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Tillage-induced impacts on the soil properties, soil water erosion, and loss of nutrients in the vineyard (Central Croatia)

Utjecaji obrade tla na svojstva tla, eroziju tla vodom i gubitak hraniva u vinogradu (Središnja Hrvatska)

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ABSTRACT

Eroded lands have deteriorated soil physical, chemical, and biological properties which reduces their productivity and represents a great threat to environmental safety and ecosystem stability. This study aims to investigate the soil management effect on the soil properties and conversely on soil erosion in vineyards by comparing tilled (TV) and permanently grass-covered vineyard (GCV) plots. The study vineyard is located in Sisak – Moslavina County, Croatia (45°31’ N, 16°43’ E). The fieldwork comprised of 8 rainfall simulations, soil sampling, and collection of overland flow. The results showed that TV plots had lower ($P<0.05$) soil organic matter content (SOM) (2.80%), mean weight diameter (MWD) (2.56 mm), and water-stable aggregates content (WSA) (53.1%) compared to GCV. Ponding time (PT) and runoff time (RT) were lower on the TV which caused longer outflow time and increased total water runoff (WR) and sediment loss (SL). The TV had 745.4 times higher SL than GCV (TV 6.87 t/ha compared to GCV 0.0092 t/ha). Higher SL resulted in higher nutrient losses on TV. Tillage is recognized as unsustainable practice on the study area and a key factor for increased soil erodibility and potential environmental hazards by high nutrient losses.

Keywords: soil management, rainfall simulations, agroecosystem sustainability

SAŽETAK

Erodirana tla karakteriziraju degradirana fizička, kemijska i biološka svojstva koja smanjuju produktivnost tla i predstavljaju veliku prijetnju okolišnoj sigurnosti i stabilnosti ekosistema. Cilj ovog rada je istražiti utjecaje upravljanja tlom na svojstva tla te eroziju tla u vinogradu, uspoređujući obrađeni (TV) i trajno zatravljeni vinograd (GCV). Istraživani vinograd nalazi se u Sisačko-Moslavačkoj županiji, Hrvatska (45°31’ S, 16°43’ I). Terenski rad sastojao se od 8 kišnih simulacija, uzorkovanja tla te prikupljanja erozijskog otjecanja. Rezultati ukazuju da su TV parcele imale niže ($P<0.05$) udjele organske tvari (SOM) (2.80%), srednje veličine strukturnih agregata (MWD) (2.56 mm) i udjele vodo-stabilnih strukturnih agregata (WSA) (53.1%) od GCV parcela. Vrijeme do površinskog stagniranja vode (PT) i vrijeme do početka otjecanja (RT) bili su niži u TV što je uzrokovalo duže vrijeme otjecanja i povećalo otjecanje vode (WR) te gubitak sedimenata (SL). Na TV je zabilježeno 745.4 puta veći SL nego na GCV (TV 6.87 t/ha naspram 0.0092 t/ha). Viši SL uzrokovao je veće gubitke hraniva u TV. Obrada tla je prepoznata kao neodrživa praksa u području istraživanja te je ključni faktor povećane erodibilnosti tla kao i potencijalnih okolišnih opasnosti uzrokovanih visokim gubitkom sedimenata.

Ključne riječi: upravljanje tlom, kišne simulacije, stabilnost agroekosistema

INTRODUCTION

Vineyards are recognized as a highly endangered land use from the point of soil erosion. Most of them are faced on the steep slopes and intensively managed using frequent tillage and machinery traffic which makes them prone to soil erosion. Also, vineyards tend to be raised on shallow and rocky soils in the dry climatic conditions, which are the factors that can induce high soil erosion rates (Prosdocimi et al., 2016; Vaudour et al., 2017; Rodrigo-Comino et al., 2018). Climate change increases the frequency of extreme rainfall events. In this context, Panagos et al. (2017) estimated a future increase in rainfall erosivity in Europe. Thus, the management practices have to be evaluated for ecosystem sustainability all across Europe, to ensure the longevity of the soil health and its ecosystem services.

Agriculture is the main cause of the sediment loss caused by the overland flow since tillage disturbs soil structure and stability (Coulouma et al., 2006) and increases soil erosion rates (Biddoccu et al., 2016). Tillage on the sloped terrains is recognized as a key factor for the sediment loss (Bogunovic et al., 2018), especially if it's in up-slope down-slope direction (de Alba, 2003; Bertol et al., 2007; DeLaune and Sij, 2012). Generally, a decrease of the bulk density (BD) can be observed following tillage (Bogunovic et al., 2017), but those effects are temporary as the soil consolidates with time (Alletto and Coquet, 2009; Al-Jabri et al., 2016). Additionally, traffic highly increases BD in vineyards (Ferrero et al., 2007; Bogunovic et al., 2019a) and distorts soil structure (de Lima et al., 2017). Tillage and traffic-induced changes in BD and soil structure modifies soil hydraulic properties (Horton et al., 1994; Dec et al., 2008; Strudley et al. 2008) and increase overland flow (Bogunovic et al., 2020). Tillage alters soil physical properties with the breakdown of the current consolidation and structure, which increases air content in the soil and exposes the mentioned aggregates to the air. Exposure of aggregates to the air accelerates oxidation and losses of the soil organic matter (SOM) (Lal, 2013), reducing structural stability of soils since SOM acts as a crucial ''binding effect'' for aggregates (Bronick and Lal, 2005; Šimanský et al., 2019). Reduction of the SOM in a majority of the cases decreases mean weight diameter (MWD) and water-stable aggregates content (WSA) (Six et al., 2000; Six et al., 2004; Spohn and Giani, 2010) which further alters the soil hydrological response.

Previous research revealed that grass-covering increases (Bogunovic et al., 2019a) and decreases BD (Ni and Ng, 2019) of the soil in addition to the tilled, depending on the previous management. The effect is dependent on the length of the period from conversion to grass-covering, as in shorter period soils are usually more compacted in addition to the tilled treatments, while in longer periods soils compaction was found to be lower as the soils were altered by the penetration and decomposition of the roots (Ni and Ng, 2019). Usually, grass-covering increases SOM (Belmonte et al., 2018; Miller et al., 2019), surface roughness (Biddoccu et al., 2016), and protects the soil from the raindrop impacts (Prosdocimi et al., 2016), reducing the water runoff (WR) (Biddoccu et al., 2017), sediment concentrations (SL) (Keesstra et al., 2016), and soil loss (SL) (Biddoccu et al., 2017; Bogunovic et al., 2020).

Furthermore, management has been shown to impact soil biological parameters (microbial biomass C, microbial biomass N, soil respiration, active-C, beta-glucosidase activity, and soil protein) (Nunes et al., 2020), while Xiao et al. (2017) observed homogenization of bacterial communities along the slope under the effects of soil erosion. Additionally, Xiao et al. (2017) report the accumulation of soil organic matter downslope which has increased soil respiration in addition to the middle and upper part of the slope. This shows that erosion has a potential of translocating soil microbiota which, potentially, can have a drastic effect on the newfound location and alter the ecosystem stability. On the other side, researchers have reported the effects of the soil biota on both increase and decrease of soil erosion (Burri et al., 2013 postulated decrease of soil erosion in soils with developed mycorrhizal fungi networks; Reichman and Seabloom, 2002 hypothesised that the extensive excavation activity of some soil-living mammals may accelerate soil erosion; Blouin et al., 2013 reported that the presence of the earthworms may reduce soil erosions rates by up to 50%). This shows that biological parameters should be included in further research related to soil erosion, as was shown or postulated that they can affect soil erosion and ecosystem productivity. Even as biological parameters weren't studied in this research, it is important to highlight that they can have an impact on soil erosion and vice-versa. This relationship should be further studied in future research.

Sustainability of the grapevine production is threatened by soil erosion (Ramos and Martínez Casasnovas, 2006), highlighting the need for sustainable land management in the vineyards. Tolerable erosion rates in the fields where degradation or loss of "one or more soil functions does not occur" were defined by the Verheijen et al. (2009), and for Europe, their value is 0.3 to 1.4 t/ha/y. Those values are often far surpassed in the vineyards regardless of the soils, parent material, and the climate (Cerdan et al., 2010; Prosdocimi et al. 2016; Rodrigo-Comino, 2018). In Croatia and South-Eastern Europe, such research is missing. Croatia has ~22 000 ha of vineyards (FAOSTAT, 2017), and a majority of them are intensively managed on the steep slopes. Moreover, the average vine producer in Croatia is not concerned with the erosion issue, as they produce sufficient quantity and quality of grapes. Such production usually involves the use of herbicides, insecticides, mineral fertilizers, and several tillage interventions on annual bases which can negatively affect soil quality and induce soil degradation (Pereira et al., 2018; Bogunovic et al., 2019b).

Thus, this study aimed to assess soil management impacts on the soil properties and their relation with soil hydraulic response which is also tied with soil erosion. This research aims to highlight the issues in the management of the vineyards in Croatia and define a suitable form of soil management which reduces soil erosion rates and enhances the longevity of soil productivity.

MATERIALS AND METHODS

Study area

The study vineyard is located in Sisak – Moslavina County, Croatia (45°31' N, 16°43' E; average elevation 194 m) on the roughly 8° (7° min to 10° max) slope with the E exposition (Figure 1). The climate of the study area is a moderate continental climate. The soil over the study area is classified as a silty loam Stagnosol on a slope, medium depth (IUSS, 2015). Part of the vineyard (cv. Škrlet) was planted 15 years ago (grass-covered - GCV), while the other part was planted 3 years ago (tilled - TV). Vineyard management is comprised of shallow tillage (up to 10 cm) with a rotary-cultivator for the first 3 years after the planting, followed by permanent grass cover after the third year. TV vineyard was tilled 2 – 3 times annually for the past 3 years depending on the growth of the weeds. GCV vineyard was grass-covered for the past 12 years and mulched by grass trimming without the removal of the cut grass 2 – 3 times a year. In both treatments, agro-technical and pomo-technical operations were performed manually, without the machinery traffic on the soil. Pruning residuals were removed from the vineyard and burned.

Rainfall simulations and sampling

Rainfall simulations were carried out on the 28th of November 2018 with UGT Rainmaker Rainfall Simulator (class of pressurized rainfall simulators), 8 per treatment (16 in total) for 30 minutes with rainfall intensity of 58 mm/h as was described in Bogunovic et al. (2020). Before simulations, the simulator was calibrated using a 1 m^2 plastic vessel. The catchment area was enclosed by a metal ring with a faucet (1 m in diameter; 0.785 m^2) stuck 5 cm in the soil with 10 cm sticking out of the soil. Faucet on the ring was faced downslope and connected to a plastic canister so that the overland flow could be collected. Before simulations, the slope was measured inside of the catchment area. During the simulations, ponding time (PT) and runoff time (RT) were measured. Soil core samples (100 cm^3 cylinders) and undisturbed soil samples were taken 10 cm downslope of the plot area for the determination of soil water content (SWC), water holding capacity (WHC), bulk density (BD), mean weight diameter (MWD) and water-stable aggregates (WSA) (Bogunovic et al., 2020).

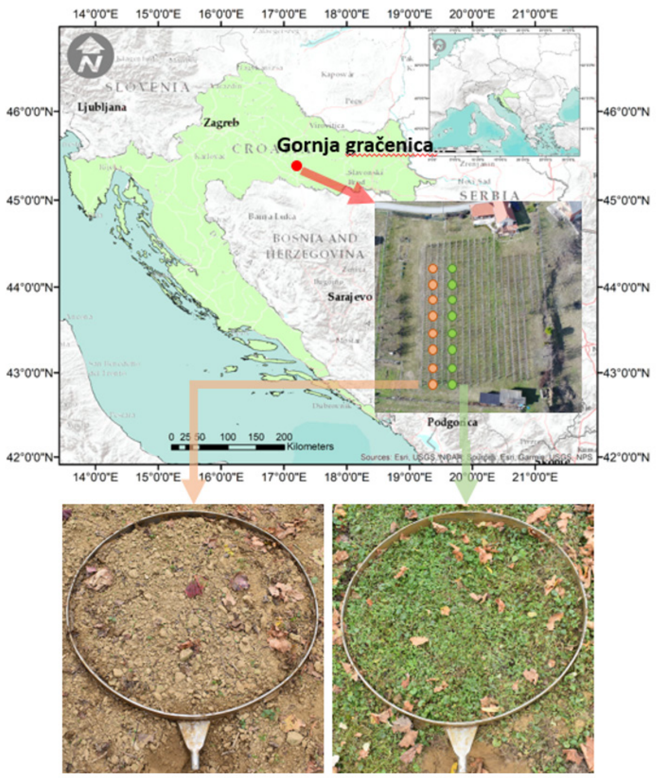


Figure 1. Study location and experimental design

Physical and chemical analyses

All 16 undisturbed soil samples were carefully separated to aggregates by hand while avoiding the further breakdown of the formed aggregates (Diaz-Zorita et al., 2002). All non-soil fragments (roots, stones, snail shells, etc.) were removed from samples at this stage. Samples were air-dried for 3 days in the greenhouse at ~30 °C and dry sieved in sieve shaker (Impact – auto sieve shaker, USA) for 30 seconds following the method of Le Bissonnais (1996). The shaker was composed of sieves varying in size as follows; 8, 5, 4, 2, 1, 0.5, and 0.25 mm. Each fraction was then collected and weighed. The >8 mm fraction is removed from the calculation because of its high variability. From the collected data MWD was calculated using the equation;

$$MVD = \sum_{i=1}^{n} x_i \times w_i$$

where x_i is the mean diameter of any particular size range of aggregates separated by sieving, and w_i is the weight of aggregates in that size range as a fraction of the total dry weight of soil used" (Blair, 2010). Eijkelkamp's wet sieving method derived from the Kemper and Rosenau (1986) was used to determine WSA with the Eijkelkamp's wet sieving apparatus (Netherlands) on all previously dry sieved samples. SL, SC, and WR were obtained with the filtration of the runoff through the filter paper of known mass, which was then dried in the oven at 105 °C for 24 h followed by the scrapping of the sediments for the chemical analyses. WR was used for the calculation of the infiltration rate (IR). Data for the SL was transformed to t/ha. The 16 collected core samples were used to obtain SWC, WHC, and BD of soil with the gravimetric core method (Casanova et al., 2016).

Following physical analyses, all undisturbed soil samples were milled and sieved through 2 mm mesh as a standard preparation for chemical analyses. Chemical analyses were performed on 16 soil and 16 sediment samples. SOM was determined following the Walkley and Black (1934) procedure of wet digestion in H_2SO_4 and $K_2Cr_2O_7$. Soil available phosphorous (AP) was extracted by ammonium lactate (AL) extraction method (Egner et al., 1960), followed by spectrophotometry analyses (Bogunovic et al., 2017). The same procedure was used to determine AP in the sediments. Sediment carbon and nitrogen content, as well as, soil total nitrogen (TN) were determined with dry combustion method on Elementar Vario Macro CHNS analyser. Contents of the carbon, phosphorous, and nitrogen in the sediment were multiplied with the SL in order to obtain the values of carbon losses (C loss), phosphorous losses (P loss), and nitrogen losses (N loss).

Statistical analyses

Statistical analyses were performed in Statistica 12.0 for Windows (Statsoft, 2013). Before the analyses, the normality of the data distribution was tested with the Shapiro-Wilk test for each variable. In cases where data didn't follow Gaussian distribution, data transformations were used (square-root, natural logarithm, box-cox) in an attempt to achieve normality of the data distribution. All of the transformations methods failed to result in normal data distribution, so the untransformed data was used to perform one-way ANOVA tests on the normally distributed data, while the Mann-Whitney U test was used on the variables that didn't follow Gaussian distribution. Where significant differences were noted in the one-way ANOVA test (P<0.05), the Tukey HSD *post-hoc* test was applied to differentiate the effects of management on the said variables. Significant differences for the Mann-Whitney U test were also defined by P<0.05.

Following ANOVA and Mann-Whitney analyses, a dataset with all untransformed variables was subjected to the principal component analysis (PCA) to analyse correlations between the variables, and connect them to the management in a projection of the variable cases.

RESULTS

Soil properties

Figure 2 summarizes the effects of soil management on soil properties. Significant differences were identified in BD between treatments (P=0.017). BD was higher in TV (1.47 g/cm^3) compared to the GCV (1.36 g/cm^3) (Figure 2A). No significant differences were noted in WHC (P=0.435) between treatments but higher inner-treatment variations were noted in TV as values ranged from 35.4% - 46.5% with mean value of 42.6%. In GCV, WHC values ranged from 40.1% - 42.8% with the mean value of 41.6% (Figure 2B). Between the treatments, no significant differences were observed in SWC (P=0.344) while higher inner-treatment variations were recorded in GCV (19.1% - 24.8%) compared to TV (21.4% - 25.6%) (Figure 2C). Figure 2D shows a significantly higher value of MWD in GCV (3.13 mm) in addition to TV (2.57 mm). GCV treatment also recorded significantly higher values of WSA (88.10%) compared to TV (53.13%) (Figure 2E). On figure 2F a significantly higher value of SOM in GCV (4.99%) over TV (2.80%) can be noticed. High inner-treatment variability can be observed for both treatments in AP as their values ranged from 323,2 – 393.8 g/kg in TV and 328.5 – 399.9 g/kg in GCV, however, no significant difference between treatments was noted (P=0.217) (Figure 2G). The TN followed a similar pattern as SOM, MWD, and WSA, as significantly higher values can be seen in GCV (0.27%) compared to TV (0.15%) (Figure 2H).

Overland flow properties

Figure 3 shows the summarized effects of soil management on the overland flow properties. Both PT and RT were significantly higher in GCV (PT 255 sec; RT 349 sec) in addition to TV (PT 148 sec; RT 303 sec) (Figures 3A and 3B). Additionally, RT was highly variable in both treatments as the values ranged from 260 – 370 sec in TV compared to 300 – 400 sec in GCV. Figures 3C and 3D show the opposite pattern in IR and WR for treatments with significant differences. GCV recorded high IR (98.4%) and low WR (4.6 m^3/ha) compared to low IR (43.4%) and high WR (165 m^3/ha) on TV. SC, SL, C loss, P loss, and N loss all follow a similar pattern as WR, where significantly higher values can be seen in TV in addition to GCV (Figures 3E – 3I). In all of the properties, variability was much higher in TV treatments (SC 32.79 – 55.77 g/kg; SL 5278.9 – 9623.2 kg/ha; C loss 92.3 – 194.3 kg/ha; P loss 1264.4 – 2497.5 g/ha; N loss 10841.2 – 32779.2 g/ha) compared to GCV (SC 1.6 – 2.4 g/kg; SL 7.0 – 12.2 kg/ha; C loss 0.49 – 0.85 kg/ha; P loss 1.9 – 3.3 g/ha; N loss 12.3 – 21.4 g/ha).

PCA analysis

Factor 1 (Figure 4) explained most of the variance in the properties (69.24%) and it grouped up WR, SC, SL, C loss, P loss, and N loss with high negative loadings on the opposite side of the SOM, TN, MWD, WSA, IR, PT, and RT group with high positive loadings. Factor 2 explained 12.04% of the variance in the properties and has loaded slope, BD, and SWC with positive loadings on the opposite side of the WHC and AP with negative loadings. The intersection of factors 1 and 2 has separated BD and SWC from AP and RT.

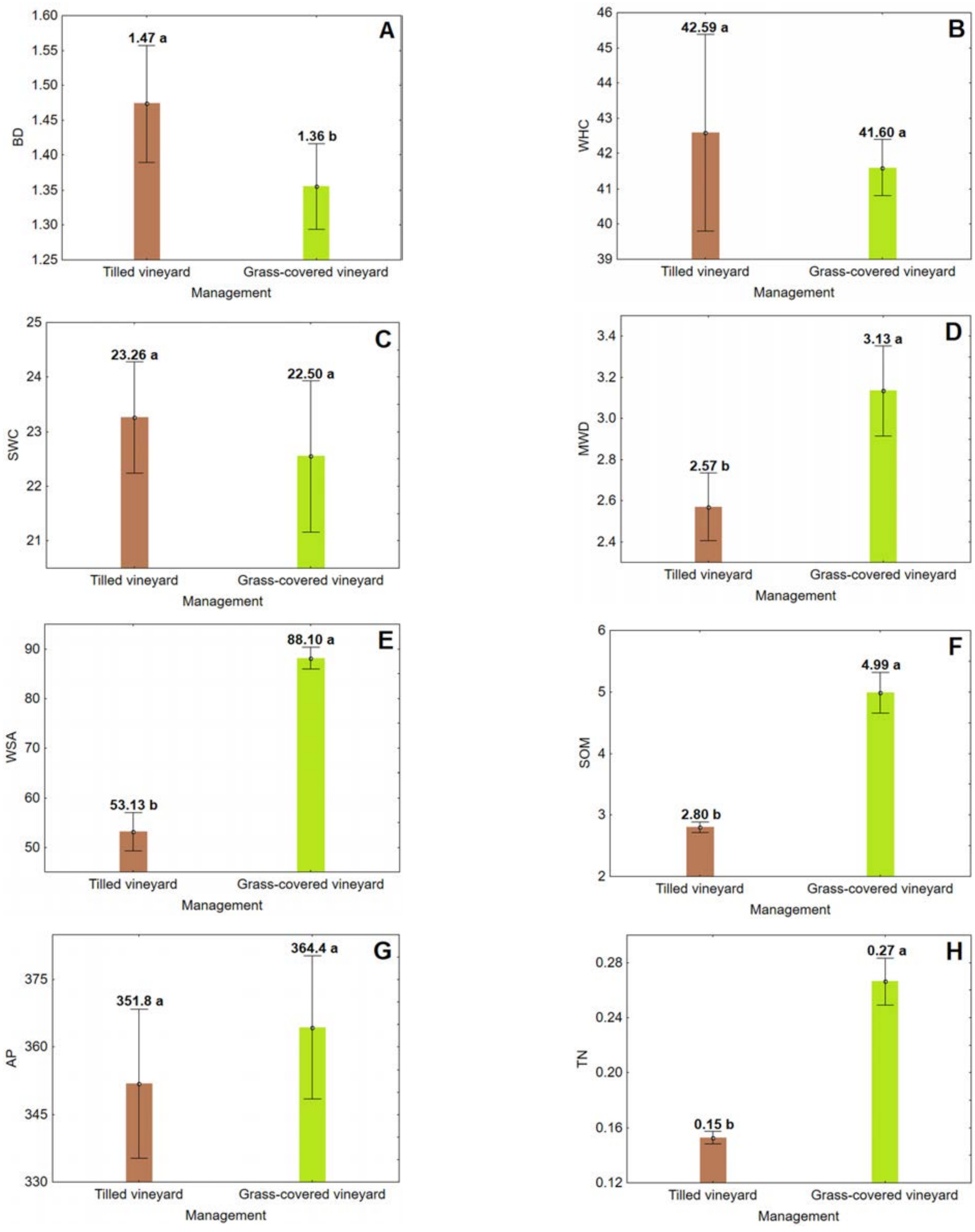
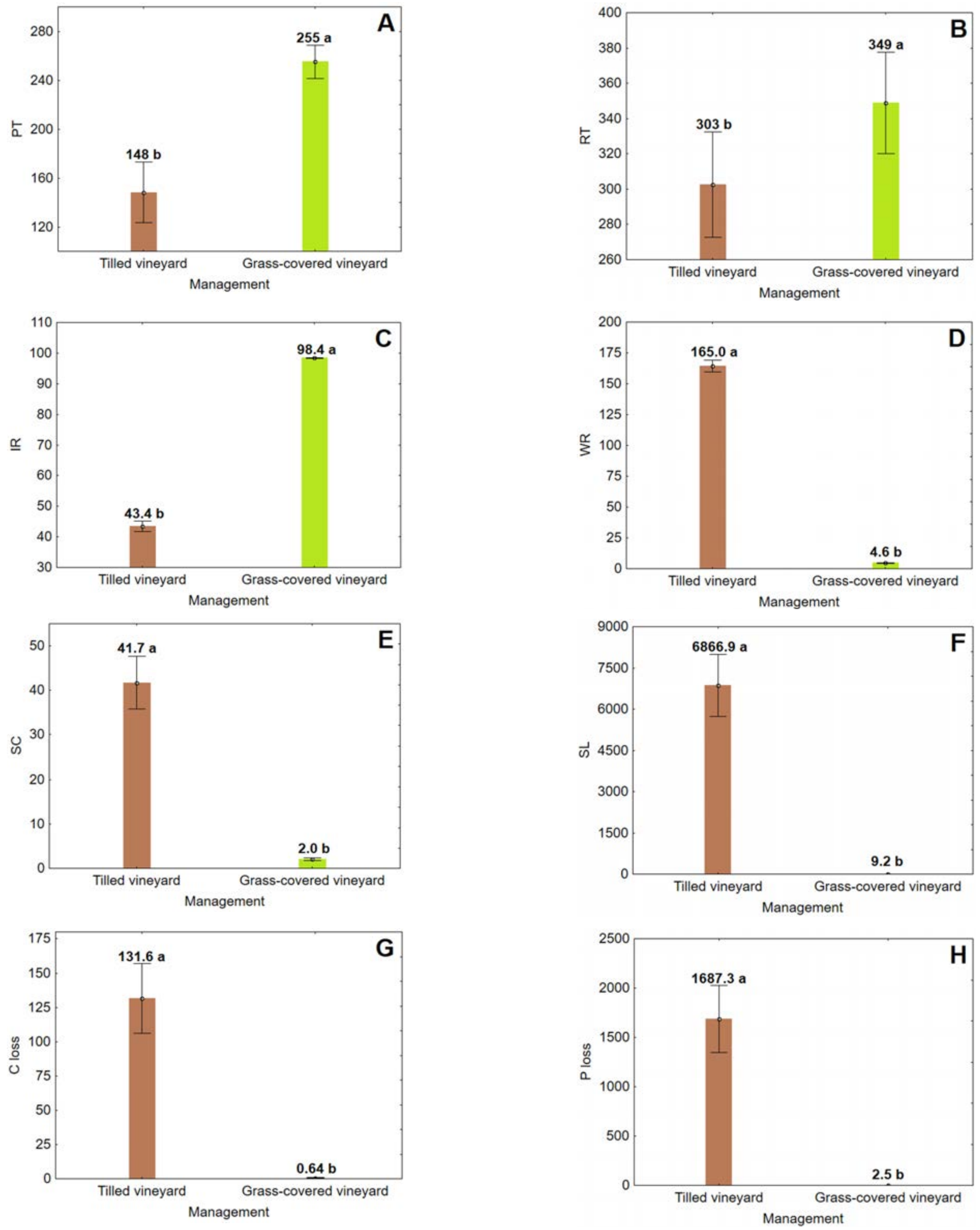


Figure 2. Effects of soil management on soil properties:
Graph A = BD, bulk density; Graph B = WHC, water holding capacity; Graph C = SWC, soil water content; Graph D = MWD, mean weight diameter; Graph E = WSA, water stable aggregates; Graph F = SOM, soil organic matter; Graph G =AP, available phosphorous; Graph H = TN, total nitrogen. Different lowercase letters indicate significant difference between treatment means at P<0.05


A
PT
255 a
148 b
280
240
200
160
120
Tilled vineyard
Grass-covered vineyard
Management
B
RT
349 a
303 b
400
380
360
340
320
300
280
260
Tilled vineyard
Grass-covered vineyard
Management
C
IR
98.4 a
43.4 b
110
100
90
80
70
60
50
40
30
Tilled vineyard
Grass-covered vineyard
Management
D
WR
165.0 a
4.6 b
200
175
150
125
100
75
50
25
0
Tilled vineyard
Grass-covered vineyard
Management
E
SC
41.7 a
2.0 b
50
40
30
20
10
0
Tilled vineyard
Grass-covered vineyard
Management
F
SL
6866.9 a
9.2 b
9000
7500
6000
4500
3000
1500
0
Tilled vineyard
Grass-covered vineyard
Management
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C loss
131.6 a
0.64 b
175
150
125
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75
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25
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Tilled vineyard
Grass-covered vineyard
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2500
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Tilled vineyard
Grass-covered vineyard
Management

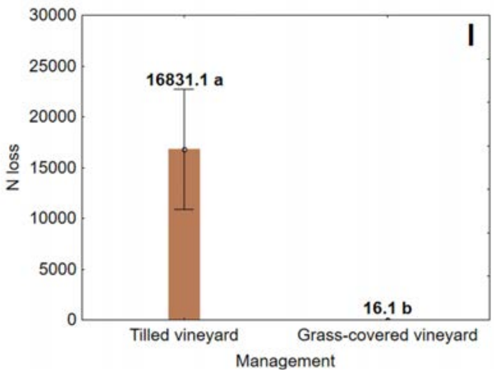

Figure 3. Effects of soil management on the overland flow:
Graph A = PT, ponding time; Graph B = RT, runoff time; Graph C = IR, infiltration rate; Graph D = WR, water runoff; Graph E = SC, sediment concentration; Graph F = SL, sediment loss; Graph G = C loss, carbon loss; Graph H = P loss, phosphorous loss; Graph I = N loss, nitrogen loss. Different lowercase letters indicate significant difference between treatment means at P<0.05

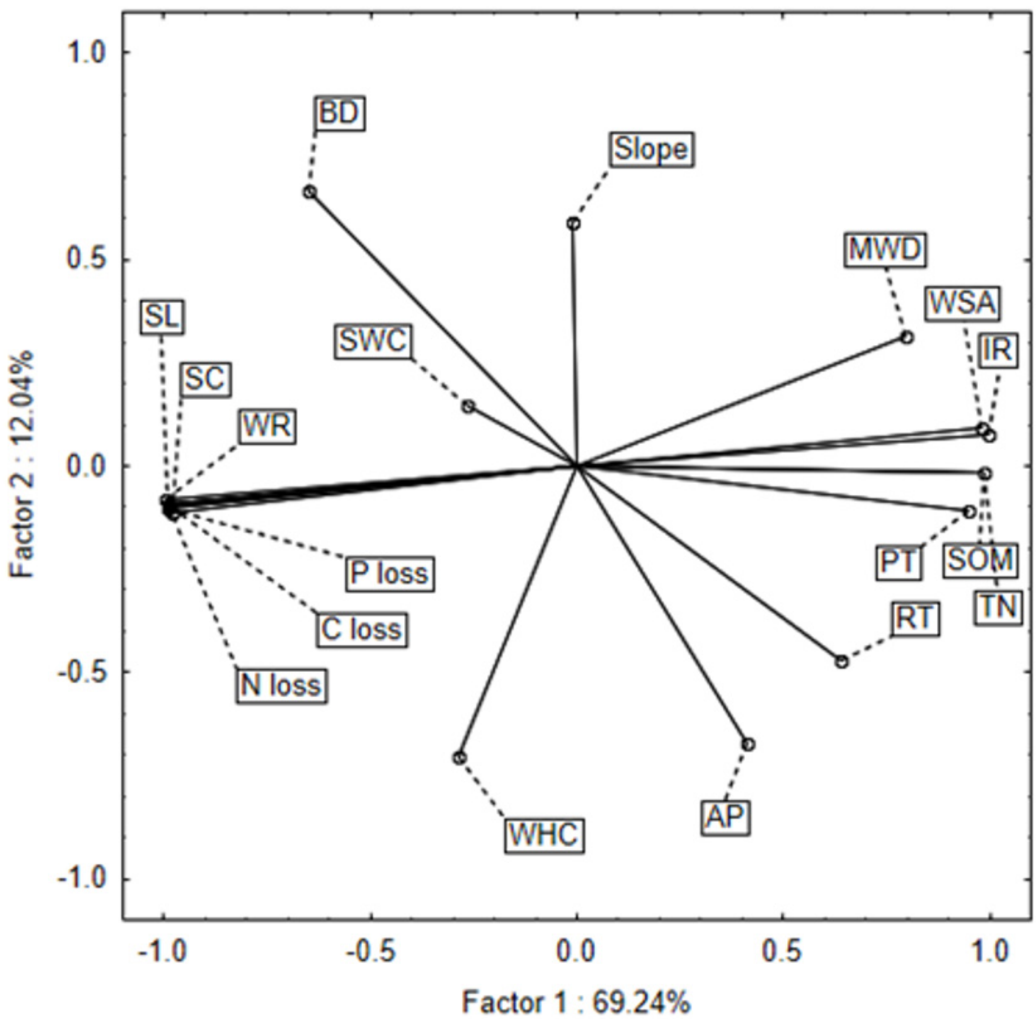

Figure 4. PCA projection of soil and overland flow properties
Abbreviations (BD, bulk density; WHC, water holding capacity; SWC, soil water content; MWD, mean weight diameter; WSA, water-stable aggregates; SOM, soil organic matter; AP, available phosphorous; TN, total nitrogen; PT, ponding time; RT, runoff time; IR, infiltration rate; WR, water runoff, SC, sediment concentration; SL, sediment loss; C loss, carbon loss; P loss, phosphorous loss; N loss, nitrogen loss)

Projection of the variable cases in figure 5 attributed high negative loadings in factor 1 to the TV plots which links them to the soil properties with high negative loading in the same factor. On the other hand, factor 2 loading for TV varied from highly negative to high positive indicating variability in the properties in which loadings were dominated by factor 2. GCV plots with high positive loadings in factor 1 were loaded on the opposite side of the TV plots, clearly separating them and attributing them to the properties with high positive loadings in the same factor. Unlike TV, GCV didn't vary as much in factor 2, indicating the lower variability in properties dominated by factor 2.

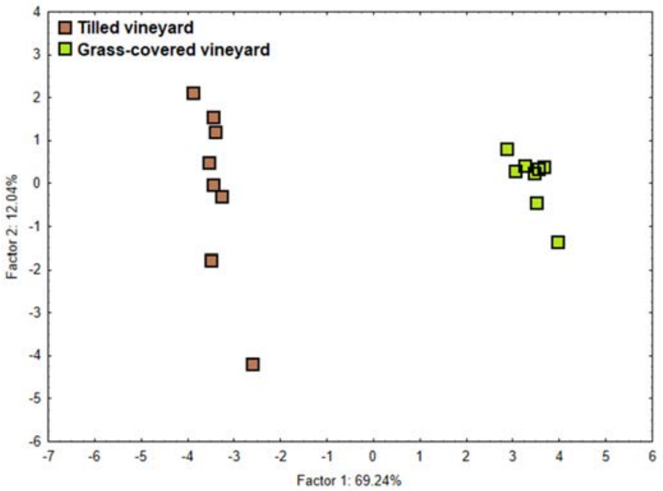

Figure 5. PCA projection of the variable cases

DISCUSSION

Soil properties

Rainfall infiltration is a process controlled by many factors; SWC, soil hydraulic properties, soil porosity, BD, surface roughness, surface cover, geomorphology factors, climatic factors, and SOM content which was found to be the driving factor for MWD and WSA (Mohamadi and Kavian, 2015; Morbidelli et al., 2018; Wei et. al., 2018). In this study case, lower BD (Figure 2A) in GCV was observed in addition to the TV due to the long period of grass-covering which was found to decrease BD in the cases where this management was long-term (Bogunovic et al., 2019a). Additionally, treatment differences were attributed to the management, since the absence of machinery traffic on the soil did not impact soil compaction (Lipiec et al., 2007; Bogunovic et al., 2019a). Tillage reduces soil compaction in the short-term, however during the season re-compaction and consolidation, BD returns to the pre-tillage level as is noted elsewhere (e.g. Osunbitan et al., 2005; Bogunovic et al., 2018). Lack of the difference in SWC (Figure 2 C) can be explained by the light rainfall event that occurred 2 days before the measurement which partially replenished the water content of the soil. SOM content (Figure 2 F) differed greatly between treatments (GCV 4.98%; TV 2.80%) mostly because of the tillage which increased SOM oxidation and mineralization (Lal, 2013), along with the effects of permanent grass-covering that increases the SOM (Olson et al., 2014; Poeplau and Don, 2015). Devine et al. (2014) and Rabbi et al. (2014) showed that agricultural management practices influence SOM, micro, and macro-aggregate distributions, and the rate of SOM turnover. Measured MWD and WSA (Figures 2D, E) were both higher in GCV following the higher SOM in the same treatment and can explain the lower BD at the TV as was discussed above. This soil structure data is in agreement with the Bronick and Lal (2005), who described SOM as the crucial factor of aggregate stability as it acts as a binding agent for the soil particles, while grassroots and root exudates enhance aggregate stability (Hillel, 2004; Jirku et al., 2013). The insignificant difference in AP (Figure 2G) can be explained by the more recent fertilization in the TV and higher SOM in the GCV which both increased AP in said treatments, achieving similar values. The higher measured value of TN (Figure 2H) in GCV is again, linked with the SOM since SOM highly correlates with TN in soils (Cheng et al., 2016).

Overland flow properties

Ponding time is a point in time where precipitation exceeds the infiltration rate capabilities of the soil and ponds start to form. In our study case, PT and RT (Figure 3A, B) were significantly higher in GCV treatment compared to TV. This can be explained by several factors. Firstly, surface vegetation cover intercepted the kinetic energy of the raindrops (Prosdocimi et al., 2016) and reduced crust formation (Birkás et al., 2008), while roots in GCV formed stable channels for easier infiltration (Ni and Ng, 2019). Secondly, higher MWD and lower BD increased soil macro-porosity and infiltration rate (Dec et al., 2008). Higher PT resulted in higher RT which then reduced the time of free water runoff. Finally, WR was additionally slowed by the surface roughness provided with grass-cover as was showed in other studies (e.g. Almeida et al., 2018). We hypothesize that the vegetation cover acts as a barrier slowing down runoff which increases the time water is in contact with the soil and further enhances the infiltration. In this context, the IR (Figure 3C) was 2.27 times higher in GCV in addition to TV which resulted in 35.7 times higher WR (Figure 3D) in TV compared to GCV. These results are in agreement with Biddoccu et al. (2016). Surface roughness and grass-cover act as a ''sieve'' which partially collects sediments, reducing SC (Keesstra et al., 2016) and can be a reason for significantly lower SC (Figure 3E) at GCV in addition to TV. Higher WR has higher kinetic energy and is capable of translocating higher contents of sediments. All these factors also affected the SL. Following previous data of soil hydrological properties, SL values (Figure 3F) were 6.87 t/ha in TV, which is 745.4 times higher than GCV 0.0092 t/ha. These values describe soil losses in a single, short, heavy rainfall event, and even here soil erosion rates for TV far surpass tolerable soil erosion rates defined by Verheijen (2009). The TV had 204.7 times higher C loss (Figure 3G), 686.9 times higher P loss (Figure 3H), and 1043.6 times higher N loss (Figure 3I) in addition to GCV. Nutrient losses (C loss, P loss, and N loss) follow a similar pattern as soil loss, where the quantity of soil loss is the main driving factor of nutrient losses, indicating the unsustainability of tilled treatment. Similar results were noted elsewhere (Kisic et al., 2002; Bogunovic et al., 2020). Such a significant difference in soil erodibility and losses of nutrients indicate unsustainable management in the study area. This data raises the concern about the inappropriate agricultural management in vineyards in this part of Europe.

Linking soil properties with overland flow

PCA analysis (Figure 4) confirmed already mentioned correlation between SOM, TN, AP, WSA, and MWD as SOM acts as a binding agent and a source of nutrients. In addition to confirming these correlations, the analysis also revealed a connection between the mentioned properties with the IR, PT, and RT. Higher MWD forms larger cavities between the aggregates, while higher WSA makes those aggregates more stable to the disaggregation under the influence of percolating water, thus reducing their slaking and blocking the mentioned cavities (Six et al., 2000, 2004). This combined effect can increase water infiltration. Increased IR has higher capabilities of transferring the water into the soil reducing its content on the surface, therefore, increasing both PT and RT. PCA also linked those properties with the GCV, highlighting this treatment as favourable in this study case (Figure 5). On the other hand, results of the same analysis confirmed already stated high correlation of the WR, SC, SL, C loss, P loss, and N loss. In addition to this, the analysis also indicated a correlation of the mentioned properties with the BD, SWC, and WHC. Higher BD and SWC were found to reduce PT and RT (Smith, 1972; Tofour et al., 2014), reduce IR (Tuffour et al., 2014), and with it increase SL (Biddoccu et al., 2017). The slope was found as an insignificant variable in this analysis due to no significant differences observed between the treatments. This analysis connected negative soil loss variables, higher BD, and SWC with the TV indicating tillage as a driver of the soil erosion in this study case.

CONCLUSION

Tillage in this study area was recognized as a key factor of lesser soil quality, deteriorated soil structure, and higher erodibility. The levels of soil and water losses in the tilled vineyards in Central Croatia are not sustainable, as a loss of 6866 kg/ha in 30 min during extreme storm events was calculated from the plot data on the ha scale. These high erosion rates exceed soil formation rates and are due to the lack of vegetation cover as a consequence of the tillage use in the poorly structured soils. However, grass-covering was shown capable of conserving soil physical state, increasing infiltration rate, and significantly decreasing water, soil, and nutrient losses while having no influence on the soil water content in the vineyards of Central Croatia as they suffer from intense rainfall events. Additionally, in this study area and period tillage did not significantly increase the soil water content which was the reasoning behind the tillage in the first place as a method of reducing water competition between cover crop and the young vines. Grass-covering of the vineyards on the slope is recognized as an appropriate form of soil management for sustainable vine production in this study area as it increases SOM, MWD, WSA, and TN while it reduces water, soil, and nutrients losses. Further monitoring of the endangered areas like vineyards in Croatia is crucial to mitigate losses of soils and enhance their sustainability with the proper form of soil management. The inclusion of biological parameters in soil erosion studies in future research could potentially explain the gaps in the understanding of soil erosion and it's effects on ecosystem stability.

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