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JAST

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In the Name of Allah

Dear colleague Dr. Bogunovic,

I am pleased to inform you that your manuscript entitled:

"The Spatiotemporal Variation of Soil Compaction by Tractor Traffic Passes in a Croatian Vineyard" by: I. Bogunovic, P. Pereira, I. Kisic, M. Birkás, J. Rodrigo-Comino

has been accepted as an article for the Journal of Agricultural Science and Technology. Your article will be published in Vol. 22, Issue1, January 2020.

Sincerely Yours,

K. Poustini
Editor-in-Chief

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The spatiotemporal variation of soil compaction by tractor traffic passes in a Croatian vineyard

ABSTRACT

Vineyards are intensively managed with machinery, leading to negative impacts on soil compaction and moisture, which can decrease grape productivity and quality. However, there is a lack of investigations at the pedon scale related to the spatio-temporal distribution of soil compaction in vineyards. The aim of the study was to quantify the impacts of tractor traffic passes on bulk density (BD) and soil water content (SWC), in a Croatian vineyard. Soil properties were measured at different depths (0-10, 10-20 and 20-30 cm), seasons (before, during and after summer), and at three different zones subject to different management actions: grass covered inter-row (GC), tilled inter-row (T) and tilled row (R). The main effects of tractor traffic passes were found at the 0-10 cm soil depth. Soil BD was significantly higher after summer than before and during summer. At 0-10 cm, SWC was significantly lower during summer than before and after. At 10-20 and 20-30 cm depths, SWC was higher in all zones, showing no significant differences between them at each depth. Significant positive correlations between BD and SWC were identified in the T zone after summer, although increased traffic decreased the SWC. Wheel traffic increased BD, which we can attribute to the high SWC. Nevertheless, this increase was agronomically not relevant. Such findings have to be applied in order to control soil compaction in vineyards through environmentally-friendly soil management practices.

Key words: bulk density; soil water content; soil management; wheel traffic; soil depth

1. INTRODUCTION

Unsustainable management practices are affecting soil quality, resulting in drastic land degradation processes (Bogunovic and Kisic, 2017; Khaledian *et al.*, 2017) and a decrease in soil quality leading to negative effects on food production and the environment (Durán Zuazo and Rodríguez Pleguezuelo, 2008). This occurs where soils are intensively used regardless of climate, parent material and soil type (Cerdà, 1999; Choudhury *et al.*, 2016).

In vineyards, the use of machinery is common where tillage, chemical protection and harvesting can be difficult to be conducted manually by farmers. However, wheel traffic reduces soil porosity, compacting soil and increasing water losses in the area under the wheel (Arnaez *et al.*, 2007). Wheel traffic also increases penetration resistance (Botta *et al.*, 2010), disturbs and changes soil structure (Nawaz *et al.*, 2013), modifies hydraulic conductivity and infiltration rate (Ozcan *et al.*, 2013; Chyba *et al.*, 2017), root development, air penetration and CO_2 liberation (Bogunovic *et al.*, 2017) and possibly plays an important role in soil fertility by affecting soil biology. A decrease in soil fertility can be related to the reduction of water storage capacity and available nutrient stocks (Ferrero *et al.*, 2005). Therefore, soil compaction in vineyards is a significant cause of soil degradation and loss of soil quality (Biddoccu *et al.*, 2016).

The variables that determine the degree of soil compaction due to traffic are vehicle axle load, tyre contact pressure, organic matter, soil structure, texture and soil water content (SWC) (Nawaz *et al.*, 2013). It has been shown that soil compaction in vineyard soils is more extensive under wet conditions compared to dry conditions (Hamza and Anderson, 2005; Biddoccu *et al.*, 2016).This negative impact can be greater when tractors are heavy (> 5 tonnes), although soil compaction was also identified using light tractors (< 5 tonnes) in other cropping systems (Botta *et al*., 2010; Håkansson, 2005).The main factor was the weight, the number of tractor passes and the time of tractor pass from last tillage intervention (Botta *et al*., 2006).

In humid-temperate and continental vineyards, such as in Croatia, there is a lack of information about the impact of multiple tractor passes on the spatiotemporal distribution of SWC and BD. Despite the relevance of the topic, few studies have been carried out about the effect of soil compaction on SWC and BD at different depths (e.g. van Dijck and van Asch, 2002; Cambi et al., 2015; Bogunovic *et al.*, 2017). The main aim of this research was to quantify the impacts of tractor traffic in different seasons at different soil depths and in different soil management zones on soil water content (SWC) and bulk density (BD), which are both influenced by soil compaction.

2. MATERIALS AND METHODS

2.1. STUDY AREA

The study area was located at the experimental station of Jazbina (45° 51' S 16° 0' E, 258 m a.s.l.) on the southern slopes of Mt. Medvednica (north west Croatia). The studied vineyard covers a total area of about 10 ha and it is oriented in a north east-south west direction. The average slope is 13%, with a minimum of 9% and a maximum of 18. The main parent material is composed of Pliocene and Pleistocene loess and the soils can be classified as *Anthrosols* created from *Stagnosols* (IUSS-WRB, 2014). Natural soil horizons were changed during the deep tillage (60 cm depth) and ameliorative fertilization that was performed prior to planting. Soil texture is silty clay loam, organic matter is very low (0.5%) and pH values are close to neutral (Table 1). The climate is temperate continental with an average annual rainfall of 852 mm (1961-1990; Meteorological and Hydrological Service of Croatia). Monthly and annual rainfall during 2014 was over 50% higher than the long term average monthly and annual rainfall (1961-1990) (Table 2). Mean annual temperature is 10.3 °C, ranging from 1.0 °C in January to 22 °C in July (1961-1990).

2.2. MANAGEMENT PRACTICES

Deep ploughing (60 cm) with intensive fertilization application was carried out before planting during 1996. This practice was followed by disking and manual planting. Annual regular soil management involved ripping and fertilization to 30 cm soil depth (Fig. 1a) of every second inter-row in the vineyard, followed by rotation digging to a depth of 25 cm (Fig. 1b). Non-tilled inter-rows were cover by grass, fertilized by mulching four to six times per season (from May to October). Cultivated and grass covered inter-rows were altered yearly. Between vines in the row, soil was cultivated to a depth of 10 cm and weeds were supressed by herbicides.

A Deutz-Fahr (Same Deutz-Fahr GR,Golden 65, Germany) tractor type (2640 kg), an manure spreader machine with ripper tines (Olmi, 120 R2, Italy) (120 kg), a harrower (Breviglieri - Agrimaster Group, MEKFARMER 80 Type 150, Italy) (495 kg), a mulcher (Berti macchine agricole, BF125, Italy) (325 kg) and Rotoripper (Olmi, Agrivitis PR 120, Italy) (170 kg) were used for soil management. A atomizer (Lochmman, APS 4/60 Q, Germany) with empty mass of 180 kg and capacity of 420 l was used for plant protection. The distance between rows of vines was 140 cm. The front and rear tractor tyre section widths were 24 and 32 cm, respectively, and the ground contact pressures of the tractor were 89.9 and 53.2 kPa in the front and the rear, respectively. Tyres were inflated to 220 kPa (front) and 200 kPa (rear). In a single pass, approximately 34% of the inter-row area was tracked by the front tyre and 46% by the rear tyre. Tillage and crop protection activities in 2014 are presented in Table 3.

2.3. EXPERIMENTAL SITE AND SAMPLING PROCEDURES

SWC and BD were measured in three different zones: tilled row (R), tilled inter-row (T) and grass covered inter-row (GC) (Fig. 1d). For each treatment, three replications were sampled. In each replication, four random points were selected and three samples per point were taken at different soil depths: 0-10 cm, 10-20 cm and 20-30 cm. In total, 36 random points were selected for sampling in each zone, before (May), during (August) and after (October) summer of 2014. At each point, samples were collected using 100 cm^3 cylinders. Overall, 324 samples were collected: 4 samples × 3 zones × 3 replicates × 3 depths × 3 sampling periods. Soil samples were oven dried at 105 ºC for 24 h to determine volumetric SWC and bulk density (BD) (Grossman and Reinsch, 2002).

2.4. STATISTICAL ANALYSIS

Prior to conducting the statistical analysis, data normality and homogeneity of the variances were tested using Shapiro Wilk and Leven's tests (Shapiro and Wilk, 1965). Data distribution and residuals did not follow a normal distribution and a homogeneity of the variances ($p>0.05$), even after logarithmic and Box-Cox transformations. Thus, statistical differences were calculated using the non-parametric test Kruskall-Wallis ANOVA (KW). If significant differences at $p< 0.05$ were observed, multiple comparison of mean ranks post-hoc test was applied. Correlations between SWC and BD were carried out using the non-parametric Spearman correlation coefficient. Significant correlations were considered at a $p<0.05$. Statistical analyses were performed using Statistica 7.0 software.

3. RESULTS

3.1. BULK DENSITY

Significant differences in BD were identified between zones at the same soil depth only for 0-10 and 10-20 cm depths. At 20-30 cm, no significant differences were identified (Table 4). At 0-10 cm of R zone, soil BD was significantly lower than in the T and GC zones. At 10-20 cm BD was significantly higher in GC than the other plots. Significant differences in BD values were identified at different depths in the same plot: R (KW=9.28, $p<0.01$), T (KW=8.26, $p<0.05$) and GC (KW=6.04, $p<0.05$). Significant differences were also observed between depths in all plots (KW=33.83, $p<0.001$). BD was significantly higher at 20-30 cm, than at other depths (Table 4). The comparison between seasons showed significant differences at the 0-10 cm depth. At 0-10 cm, BD was significantly higher after summer than before and during summer (Table 5). Significant differences were identified between depths before ($KW=20.21$, $p<0.001$) and during summer ($KW=24.26$, $p<0.001$). In these seasons, BD was significantly higher at 20-30 cm than at 10-20 and 0-10 cm.

3.2. SOIL WATER CONTENT

Significant differences in SWC were not identified between plots within the same soil layer (Table 6). However, significant differences were observed between depths in the same plot: R ($KW=9.28$, $p<0.01$), T ($KW=20.01$, $p<0.001$) and GC ($KW=31.23$, $p<0.001$). Significant differences were also identified between all depths ($KW=55.91$, $p<0.001$). The SWC was significantly higher at 20-30 cm than at 0-10 and 10-20 cm, considering each plot and all samples (Table 6). Significant differences were observed between all months at the same depth (Table 7). At 0-10 cm, before and after summer, SWC was significantly higher than during summer. At other soil depths, it was significantly higher before summer than during and after summer. The comparison between soil depths in the same season showed significant differences in all cases: before summer ($KW=40.12$, $p<0.001$), during summer ($KW=17.09$, $p<0.001$) and after summer ($KW=13.82$, $p<0.001$). SWC was significantly higher at 10-20 and 20-30 cm than at 0-10 cm (Table 7).

3.3. CORRELATION BETWEEN VARIABLES

The correlation between BD and SWC considering all soil samples is low but significant ($r=0.12$, $p<0.05$) (Table 8). A significant negative correlation was observed at 20-30 cm. Considering each treatment, the correlation between BD and SWC was positively significant in the T zone. Considering sampling dates, a significant positive correlation was identified only during summer (Table 8).

4. DISCUSSION

4.1. BULK DENSITY

Soil management influenced soil compaction. Bulk density was higher in GC than in T at 0-10 and 10-20 cm, confirming that tractor passes affected this soil property. Previous studies have also shown that non-tilled soils have a higher BD than tilled soils (Grant and Lafond, 1993; Osubitan *et al*., 2005). In the areas where the tractor drive (T and GC), BD was significantly higher. These results agreed with earlier studies, which observed that tractor traffic increases BD, mainly in the top 20 centimetres of soil (Cambi *et al*., 2015; Pagliai *et al*., 2003). At 20 - 30 cm depth, significant differences were not observed between treatments, showing that the impacts of traffic were absent. When vehicle loads are transmitted into the soil, the pressure is dispersed over the soil profile, reducing the impact per unit of soil (Ampoorter *et al*., 2012). Thus, it is noted that the loads exerted by this tractor were too low to affect BD at 20-30 cm depth (Grant and Lafond, 1993; van Dijck and van Asch, 2002).

Another relevant factor to be taken into account is soil texture (Håkansson and Lipiec, 2000). As Ellies Sch *et al*. (2000) showed, in soils with coarse texture, wheel loads generated a vertical preferential direction of pressure, while in soils with finer soil texture the propagation of the pressure was multidirectional. Soils with fine to medium texture demonstrate a higher vulnerability to compaction than sandy soils (Ampoorter *et al*., 2012), while soils rich in silt are more susceptible to compaction than sandy or clayed soils (Nawaz *et al*., 2013). Defossez *et al*. (2003) observed an increase of 0.3 Mg m^{-3} in BD in the first 10 cm of a Loess and Chalky silty soil. In present study area, the soils have a high silt content and are vulnerable to soil compaction. BD is also related with another important soil property, aggregate stability. Soils with poor structure and aggregation are extremely vulnerable to the impacts of wheel traffic (Nawaz et al., 2013), while susceptibility to compaction can be reduced with an increase in soil aggregation (Troldborg *et al*., 2013). Areas with a lack of vegetation cover, roots and, subsequently, low organic matter content, such as the T zone, show lower aggregate stability than zones like GC and R. Susceptibility to soil compaction may be also reduced by increased organic matter content (Lado *et al.*, 2004). Previous works also reported that microfauna, such as ants and earthworms, activity are able to reduce soil BD (Rogasik *et al*., 2014; Ferreira de Araujo *et al*., 2015). In present study area, in R areas, this activity was also observed. In Fig. 2, biota (ants) is acting as driving factor of BD decrease. Chemical properties, such as soil pH, also affect aggregate stability and, subsequently, BD (Jones *et al*., 2003). Previous work has shown that soil BD increases with soil pH and reduces with organic matter (Shrestha and Lal, 2011; Karami *et al*., 2012). Soils in present research have close to neutral pH values and a low organic matter content (Table 1). Therefore, it is likely that this soil has poor structure and low aggregate stability, increasing its vulnerability to wheel traffic compaction (Rubinić *et al*., 2014).

In relation to the temporal variations, soil compaction was significantly different between soil depths before summer and during summer. In October, after summer, BD was similar at all depths, but higher than the other seasons. The main influence of this temporal difference may be related to traffic frequency in the studied vineyard.

From an agronomic point of view, other authors suggest that despite the fact that the major impact of wheel traffic is produced in the first passage (Nawaz *et al*., 2013), increasing the number of passes will continue to increase soil compaction (Cambi *et al*., 2015). Repetitive tractor passes over the same track apply additional stress (Botta *et al*., 2012). This was demonstrated by Pagliai *et al*. (2003), who observed an increase of BD after four tractor passes in control and tilled plots. Botta *et al*. (2006) also identified an increase in soil compaction with the number of tractor passes in the same track using a light tractor.

4.2. SOIL WATER CONTENT

There were no differences in SWC between the different treatments at the studied depths. This suggests that SWC was affected by the weather, rather than traffic or tillage management. Previous studies also show that tractor passes did not affect SWC, as Cambi *et al*. (2015) observed no significant differences in SWC between wheeled soils with respect to the control. Holloway and Dexter (1990) identified similar values between control and wheel traffic affected soils.

However, significant differences between soil depths in all zones were determined. The 20-30 cm depth had higher SWC than the shallower depths. This was also previously reported by other authors, such as Berisso *et al*. (2012), who identified an increase of SWC with depth, whether the soil was compacted or not. Further, Holloway and Dexter (1990), found SWC increased with depth in virgin and cultivated soil.

At each depth, SWC was significantly different between months. At 0-10 cm depth SWC was significantly higher before and after summer than during summer. At the other two depths, SWC before summer was significantly higher than in other seasons. Rainfall was higher before and after summer (Table 2), which may explain the increase of SWC during these seasons at 0-10 cm depth. It is well-known that air temperature and precipitation variability mostly affect the upper soil depths (Mahmood *et al*., 2012). However, we can hypothesize that the similar values obtained in summer and after summer (despite the rainfall) can be attributed to the number of tractor passes. As mentioned above, soil compaction increases with the number of tractor passes, especially at the soil surface. This increase of soil compaction after summer may have reduced the hydraulic conductivity. As other authors observed, water infiltration and permeability are reduced by soil compaction (Nawaz *et al*., 2013; Rodrigo-Comino *et al.*, 2017) and the high BD at 0-10 cm depth observed after summer may have reduced the water content of soil at 20-30 cm depth. After successive tractor passes, very few flow paths remain from the top to the lower soil depths (Kulli *et al*., 2003), reducing infiltration. The successive tractor passes in the studied vineyard may have destroyed this connection, reducing water movement at greater depths and enhancing water retention at the soil surface. Soil hydraulic conductivity can be also reduced with the increasing of vehicle passes (Pagliai *et al*., 2003).

4.3. LINKS BETWEEN SOIL WATER CONTENT AND BULK DENSITY

Soil compaction will increase with SWC, up to a certain level called the critical water content (around 12%), above which the increase in SWC reduces soil compaction, since the soil becomes more plastic and difficult to be deformed by vehicle traffic (Hamza and Anderson, 2005; Ampoorter *et al.,* 2012). When SWC is very high, BD can increase only if water is extracted, which is more difficult than removing the air (Logsdon and Karlen, 2004). At all depths and in the studied seasons, SWC was always higher than the critical level (12 %) (Hamza and Anderson, 2005), showing a higher resistance to soil compaction. According to Froehlich and McNabb (1994) in soils with medium to fine texture, the pore volume is mainly composed of meso- and micro-pores that can easily resist mechanical pressures. When these types of soils are saturated, they cannot be compressed. At this SWC level, the impacts of traffic are reduced in BD, but others continue to occur such as rutting and smearing. As a consequence of the relationship between the degree of compaction and SWC, small differences in compaction in different treatments may be expected when SWC is high (Ampoorter *et al.*, 2012). This may explain the small differences in soil BD between treatments and sampling dates (despite the significant differences observed) in this vineyard´s soils.

A positive significant correlation between SWC and BD was observed in all samples. Nevertheless, this correlation was very low, and this significance is attributed to the high number of samples. However, while observing the correlation between these variables, a different trend was observed in this study. The high SWC impacts on BD, which may explain the significant negative correlation observed at the 20-30 cm depth. On the other hand, significant positive correlations were observed in the T zones during summer. It is hypothesized that the type of management and the season affects the relationships between SWC and BD. In addition, other variables not considered in this work, such as organic matter, cation exchange capacity or pH, may have an influence. Further research is needed to clarify this.

5. CONCLUSION

Light tractor traffic increased soil BD at 0-10 and 10-20 cm. During the study period, tractor passes did not significantly affect soil BD at 20-30 cm depth. SWC was not significantly different between the zones at any depth, apart from at 20-30 cm depth where SWC was higher.

Soil BD between sampling periods was significantly different at 0-10 cm depth. It was significantly higher after summer, but no differences were identified at other depths. SWC was higher before and after summer than during this season at 0-10 cm depth. On the other, from 20 - 30 cm, SWC was higher before summer than in other sampling periods. A significant positive correlation between BD and SWC was recorded for the T zone during summer, in all samples. Wheel traffic did not substantially increase BD, which we can attribute to the high levels of SWC. Change in BD with higher SWC was very low. Further research will be focused on the identification of variables that can explain the spatiotemporal dynamic of soil compaction, such as pH, soil structure and organic matter in order to have a better understanding of the variables that can be used to control soil compaction in vineyards.

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Table 1. Soil properties of the Anthrosols (IUSS-WRB, 2014) in the study area

Depth (mm)	0 - 600	600 - 1100	1100 – 1600	> 1600
Horizons	Ap	Btg	Cg	Cg2
Colour	10YR 4/3	10YR 4/3	10YR 5/4	10YR 5/4
OM (g kg^{-1})	5.34	2.36	4.10	3.15
pH in H_20 (w w^{-1} 1:5)	6.67	5.88	6.23	7.20
EC (µs cm^{-1})	54	75	60	68
CEC ($cmol_{(+)}kg^{-1}$)	18.3	21.2	21.6	16.0
Ca_{ex} ($cmol_{(+)}kg^{-1}$)	12.1	11.9	10.1	8.12
Mg_{ex} ($cmol_{(+)}kg^{-1}$)	4.86	8.12	10.4	6.35
P_2O_5 (g kg^{-1})	36.8	19.7	15.7	21.7
K_2O (g kg^{-1})	180	174	112	79.1
Clay (g kg^{-1})	320	410	360	290
Fine silt (g kg^{-1})	350	270	300	330
Coarse silt (g kg^{-1})	270	270	290	270
Fine sand (g kg^{-1})	20	20	30	50
Coarse sand (g kg^{-1})	40	30	20	60

OM: Organic matter; EC: Electrical conductivity; CEC: Cation exchange capacity; Ca_{ex}: exchangeable calcium; Mg_{ex}: exchangeable calcium; P_2O_5: plant available phosphorus ; K_2O: plant available potassium

Table 2. Comparison between the monthly rainfall and temperature in 2014 and the average monthly rainfall and temperature (1961-1990).

	2014		1961-1990	
	mm	°C	mm	°C
January	58	1	46	0.5
February	141	3.1	42	2.2
March	21	7.2	56	6.8
April	70	12	64	11.4
May	145	17	79	16.5
June	147	20	100	19.6
July	158	22	83	21.5
August	115	21	95	19.3
September	179	16	79	16.3
October	128	12	69	11.3
November	85	6.4	81	5.8
December	71	1.4	58	1.6
Total	1318	12	852	10.3

Table 3. Chronology of agro-technical activities during the research period

Activity	R	T	GC
Fertilization	-	April 2	April (2)
Chemical protection	April 4	April 4	April 4
Ripping+rotation digging	-	April 15	-
Chemical protection	May 6	May 6	May 6
Row harrowing	May 14	-	-
Mulching	-	-	May 20
Herbicide application	May 20	-	-
Chemical protection	May 27 June 16 July 2 July 14 August 8	May 27 June 16 July 2 July 14 August 8	May 27 June 16 July 2 July 14 August 8
Vintage	September 19	September 19	September 19

*R: tilled row; T: tilled inter-row; GC: grass covered inter-row.

Table 4. Statistical comparisons of bulk density (BD) values between different treatments at the same soil depth (upper case), between the same positions at different depths (lower case) and between all treatments at different depths (upper case in bold).

Depth (cm)	Position	Mean	Min	Max	SD	KW
0-10	R	1.45Cb	1.29	1.59	0.07	16.11, p<0.001
	T	1.51Bb	1.35	1.65	0.08	
	GC	1.53Ab	1.36	1.73	0.09	
	All	1.53**B**	1.29	1.73	0.08	
10-20	R	1.49Bb	1.29	1.66	0.08	9.93, p<0.01
	T	1.52Bb	1.30	1.63	0.08	
	GC	1.54Ab	1.37	1.60	0.07	
	All	1.52**B**	1.29	1.66	0.08	
20-30	R	1.53Aa	1.13	1.67	0.10	n.s
	T	1.56Aa	1.42	1.66	0.05	
	GC	1.57Aa	1.38	1.70	0.06	
	All	1.55**A**	1.14	1.70	0.07	

*Different letters represent significant differences ($p< 0.05$). n.s (not significant). Data in Mg m^{-3}; R: tilled row; T: tilled inter-row; GC: Grass covered inter-row.

Table 5. Statistical comparisons of bulk density (BD) values between different months at the same soil depth (upper case) and between the same months at different depths (lower case).

Depth (cm)	Month	Mean	Min	Max	SD	KW
0-10	Before summer	1.48Bb	1.36	1.59	0.06	15.87, p<0.001
	During summer	1.47Bb	1.29	1.64	0.07	
	After summer	1.54Aa	1.31	1.72	0.09	
10-20	Before summer	1.51Ab	1.35	1.62	0.07	n.s
	During summer	1.51Ab	1.30	1.66	0.09	
	After summer	1.55Aa	1.29	1.66	0.07	
20-30	Before summer	1.56Aa	1.38	1.67	0.06	n.s
	During summer	1.56Aa	1.31	1.70	0.07	
	After summer	1.55Aa	1.14	1.66	0.09	

*Different letters represent significant differences at a $p< 0.05$. n.s (not significant at a $p< 0.05$). Data in Mg m^{-3}.

Table 6. Statistical comparisons of soil water content (SWC) between different treatments at the same soil depth (upper case), between the same treatments at different depths (lower case) and between all treatments at different depths (upper case in bold).

Depth (cm)	Position	Mean	Min	Max	SD	KW
0-10	R	35.4Ab	26.6	44.4	3.7	n.s
	T	33.9Ac	26.9	38.6	2.9	
	GC	34.3Ab	21.5	38.9	2.9	
	All	34.6**C**	21.5	44.4	3.2	
10-20	R	37.1Ab	29.9	56.0	4.3	n.s
	T	36.1Ab	29.4	41.3	2.6	
	GC	36.7Aa	26.5	42.4	3.0	
	All	36.6**B**	26.5	56.0	3.4	
20-30	R	37.7Aa	29.5	44.0	2.6	n.s
	T	37.0Aa	29.7	42.9	2.6	
	GC	37.9Aa	33.3	44.7	2.3	
	All	37.5**A**	29.5	44.7	2.5	

*Different letters represent significant differences ($p< 0.05$), n.s (not significant). Data in %; R: tilled row; T: tilled inter-row; GC: grass cover inter-row.

Table 7. Statistical comparisons of soil water content (SWC) between the different months at the same soil depth (upper cases) and between the same months at different depths (lower cases).

Depth (cm)	Month	Mean	Min	Max	SD	KW
0-10	Before summer	35.0Ab	26.6	38.9	3.0	11.56 p<0.01
	During summer	33.1Bb	21.5	37.6	3.9	
	After summer	35.6Ab	33.0	37.3	1.9	
10-20	Before summer	38.1Aa	28.7	42.4	2.5	29.10, p<0.0001
	During summer	35.2Ba	26.5	56.0	4.5	
	After summer	36.6Bab	31.5	40.5	1.9	
20-30	Before summer	39.1Aa	29.5	44.7	2.4	29.81, p<0.0001
	During summer	36.4Ba	29.7	44.0	2.6	
	After summer	37.2Ba	35.1	41.0	1.7	

*Different letters represent significant differences at a p< 0.05. Data in %.

Table 8. Correlations between bulk density (BD) and soil water content (SWC)

All data r=0.12, p<0.05		
Soil depth		
0-10 cm	10-20 cm	20-30 cm
r=0.11, n.s.	r=0.11, n.s.	r=-0.21, p<0.05
Inter-row and row positions		
R	T	GC
r=0.16, n.s.	r=0.34, p<0.001	r=-0.05, n.s.
Different seasons		
Before summer	During summer	After summer
r=0.14, n.s.	r=0.24, p<0.01	r=-0.18, n.s.

n.s.: No significant; R: tilled row; T: tilled inter-row; GC: grass cover inter-row.

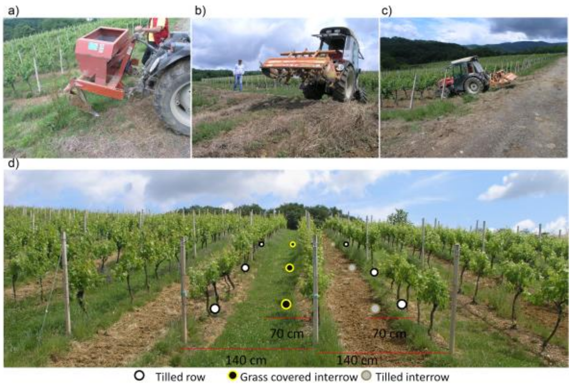

Fig. 1.Tools used for soil management: a) ripper (Olmi, 120 R2, Italy), b) rotation digging (Olmi, Agrivitis PR 120, Italy), c) tillage, d) sampling scheme