–October), also known as the Winkler index, is 1713.8, placing this region in zone III according to Winkler [34].

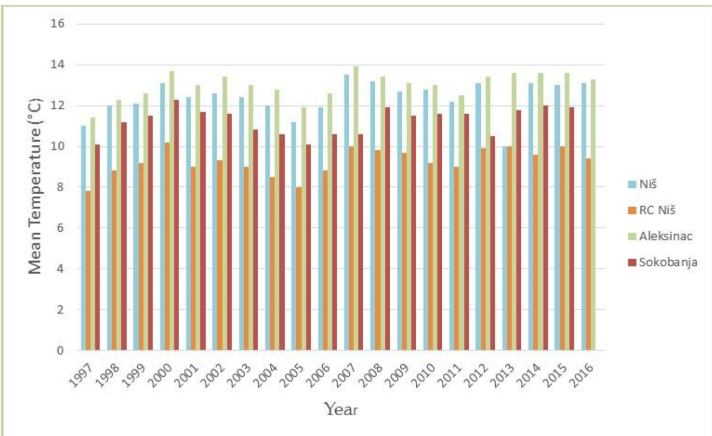


Figure 3. Mean annual temperatures in the Niš region from 1997 to 2016, obtained from four meteorological stations.

Huglin's (heliothermic) index (HI) (April–September) for the Niš region is 2259.7, which puts the lower parts of the region in the HI + 1 group of regions, in the interval > 2100 $\leq$ 2400 with the climate type moderate-warm [35]. The value of the drought index for the Niš region is 138.0 mm, which classifies this region as a DI-1 sub-humid (medium humid) region, with typical absence of drought [36].

For the last 20 years, the mean annual precipitation levels were 629, 746, 624 and 700 mm at the Niš, RC Niš, Aleksinac and Sokobanja meteorological stations, respectively (Figure 4).

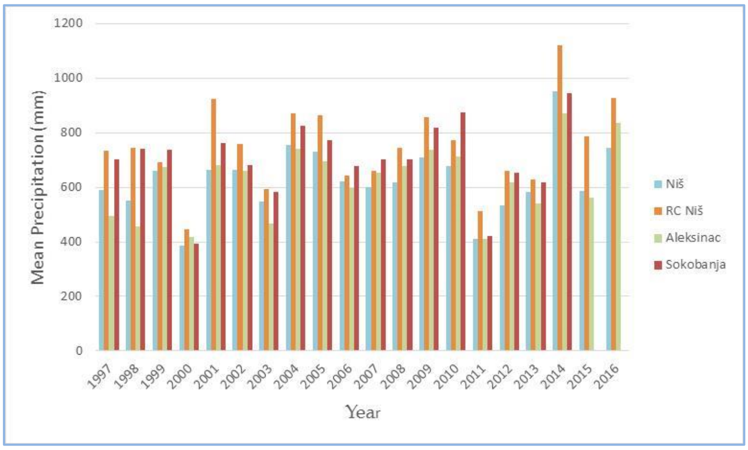


Figure 4. Mean annual precipitation levels in the Niš region from 1997 to 2016, obtained from four meteorological stations.

2.3. Soil Management Practices

The soil management data were derived from long-term management records for the period 1997–2016. Soil management practices usually involve ameliorative fertilization with large amounts of mineral fertilizers (300–500 kg P_2O_5 ha^{-1} and 200–300 kg K_2O ha^{-1}) with the addition of organic amendments, most often manure (30–40 t ha^{-1}), when planting vineyards. Common practice also includes deep tillage to an average depth of 60–80 cm, mixing of soil horizons and placing of organic materials into deeper soil layers. Some wine producers avoid deep tillage and plow at 30–40 cm. In the first years of the vineyard plantation, no fertilization is carried out, or smaller amounts of mineral fertilizer are applied. During the following years of exploitation, mineral fertilizers are applied, while opinions are divided on the issue of applying organic fertilizers. Some wine producers avoid using organic fertilizers for grape production, because they fear there will be a negative impact on the quality of the grapes. Winegrowers generally do not bring grape pomace back to the soils. Other growers apply organic fertilizers, usually manure, every fourth year. Frequent tillage between the rows is a common practice during exploitation to keep the soil free of weeds.

2.4. Soil Sampling

The study was carried out in 10 representative vineyard localities (Table 1). Some localities are shown in Figure 5 and Supplementary Materials, Figure S1. Field work took place during 2016. In each topographic position samples were taken from the vineyard and forest soils. The total analyzed area included 20 production vineyard plots and 10 forest soils in the close vicinity of the vineyard plots. These plots exhibited uniform micro-relief and slope in their terrain, as well as having the same cultivation practices. The size of the plots (subplots) varied from 1400 to 34,500 m^2.

Table 1. Locations, vine growing districts, global positioning system (GPS) coordinates and soil types of the vineyards.

Locality	Vine Growing District	GPS (E)	GPS (N)	Soil Type (FAO–WRB)
Jasenje	Aleksinac	21.575951	43.629562	Haplic vertisol (ochric), VR-ha-oh
Šurić	Žitkovac	21.644822	43.453924	Haplic vertisol (ochric), VR-ha-oh
Beli Breg	Aleksinac	21.814915	43.478903	Haplic vertisol (ochric), VR-ha-oh
Beli Potok	Sokobanja	21.859135	43.674641	Haplic vertisol (ochric), VR-ha-oh
Vele Polje	Čegar	21.827743	43.450464	Haplic vertisol (ochric), VR-ha-oh
Svrljig	Svrljig	22.069715	43.414675	Abruptic luvisol (clayic), LV-ap-ce
Jasenovik	Čegar	22.030862	43.355521	Haplic vertisol (ochric), VR-ha-oh
Malča	Čegar	22.010568	43.316971	Haplic vertisol, VR-ha-oh
Sićevo	Čegar	22.081987	43.346480	Skeletic, dolomitic, eutric leptosol (clayic, ochric), LP-sk.do.eu-ce.oh
Gornji Barbeš	Kutina	21.950723	43.188976	Vertic, eutric cambisol (ochric), CM-vr.eu-oh

(a) **(b)** **(c)**

Figure 5. Some localities of the vine-growing region of Niš: (**a**) Svrljig—abruptic luvisol (clayic), LV-ap-ce; (**b**) Beli Breg—haplic vertisol (ochric), VR-ha-oh; (**c**) Sićevo—skeletic, dolomitic, eutric leptosol (clayic, ochric), LP-sk.do.eu-ce.oh.

The soil was sampled from two depths, 0–30 cm and 30–60 cm. Composite soil samples amounted to about 20 individual samples. The total number of these composite soil samples was 60.

In order to determine the indigenous soil type of the vineyard, i.e., the soil that had not been altered by powerful ameliorative measures (deep tillage) during the vineyard establishment and turned into an anthrosol (eutric, clayic, regic; AT-eu.ce.rg), soil profiles were analyzed at a nondisturbed site in the vineyards or near the vineyards (Figure 6).

Soil profiles were analyzed at 10 representative locations, up to a maximum depth of 200 cm or to the parent material. Samples for soil profile description and classification were taken in disturbed state using an Eijkelkamp Edelman auger. The total number of this soil samples was 45.

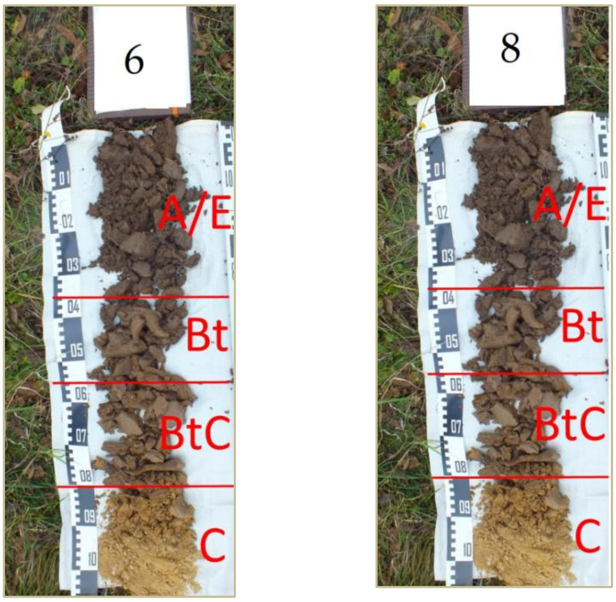
Georeferencing of soil and parcel samples in this study was performed using GPS receivers (Trimble GPS GeoXH 3000, Trimble GPS Juno SC, Terrasync Professional software; Trimble, Inc., Sunnyvale, CA, USA). Data processing was carried out using the ESRI ArcEditor 10 geographic information system (GIS).

2.5. Soil Compaction Measurement

Soil compaction was determined using an Eijkelkamp penetrologger by measuring resistance to penetration in all plots. The measurement depth was 80 cm. The threshold values of soil compaction are shown in Table 2.

Table 2. Threshold values of soil compaction [37].

Soil Compaction	Threshold Values
Optimal	1.0–2.5 MPa
Moderate compaction	2.5–3.0 MPa
High compaction	3.0–5.0 MPa



(**a**) (**b**)

Figure 6. Some of the soil profiles: (**a**) Svrljig locality—abruptic luvisol (clayic), LV-ap-ce; (**b**) Malča locality—haplic vertisol, VR-ha-oh.

2.6. Laboratory Analysis

All laboratory analyses were performed at the Laboratory for Soil and Agroecology of the Institute of Field and Vegetable Crops, accredited according to the standard ISO/IEC 17025:2017 [38].

The soil samples collected were naturally air-dried, milled and passed through a 2.0 mm sieve, following ISO 11464:2006 [39]. Soil pH value was determined with the potentiometric method following ISO 10390:2005 [40] in a 1:5 suspension of soil in 1 M KCl using a Mettler Toledo SevenCompact pH meter with glass electrode (Mettler Toledo, LLC, Columbus, OH, USA). The carbonate content (as $CaCO_3$) was determined according to the ISO 10693:1995 [41] volumetric method. SOC was determined by elementary analysis using a CHNSO VarioEL III Elementar (Elementar Analysensysteme GmbH, Langenselbold, Germany) after dry combustion and carbonate removal, in accordance with ISO 10694:1995 [42]. The particle size distribution was determined in the <2 mm fraction using the pipette method [43]. The size fractions were defined as clay (<2 μm), silt (2–20 μm), fine sand (20–200 μm) and coarse sand (200–2000 μm).

2.7. Soil Erosion Intensity Assessment

Soil erosion intensity assessment was carried out using the Universal Soil Loss Equation (USLE) model [44]:

$$A = R \cdot K \cdot LS \cdot C \cdot P$$

where A (t ha^{-1} yr^{-1}) is the mean annual soil loss, R (MJ mm h^{-1} ha^{-1} y^{-1}) is the rainfall erosivity factor, K (t ha h ha^{-1} MJ^{-1} mm^{-1}) is the soil erodibility factor, LS is the topographic factor, C is the land use/cover factor, and P is the practice factor (conversational measures, because erosion measures in the examined area were not taken into account).

Climatic data from the measuring stations around the studied territory were used to calculate the R factor. In this study, a simplified GJRM model was used to obtain the value of this factor [45,46]. The K factor was calculated using the Wischmeier and Smith equations [44]. In generating the LS factor of the study area, the SAGA GIS module was used, calculated from the ratio developed by Desmet and Govers [47], while the CLC database was used to calculate the C factor.

The classification of soil erosion risk categories according to the Organization for Economic Cooperation and Development (OECD) [48] uses the following ranges: tolerable (<6.0 t ha^{-1} yr^{-1}), low (6.1–10.0 t ha^{-1} yr^{-1}), moderate (10.1–22.0 t ha^{-1} yr^{-1}), high (22.1–33.0 t ha^{-1} yr^{-1}) and severe erosion (>33.1 t ha^{-1} yr^{-1}).

2.8. Statistical Analyses

Study data were processed using the methods of descriptive statistics. A general linear mixed model was fitted for SOC data. All factors, including the main effects of land use, topographic position and soil depth, as well as the corresponding interactions in the model, were considered as fixed. Additionally to this base model, several alternative candidate models with diagonal structures for the main effects and interactions were fitted. The best model based on the AIC value criterion was selected for further discussion and for least squares means comparisons. The differences were tested when significant effects were detected. Correlation analysis between SOC content and resistance to penetration of soil, as well as between mean annual soil loss and altitude, was explored by using the Pearson correlation at a significance level of $p < 0.05$. All statistical analyses were performed using SAS software and Statistica 12.6 (StatSoft, Inc. Corporation, Tulsa, OK, USA).

3. Results and Discussion

3.1. Characteristics of the Soil

Physical and chemical soil properties of the investigated area for the soil layers at 0–30 cm and 30–60 cm and for the profile horizons (<200 cm) are given in Table 3. In topsoil and subsoil, the pH value was highly acid to slightly alkaline, according to the classification for vineyard soils [49]. Soil pH value comes from the pH reaction of the parent substrate in which the soil was formed. The topsoil layer (0–30 cm) had an acidic pH value for the most part (62% of the region's surface area). In the soil profile horizons, the pH values of most soils increased with depth. The most suitable soil pH in terms of vine cultivation is neutral [50]. According to White [51], the optimum pH range for vine growth is 5.5–8. Slightly acidic and neutral vineyard soils have a better nutrient balance for plant growth.

Table 3. Descriptive statistics of soil properties in layers: 0–30 cm, 30–60 cm and profile horizons (<200 cm).

Soil Properties	Mean ± Standard Deviation
0–30 cm	
pH (in 1 M KCl)	5.42 ± 1.15
$CaCO_3$ (%)	2.65 ± 10.84
Clay (%)	36.67 ± 9.91
Silt (%)	22.32 ± 4.86
Fine sand (%)	28.57 ± 7.17
Coarse sand (%)	12.44 ± 8.26
30–60 cm	
pH (in 1 M KCl)	5.46 ± 1.15
$CaCO_3$ (%)	5.01 ± 10.84
Clay (%)	39.92 ± 9.78
Silt (%)	21.35 ± 4.94
Fine sand (%)	26.71 ± 7.28
Coarse sand (%)	12.02 ± 8.24
Profile horizons, 0–200 cm	
pH (in 1 M KCl)	5.62 ± 1.13
$CaCO_3$ (%)	6.26 ± 10.79
Clay (%)	35.12 ± 9.93
Silt (%)	21.04 ± 4.85
Fine sand (%)	31.04 ± 7.18
Coarse sand (%)	12.80 ± 8.00

Samples of topsoil and subsoil belonged to the noncalcareous to highly calcareous soil categories [49]. The content of $CaCO_3$ in completely carbonate-free soils was either uniform in terms of profile depth or a small amount of carbonates appeared at the lower layer. In other soils, the carbonate content increased with the depth of the profile. The content of $CaCO_3$ largely depended on the parent substrate.

Increased clay content was recorded in both soil layers and varied between 21.44% and 61.88% in topsoil and 21.56% and 51.92% in subsoil. Most of the samples were concentrated in the classes of light clay and heavy clay. This texture is unfavorable for most cultivated plant species. Loamy soils with high organic matter, low-water-holding capacity and well-drained characteristics are more suitable for plant production [52].

3.2. Intensity of Soil Erosion

The mean annual soil loss in the Niš region was 5.42 t ha^{-1} yr^{-1}, determined using the USLE model [44] (Figure 7). The average erosion intensity in the observed localities ranged between 0.05 and 9.80 t ha^{-1} yr^{-1}, with a mean value of 4.43 t ha^{-1} yr^{-1} (Table 4), which classifies this area as having tolerable erosion risk according to the OECD classification [48].

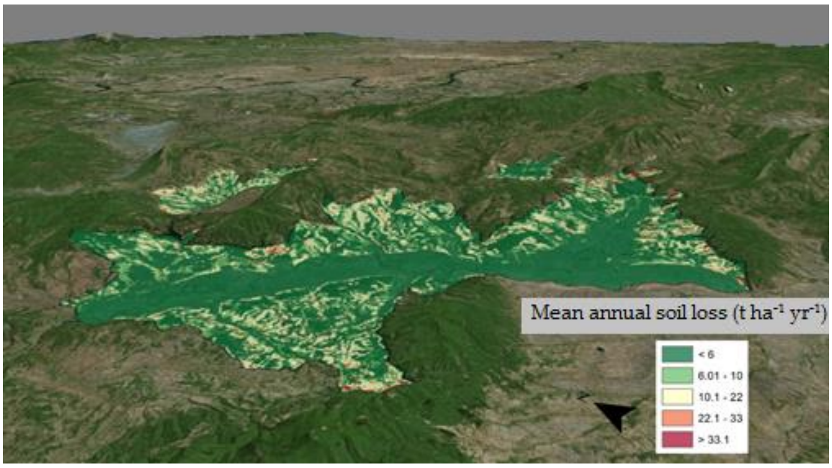


Figure 7. Mean annual soil loss in the Niš region (t ha^{-1} y^{-1}).

Table 4. Mean annual soil loss in observed localities.

Locality	A
Jasenje	5.64
Šurić	5.83
Beli Breg	3.43
Beli Potok	9.82
Vele Polje	5.86
Svrljig	0.58
Jasenovik	1.78
Malča	2.77
Sićevo	8.81
Gornji Barbeš	3.24

A—Mean annual soil loss (t ha^{-1} yr^{-1}).

A low risk of surface soil erosion was determined for 12.45% of the surface, while 16.52% of the territory was found to be under a moderate erosion processes. High risk of erosion was detected for 2.73% of the territory and severe risk of soil erosion was observed for 0.73% of the territory. The most endangered vine-growing districts were Sokobanja, with 8.15% of the territory under high and severe risk and Čegar, with 5.92% of the territory under high and severe risk. The highest mean annual soil loss was in the Beli Potok (9.80 t ha^{-1} yr^{-1}) and Sićevo (8.81 t ha^{-1} yr^{-1}) localities. The lowest mean annual soil loss was in the Svrljig locality (0.58 t ha^{-1} yr^{-1}).

3.3. *Effect of Topographic Position and Soil Depth on SOC Content*

The effect of topographic position on SOC content is shown in Table 5 and Figure 8. After fitting several candidate models that assumed heterogeneous error variance for the model term, the most suitable model with a heterogeneous error variance structure for the factors was selected based on the AIC value (data not shown). All further discussion (throughout the study) is based on inferences from the selected model. Topographic position was a significant factor, while soil depth was highly significant.

Table 5. Tests of fixed effects from the model with a suitable error variance structure.

Effect	Num DF	Den DF	*F*-Value	Pr > F
Land use	1	18.2	8.57	0.0089
Soil depth	1	18.2	12.33	0.0025
Topographic position	2	18.2	5.35	0.0148
Land use × soil depth	1	18.2	0.68	0.4191
Land use × topographic position	2	18.2	5.76	0.0115
Soil depth × topographic position	2	18.2	0.01	0.9910
Land use × soil depth × topographic position	2	18.2	0.08	0.9248

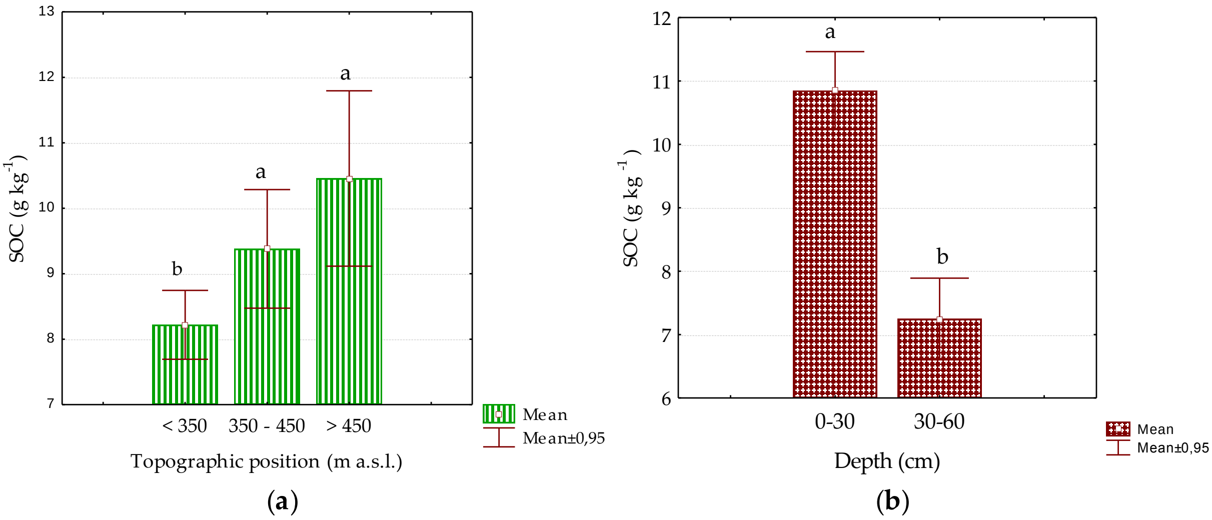


Figure 8. Soil organic carbon content: (**a**) for different topographic positions, $p < 0.05$; (**b**) in soil layers, $p < 0.01$ Significant differences between soil groups are labeled with different letters, (N = 60).

The SOC content was significantly higher at the upper and the middle position than at the lower positions. The SOC in the lower topographic position (<350 m.a.s.l.) of the vine-growing region of Niš ranged between 2.55 and 13.46 g kg^{-1}, with a mean value of 8.22 g kg^{-1}. At 350–450 m, SOC content ranged from 3.48 g kg^{-1} to 14.09 g kg^{-1}, with a mean value of 9.38 g kg^{-1}. At the highest altitudes above 450 m, the SOC content ranged from 5.34 g kg^{-1} to 24.13 g kg^{-1}, with a mean value of 10.45 g kg^{-1}.

These results might be attributable to the differences in temperature and precipitation between different topographic positions. Decreasing temperature and increasing precipitation with altitude can be seen in Figures 3 and 4. The highest mean annual precipitation (746 mm) and the lowest temperature (9.3 °C) were at the highest altitude (807 m.a.s.l.). The lowest mean annual precipitation (624 mm) and the highest temperature (13 °C) were at the lowest altitude (180 m.a.s.l.).

Altitude affects climatic characteristics, composition and productivity of vegetation [51], soil water balance, soil erosion, geological deposition processes, soil microbiological activity and other processes [52,53], thereby influencing the content of and changes in organic carbon in the soil. At higher altitudes, SOC accumulation is higher due to decreases in temperature and increasing levels of soil moisture [54–56]. At the, increasing soil temperature accelerates the rate of SOC decomposition [57,58], improves the level of soil respiration [57] and leads to a significant decrease in SOC content [58–60]. These findings are consistent with the results obtained by Sims and Nielsen [61], who reported that SOC had a significant relationship with altitude in Montana, USA. Also, Dai and Huang [62] reported that SOC stocks had a linear and positive correlation with altitude. Decreasing temperature with altitude has been shown to limit SOC turnover in forest soils, leading to enhanced SOC storage [63]. lower positions

Previous studies in Serbian soils have shown that organic carbon content has decreased from 52.7 g kg^{-1} (1450 m.a.s.l.) to 39.4 g kg^{-1} (500 m.a.s.l.) [21]. In the study by Vidojević [55], SOC increased from lower to upper positions. In this study, the SOC content was: 35.60 g kg^{-1} at 500–1000 m.a.s.l., 18.70 g kg^{-1} at 200–500 m.a.s.l. and 15.20 g kg^{-1} at altitudes below 200 m.a.s.l. In the examination by Fang et al. [64], SOC in forest land increased with altitude and levels were significantly different at 0–200 and 400–800 m in the 10–30 cm soil layer. Similar results were obtained by Abebe et al. [65], where SOC stock in bushland was the highest (166.22 Mg ha^{-1}) in the upper position.

In contrast, numerous studies have confirmed carbon leaching through erosion related to topography [65–68]. With increasing slope, infiltration decreases because the increasing slope area and the velocity of the water flow lead to increasing runoff. Although a part of the surface of the examined area was endangered by erosion processes, a high threat of erosion was found only for 2.73% of the territory and a severe threat for 0.73%. The average erosion intensity in the observed localities ranged between 0.05 and 9.80 t ha^{-1} yr^{-1}, with a mean value of 4.43 t ha^{-1} yr^{-1}, which classifies this area as having tolerable soil loss according to the OECD classification [48]. The correlation between mean annual soil loss and altitude (r = 0.29) was not significant. It can be concluded that erosion did not significantly contribute to leaching of organic matter.

The overall mean SOC concentration of the samples in topsoil (0–30 cm), 10.85 g kg^{-1}, was significantly higher than SOC concentrations in subsoil (30–60 cm), 7.25 g kg^{-1}. This is in agreement with the results of other research [1,32].

3.4. The SOC Content for Different Land Uses

The SOC contents were significantly affected by land use (Table 5 and Figure 9). Vineyard areas exhibited lower values of SOC (8.28 g kg^{-1}) compared to forest areas (10.58 g kg^{-1}), indicating that the management adopted in these areas contributed to the reduction of these fractions. Forests have dense cover, which protects soil from being exposed to any other factors, such as erosion; hence, the SOC content is less affected [69]. This finding has been confirmed by many authors, who have shown that forest soils supply a large carbon input and have low litter decomposition [32]. This means that forest soils are distinguished by higher SOC, which is highly related to the lower degree of natural and human-induced disturbance.

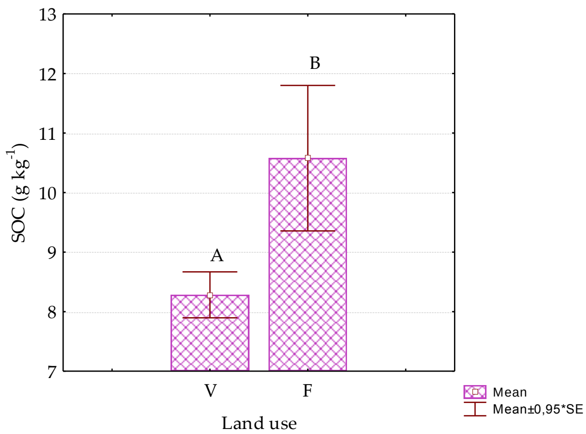


Figure 9. Effect of land use on soil organic carbon content. Significant differences between soil groups are labeled with different letters, $p < 0.01$ (N = 60).

Due to the specificities of soils in vineyards, such as limited soil development and their coarse texture and low capacity to protect SOM from binding to soil minerals, these soils are sensitive to degradation [28–30]. In addition, intensive viticulture under conventional cultivation systems is likely to increase the risk of soil degradation in the studied area. Intensive viticulture could lead to the loss of soil fertility, acceleration of soil erosion and SOM mineralization and increases in CO_2 emissions [59,70,71]. Soil tillage affects soil respiration, temperature, water content, pH, oxidation–reduction potential and the soil ecology [6,61]. In particular, it enhances the microbial biomass turnover and, in turn, the short-term CO_2 evolution by improving soil aeration, increasing the contact between soil and crop residues and exposing organic matter to microbial attack [17].

Similar results were obtained in wine-producing regions in the state of Santa Catarina, Brazil [65]. In the study by Gatullo et al. [72], the SOC content in a table grape vineyard in southern Italy was 2.86 g kg^{-1}. Similar results were recorded by Doğan and Gülser [54] in a soil study in the Menderes district of Izmir, Turkey, where the SOC content was in the range of 2.70–14.91 g kg^{-1}. Zhou et al. [4] concluded that land use is the main SOC change driver.

Previous studies in Serbian soils have shown that land use is an important factor in SOC variability. Manojlovic et al. [21] observed a significantly higher SOC content in forest land (0–20 cm depth) compared to agricultural land. Vidojević [55] stated that the largest reserves of organic carbon are in forest soil (27.8 g kg^{-1}), while they are significantly lower (15.80 g kg^{-1}) in agricultural land. In the study by Antonović and Mrvić [73], the average SOC content in forests was 15.20 g kg^{-1}. The SOC in vineyards was lower, 12.91 g kg^{-1}.

3.5. Effects of Land Use on SOC Across Topographic Positions

The interaction between topographic position and land use had a significant effect on SOC (Figure 10). The SOC contents of forest land were significantly higher at the upper position (17.32 g kg^{-1}) than that at the middle (9.56 g kg^{-1}) and lower positions (8.46 g kg^{-1}). However, SOC contents in vineyards were not significantly different across topographic positions. At the lower positions in vineyards, SOC ranged from 3.95 g kg^{-1} to 12.24 g kg^{-1}, with an average value of 8.09 g kg^{-1}. At the middle positions, the SOC content ranged from 4.17 to 12.47 g kg^{-1}, with a mean value of 9.20 g kg^{-1}. At the upper topographic position in vineyards, the SOC content ranged from 3.88 g kg^{-1} to 15.49 g kg^{-1}, with an average value of 8.17 g kg^{-1}.

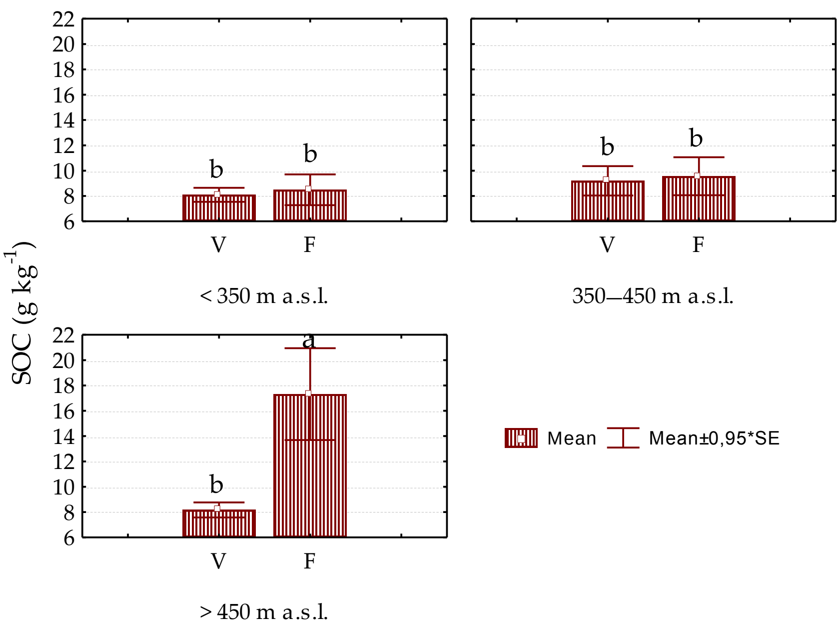


Figure 10. Effects of land use on SOC across topographic positions. Significant differences between soil groups are labeled with different letters, $p < 0.05$ (N = 60). V—vineyard, F—forest.

Unlike forests, which have less human interference, agricultural land is often disturbed by soil management. Variations in the SOC content at the same altitude and with the same soil type were primarily due to the different approaches of winegrowers to vineyard fertilization and tillage (see Section 3.6). Some winegrowers avoid using organic fertilizers because they fear there will be negative effects on the quality of the grapes (extended period of grape ripening, low sugar and high acid content). Furthermore, there is also a higher risk of SOC being leached from upper to lower topographic positions in agricultural land compared to forests. Similar results were obtained by Dortzbach et al. [74]. Their study found that the irregular spatial distribution of SOC in the vineyard soils was significantly influenced by management practices and soil disturbance, in addition to altitude and climatic factors. Furthermore, Abebe et al. [65] observed irregularities in the spatial distribution of SOC in vineyard soils.

3.6. The Influence of Soil Management on SOC

Figure 11 shows the SOC content, which depended on the management practice, in the topsoil and subsoil of vineyards. The effects of soil type and location on the SOC of vineyards were not significant in our study. Vineyards, in which deep tillage was performed along with the application of organic amendments, had a higher average SOC content in subsoil in comparison to vineyards in which tillage was performed at depths of 30–40 cm. There was no difference in the surface layer.

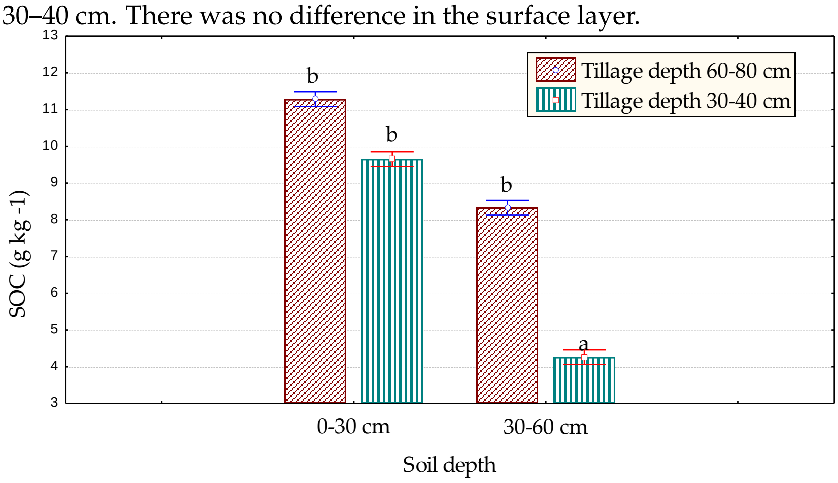


Figure 11. Soil organic carbon (SOC) content in soil layers of vineyards for different tillage depths (N = 60). Significant differences between soil groups are labeled with different letters, $p < 0.05$.

The SOC content in the subsoil of deeply tilled vineyards was similar to the value in the subsoil of forest land. Deep tillage (60–80 cm) has led to deep placement of organic amendments. This practice shows high potential for SOC preservation in the deeper soil layer and for prevention of carbon loss from the surface layer. Subsoil has high potential for the storage of additional soil organic carbon because of the large number of unsaturated mineral surfaces and environmental conditions that impede SOC decomposition, e.g., a more constant moisture and temperature regime or oxygen limitation [75]. Subsoiling can break compacted hardpan layers and it reduces soil strengths and improves water use efficiencies [75–77]. Similar results have been obtained by other authors. According to Liu et al. [16], deep tillage (subsoiling) increased SOC and N compared to conventional tillage. Cervantes et al. [78] stated that after the deep plowing, the layer of the deeply plowed fields accumulated 0.4 ± 0.1 Mg SOC ha^{-1} yr^{-1} on average. In the study by Shen et al. [79], subsoiling was found to increase aggregate-associated organic carbon, dry matter and maize yield on the North China Plain.

3.7. SOC and Soil Compaction

In our study, in the surface horizon (0–30 cm) on all plots (Figure 12, line a), the compaction was within the optimal values. At a depth of 30 cm, the compaction went beyond the optimum range, as it entered the range of moderately compacted soil up to the fiftieth centimeter, where it continued to grow. In some plots, a significant increase in penetrometric resistance or soil compaction at the depth of tillage could be observed (Figure 12, line c), which can negatively affect the growth and development of the root system of plants. Also, the presence of a soil layer with low permeability has resulted in the the top soil layer being more prone to saturation with water. The top soil layer is thus at risk of causing landslides. In contrast, individual plots were characterized by optimum values throughout the entire soil layer in which the plant root system had already developed (Figure 12, line b). Increased soil compaction has a very unfavorable effect on both soil and plants [46]. Soil compaction can induce or accelerate other soil degradation processes, such as erosion or landslides. Compaction reduces the infiltration rate, which increases run-off in sloping [80].

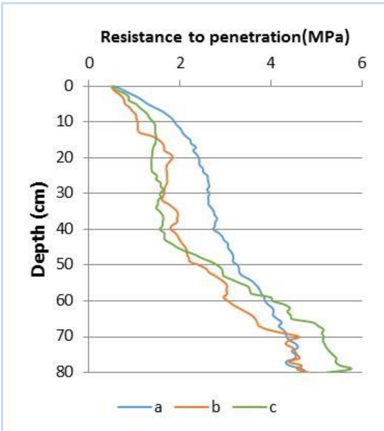


Figure 12. Penetrometric resistance of the tested soil: (a) average value for all plots; (b) Jasenovik locality—haplic vertisol (ochric), VR-ha-oh; (c) Malča locality—haplic vertisol, VR-ha-oh.

Heavy mechanization, extensive cultivation activities—especially if performed under unfavorable soil moisture conditions—and a trend of decreasing organic matter content in agricultural soils increase soil compaction and disturb the water, air and temperature regime.

Soil structure can be improved by increasing soil organic matter [81] and reducing the soil's susceptibility to compaction, erosion and landslides [82,83]. Increases in organic matter can reduce compactibility by increasing resistance to deformation and/or increasing elasticity (rebound effects) [84]. In our study, a significant negative correlation (−0.53) was found between the SOC content and soil compaction, expressed through penetrometric soil resistance. Similar results were obtained in the study by Vasin et al. [85]. Compactibility is sensitive to even quite small changes in the amount of organic matter. These observations have important implications for the improvement of soil management in order to avoid over-compaction problems in crop production.

4. Conclusions

The amount of organic carbon in soil and its spatial distribution depend on the land use, soil depth, altitude and management practices, as well as the interaction between land use and topographic position. Land use proved to be an important factor influencing SOC distribution. Due to specific soil properties in vineyards and the conventional land cultivation and specific fertilization strategies used, vineyards contained less SOC than forest land. The effect of topographic position was significant. The distribution of SOC in forest soils was influenced by altitude. At higher altitudes, SOC accumulation was higher due to lower temperatures and increased levels of soil moisture. At lower positions, higher soil temperatures led to a significant decrease in SOC content. The spatial distribution of organic carbon in the vineyards was not dependent on altitude, but most likely resulted from different soil management practices. Deep tillage at 60–80 cm, along with application of organic amendments, has high potential for the preservation of SOC in the deeper soil layer and for the prevention of carbon loss from the surface layer. Continuous tillage in vineyards at constant depths has led to the formation of a layer with low permeability. Increases in SOC content, i.e., organic matter, reduce soil compaction and lower the risk of erosion and landslides.

Knowledge of soil carbon distribution as a function of topographic position, land use and management practice is important for sustainable soil management and climate change mitigation. Systematic monitoring and more efficient soil management should be considered for the improvement of SOC status.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/agronomy11071438/s1, Figure S1. Some of the observed vineyards in the vineyard region of Niš.

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