Permanent cover for soil and water conservation in mechanized vineyards: A study case in Piedmont, NW Italy

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Abstract

Vineyards' soils are especially threatened by the risk of soil compaction and soil erosion, with negative consequences for wine production and provisioning of ecosystem services. The adopted inter-rows soil management influences the response of vineyard to different types of rainfall events, in terms of runoff and soil erosion. Actually, the use of cover crops in vineyards is widely considered as an effective measure for conservation of water and soil. A 3-years study was carried out in Piedmont (NW Italy) to evaluate the effectiveness of grass cover as a soil water conservation measure, compared with tillage, and particularly the influence of different types of rainfall events and tractor traffic in determining hydrological and erosive response of the vineyard. During the investigation period (November 2016 - December 2019), climate variables, runoff, and soil losses were continuously monitored along with vineyard management operations. Very different yearly precipitation characterized the observed period, including the driest and wettest year in the last 20 years. Runoff and soil erosion caused by different types of rainfall events (long-lasting, intense and normal) in two vineyard's plots managed with permanent grass cover and tillage, respectively, have been compared. In addition, the influence of the number of tractor traffic was taken into account. Runoff volume was principally affected by soil management, while sediment yield was influenced by the type of event. Both were higher in the tilled plot than in the grassed one, for all types of events, even if differences were not always significant. Grass cover reduced by 65% the runoff, with the highest efficiency during intense events. Soil losses were reduced on average by 72%, with 74% efficiency during the most erosive intense events and the lowest protection (56%) during long-lasting rainfall. Moreover, the response of grass cover plot was less influenced by traffication. The study demonstrates the efficiency of grass cover in reducing water and soil losses also during extreme events, that are predicted to be more frequent in the climate change scenario.

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Introduction

Viticulture is one of the most diffused cultivations in the world and has been practised in the Mediterranean area for millennia (Corti *et al*., 2011). Nowadays, France, Spain, and Italy represent the three European countries with the largest surface covered by vineyard cultivation, covering together 33% of the world vineyard area (OIV, 2019). The provision of ecosystem services, defined as '*the resources or processes of natural (or anthropized) ecosystems that benefit human beings*' (Millennium Ecosystem Assessment, 2005), are increasingly relevant in the definition of agricultural policies and for the Millennium Development Goals (FAO, 2020). Vineyard agricultural system is potentially well suited in Mediterranean conditions for delivering not only provisioning services such as grapes for table or wine production, but also others related to the regulation of climate and hydrologic cycle (*e.g*., Aguilera *et al*., 2013) or cultural ones such as landscape and aesthetic values (Foronda-Robles, 2018). However, in the current situation winegrowing is frequently associated with some negative impacts on the ecosystem. Soil erosion and soil compaction have been identified as two of the major threats that affect worldwide agricultural soils by the Soil Thematic Strategy from the European 45 Union (CEC, 2006a, 2006b) and the FAO Status of the World's Soil Resources (FAO and ITPS, 2015). Vineyards are one of the most intensively managed agroecosystems, typically involving numerous pesticide applications, soil tillage operations and landscape modifications (Nicholls *et al*., 2008). Multiple tractor passages on fixed paths in the inter-rows are required every year for the vines' management, and this traffic sometimes occurs on wet soil conditions, increasing the risk of soil compaction in most of the vineyard surface (Hamza and Anderson, 2005; Lagacherie *et al*., 2006). Soil compaction intensity also depends on current and past soil management of the field and it has a negative effect on soil physical fertility, soil organic carbon stock, and soil biodiversity. Furthermore, it results in the reduction of soil porosity, water infiltration capacity, and increased runoff, with a decrease of storage and supply of water in the soil (Ferrero *et al*., 2005; Hamza and Anderson, 2005; Biddoccu *et al*., 2017; Spinelli *et al*., 2019). Such degradation of soil quality may bring serious problems for wine production as soil represents a key component of the concept

of terroir (van Leeuwen *et al*., 2004). Vineyards and other permanent crops show the highest soil erosion rate among agricultural land uses (9.47 Mg ha^{-1}), accounting for 10% of the total soil losses in the European Union (Panagos *et al*., 2015b). The use of cover crops in vineyard is widely considered as an effective agricultural conservation measure, providing various ecosystem services such as reduction of runoff and erosion processes, increasing of soil organic matter, weed control, pest and disease regulation, water supply, water purification, improvement of field trafficability, and maintenance of soil biodiversity (Garcia *et al*., 2018; Winter *et al*., 2018; Guzman *et al*., 2019).

In NW Italy, Piedmont is a long established and specialized vine-growing region and produces some of the best-known, top quality Italian wines, with 17 DOCG (Denomination of Controlled and Guaranteed Origin) and 42 DOC (Denomination of Controlled Origin) wines. In 2014 *The Vineyard Landscape of Piedmont: Langhe, Roero and Monferrato* was recognized as an UNESCO World Heritage Site for the outstanding landscapes and the importance of vine-growing and winemaking in the Region (UNESCO, 2020). More than 95% of the vineyards of the region (that covers nearly 41 400 ha) are located on hills, whose soils are mainly characterized by moderately high or high erodibility (Regione Piemonte, 2015). In the 1980s, Tropeano (1984) ran the first soil erosion measurements in vineyards for about two years, measuring soil losses up to 47.4 Mg ha^{-1} in a deeply ploughed vineyard located in the Monferrato area.

In the last decade, grass cover in vineyards has been comprised in the most relevant European policies for soil conservation, including the Standards of Good Agricultural and Environmental Condition (GAEC), established by Council Regulation No. 73/2009 (CEC, 2009). A recent analysis included in the Impact Assessment of the post 2020 Common Agricultural Policy (European Commission, CAP 2021-2027, 2018) estimated the impact of cover crops on soil erosion reduction in permanent crops by up to 37%. However, associating cover crops with grapevines may also generate competition for nutrients and water, depending on local soil and climate conditions (Celette *et al*., 2008; Ruiz-Colmenero *et al*., 2013). The challenge of climate change, with models predicting for the Mediterranean region scenarios of increasing temperature combined with more extreme events such as droughts and storms (IPCC, 2014), increases the importance of addressing the environmental and economic sustainability of this relevant agro-ecosystem.

In Europe, in more humid climate conditions, permanent grass cover is commonly implemented, but in semi-arid Mediterranean regions wine growers are reluctant to use permanent cover crops due to concerns over soil water competition. In Piedmont, since 2007, the Rural Development program supports the use of grass cover in the inter-rows to prevent soil erosion and improve soil organic content, involving 15.4% of the regional agricultural area utilized for orchards and vineyards in the period 2007-2013 (Regione Piemonte, 2013). Nevertheless, given the observed and predicted warming temperatures and extreme events (droughts on one side and heavy precipitation on the other), more attention should be paid in viticulture to the risks related to soil degradation and water scarcity, even in regions like Piedmont where vineyards are traditionally rainfed. In this perspective, it is crucial to know the response of vineyard soil to rainfall events, in terms of water and soil losses, in order to adopt the best management to conserve these fundamental resources maintaining vineyard productivity. This paper presents the results of an experimentation run in the Piedmont Region during three-years characterized by contrasting meteorological conditions. Climate variables, runoff, soil losses, and soil water content were monitored along with vineyard management operations, in order to evaluate: i) the effectiveness of grass cover as a soil water conservation measure compared with tillage; ii) the influence of different types of rainfall events; and iii) the effect of tractor traffic in determining hydrological and erosive response of the vineyard.

Materials and methods

Study site

This study presents data collected for three years, from autumn 2016 to winter 2019, at the '*Tenuta Cannona Experimental Vine and Wine Centre of Agrion Foundation*', which is located at 296 m above sea level (a.s.l.) in the Alto Monferrato hilly area of Piedmont, North-West Italy. The study site lies on Pleistocenic fluvial terraces in the Tertiary Piedmont Basin, including highly altered gravel, sand and silty-clay deposits with red alteration products (Servizio Geologico d'Italia, 1969). The soil is characterized by a clay to clay-loam texture and is classified as fine-loamy, mixed, calcareous, mesic, Typic Ustorthents (Soil Survey Staff, 2010) or Dystric Cambisols (FAO/ISRIC/ISSS, 1998). The climate of the area is sub-litoranean: the nearest long period weather station (Ovada, 187 m a.s.l.) recorded a mean annual precipitation (MAP) of 965 mm over the period 1951-1990 (Biancotti *et al*., 1998), while the MAP measured in the period 2000-2019 in the study site is 881 mm, ranging from a maximum of 1455 mm (year 2019) to a minimum of 493 mm (year 2017). The annual mean air temperature in the same period was 13°C. About 40% of the annual precipitation occurs in autumn: rainfall events are mainly concentrated in October and November, when major runoff events usually occur (Biddoccu *et al*., 2016), and, secondarily, in March. The driest season is summer (12% of annual precipitation) and particularly July.

The 3-years experiment was carried out in a vineyard planted in 1988 with Barbera vines managed according to conventional farming for wine production. Two vineyard plots of 1221 m^2 (16.5 m wide and 74 m long) each were considered. Each plot was composed of 6 rows aligned along the slope (SE aspect, average slope 15%), spaced 2.75 m, where the vines are spaced 1.0 m along the row. Since 2000 the soil of the two plots has been managed with different techniques: conventional tillage (CT, hereafter) cultivation with chisel (at a depth of about 0.25 m) and controlled grass (GC) mulching of the spontaneous grass cover. Both practices were usually carried out twice a year, in spring and autumn. Most of the farming operations in the vineyard were carried out using tracked or tyred tractors carrying or towing implements, with intensification of passages from spring to grape harvest time (from 14 to 27 passages per year). According to Capello *et al*. (2019a), the average annual soil loss measured in the 2000-2016 period was 6.6 Mg ha^{-1} and 1.5 Mg ha^{-1} in CT and GC, respectively; the mean annual runoff coefficient measured in the same period was 21 % in CT and 11 % in GC.

Measurements

From September 2016 to December 2019, rainfall and runoff amounts, soil losses, and hourly soil water content related to 89 runoff events were recorded for the two plots. Rainfall was recorded at 10-min intervals by a rain-gauge station, with 0.2 mm resolution, placed near the plots (see Biddoccu *et al*., 2016 for details).

Each vineyard plot was hydraulically '*isolated*' and runoff generated by rainfall was collected separately for each plot by a channel connected with a sedimentation trap and then a tipping bucket

device, which measured the hourly volumes of runoff (RO, mm) in both CT and GC. Runoff samples were collected to obtain sediment concentration for erosive events, and, if sedimentation occurred in the channels and sediment trap, then the sediment yield was collected and weighted.

Soil water content was recorded every hour from the average of 1-min by indirect method (Raffelli *et al*., 2017) measurements of capacitance/frequency domain sensors (ECH_2O-5TM sensors, Decagon Devices Inc., Pullman, WA, USA), gravimetrically calibrated, placed at 0.1, 0.2, and 0.3 m depth, and stored by a Decagon EM50 Datalogger.

Measurements were carried out in the two plots both in the track position (T), which is the portion of inter-row affected by the passage of tractor wheels or tracks, where the compressive effects tend to concentrate (Sohne, 1953), and in the middle of the inter-row, identified as the no-track position (NT), which is not affected by direct contact with tractor wheels or tracks. Thus, measurements were carried out in four positions: CT-T and CT-NT in the tilled plot, and GC-T and GC-NT, in the grassed plot.

Dates of tractors passages and field operations (*e.g*., tillage) were recorded.

Data analysis

Data collected by monitoring stations during the 2016-2019 period were processed and some derived parameters were calculated. All rainfall events recorded were checked and only events with runoff higher than 0.03 mm in at least one of the two plots or, according to the RUSLE procedure, with cumulative rainfall higher than 12.7 mm, were selected and considered as significant for this study. Soil-loss and runoff produced by snowfall melting event were not included in the analysis, because of the different relationships between precipitation characteristics of such events and the generation of runoff and erosion processes (Renard *et al*., 1997). Following these criteria, 60 events were considered. Based on the records, RIST (Rainfall Intensity Summarization Tool, ARS-USDA, 2015) was used to obtain the precipitation depth (P, mm), event duration (D, hrs), rainfall maximum intensity over a 30-min period (Imax30, mm h^{-1}), mean precipitation intensity (Imed, mm h^{-1}), precipitation energy (E, based on the equation proposed by Brown and Foster, 1987), and the event erosivity index (EI30, MJ mm ha^{-1} h^{-1}, Renard *et al*., 1997) for each precipitation event. Rainfall events were defined as the time between the initiation and cessation of rainfall or runoff with a lack of both of them for at least 12 h. Runoff coefficient (RC, %) indicates RO depth divided by P depth. Total soil loss (SL, kg ha^{-1}) related to each erosive event was calculated as sediment concentration multiplied by the runoff volume and added to the weight of deposited sediments.

Soil water content (SWC) was calculated as the mean of the value measured in the 24 h antecedent the event in both the plots at –10 cm depth.

Classification of rainfall events

According to explored literature, there are no univocal references to classify rainfall events (Sansom and Thomson, 1992; Gaál *et al*., 2014; Panagos *et al*., 2015a; Dolšak *et al*., 2016; Li *et al*., 2016; World Meteorological Organization, 2016). The events taken into consideration have been classified according to rainfall event characteristics following the method proposed by Bagagiolo *et al*. (2018) into three main types: '*long-lasting*' (D>50 h), '*intense*' (Imax30>16 mm h^{-1}) and normal (other events). One exceptional event of nearly 500 mm rainfall begun on November 14, 2019 and finished on December 10, 2019. It has been classified separately as '*extreme*'. Four events matching both the criteria D (>50 h) and Imax30 (>16 mm h^{-1}) were classified in types closer as features.

Considering the number of tractor passages that have been carried out since the execution of the tillage, the events have been classified as occurring on compacted (Comp, 3 or more passages) or not compacted (NComp, less than 3 passages) soil conditions.

Statistical analysis

Rainfall, runoff and soil erosion variables at event scale were averaged and summarized for each type of event. Data were checked for normality using the Shapiro-Wilk test and since normality test failed, statistical differences between treatments (GC and CT) or between types of event (for each plot) were checked using the Kruskall-Wallis rank sum test. The same test was used to investigate differences between events occurred on compacted or not-compacted soil. The elected significance level for all tests was $\alpha < 0.05$. Statistical analyses were computed using R (R Core Team, 2020).

Results and discussion

Considering the last 20 years, 2017 was the least rainy (56% MAP) and, in particular, summer was very dry. As a consequence of very low precipitations, runoff was lower than 1% of precipitations and soil loss was only 4.1 and 0.4 kg ha^{-1} in CT and GC, respectively. Sediment yield was less than 0.1% of the average annual soil loss measured in the 2000-2016. On the opposite, 2019 was the rainiest year (165% MAP): over 1000 mm of rainfall - more than the MAP - was concentrated in October, November, and December. These three months accumulated more than 99.5% of the annual runoff, in both CT and GC. Yearly RC was equal to 37.3% in CT and 17.9% in GC, higher than the average annual runoff coefficient measured in the 2000-2016 period (21 and 11% in CT and GC, respectively, according to Capello *et al*., 2019a) and it was the highest of the last 5 years. SL values of November and December are not available yet, but in October the highest monthly value of the investigated period was recorded.

However, precipitations in 2018, as well as at the end of 2016, were similar to the mean annual rain distribution, with only July and October that present P and SL higher than the mean. Nevertheless, yearly RC (11.6 and 2.6% in CT and GC, respectively) were lower than expected in 2018. Net of the last months of 2019 missing data, SL was the highest of the last 5 years (3.2 and 0.5 Mg ha^{-1} in CT and GC, respectively), but lower than the yearly average.

Despite the high precipitation amount recorded during two years, the total amount of RO and SL are lower than long-term average observed in the monitored site: during the study period, nearly 5 Mg ha^{-1} of soil was lost in CT and 1.4 in GC, corresponding to annual average soil losses lower or closer to the upper limit of the tolerable soil erosion rates (1.4 Mg ha^{-1} $year^{-1}$) proposed for Europe by Verheijen *et al*. (2009). As observed by Rodrigo-Comino *et al*. (2018), as the vineyard gets old, the measured erosion rates gradually decrease, since the highest sediment loss usually occurs in the first years after plantation. In form of runoff, 685 and 293 mm of rainfall were lost by runoff in CT and GC, respectively, which represent portions of water not available for the vine need during growing season or for soil water recharge in winter (Celette *et al*., 2009).

Rainfall events characteristics

Table 1 shows the mean values for the main characteristics of the selected rainfall events: 29 events have been classified as normal (48% of the total), 15 as long-lasting, and 15 as intense. The total precipitation considered in the 3 years was 3093 mm: 790 mm (25%) accounting for normal events, 984 mm (32%) for long-lasting, 834 mm (27%) for intense, and 482 mm concentrated in a single extreme event. Mean rainfall depth in normal events (27.3 mm) is lower than the mean of all events (44.2 mm), and it is about half of the P mean of long-lasting and intense events (65.6 and 55.6 mm respectively). All long-lasting events occurred in late autumn and winter, on the contrary, intense events occurred from spring to early autumn. Mean duration of events ranges from 22.5 h (intense events) to 82.0 h (long-lasting events). The longest event is the '*extreme*', which lasted more than 240 h. The highest Imax30 mean is in the intense class (29.6 mm h^{-1}) as well as the Imed (4.0 mm h^{-1}), the lowest mean Imax30 is in the normal class (7.6 mm h^{-1}) while the lowest Imed is in the long-lasting class (0.8 mm h^{-1}). The highest Imax30 (71.4 mm h^{-1}) and Imed (20.7 mm h^{-1}) were recorded during two different intense summer storms in 2018. The mean rainfall energy (E) and the mean erosivity of rainfall events (EI30) are the highest for intense (10.1 MJ ha^{-1} and 424.5 MJ mm ha^{-1} h^{-1}, respectively) and long-lasting (8.7 MJ ha^{-1} and 178.2 MJ mm ha^{-1} h^{-1}, respectively) events. The overall mean EI30 (175.6 MJ mm ha^{-1} h^{-1}) is very close to the long-lasting one (178.2 MJ mm ha^{-1} h^{-1}). The extreme event occurred in 2019 autumn shows the highest value in absolute for E (64.2 MJ ha^{-1}), but another intense event, happened in the same period, recorded the highest EI30 (near 2200 MJ mm ha^{-1} h^{-1}). The average values of the main characteristics of the selected rainfall events were in the range of those obtained in the same site from 2000 to 2014 (Bagagiolo *et al*., 2018). In other studies, in the Mediterranean area, Imed and Imax30 varied in the intervals 3.6-9.3 and 7.0-26.7 mm h^{-1}, respectively (Raclot *et al*., 2009; Taguas *et al*., 2010; Corti *et al*., 2011). Gómez *et al*. (2014), over a 5 years period of observations in Spain, obtained high coefficients of variations comparable to ours, being the variability at event scale notably larger than the one observed at annual scale.

Runoff and soil losses for different types of rainfall events

Results related to mean values in terms of runoff and soil losses in the two plots are summarized in Table 2. During the study period, 49 events generated runoff higher than 0.03 mm in at least one of the two plots, and 21 rainfall events generated soil loss. The overall mean runoff and soil losses in GC are lower than in CT (3.7 and 3.5 times, respectively). Furthermore, in 90% of the overall runoff and 100% of the overall soil losses events, volumes are lower in GC than in CT. In spite of this, a statistically significant difference ($P<0.05$) between the two plots is detected only for RC. Overall mean RO and SL of the selected events are lower than expected, similarly to the annual average, also if some single events have given values

Table 1. Summary of mean values and coefficient of variation of rainfall variables at event scale in the study site.

Type	No.		P (mm)	D (h)	Imed (mm h^{-1})	Imax30 (mm h^{-1})	E (MJ ha^{-1})	EI30 (MJ mm ha^{-1} h^{-1})
All events	60	Mean	51.6	42.8	1.8	13.6	7.4	175.6
		CV	139%	93%	156%	104%	150%	252%
Normal	29	Mean	27.3	26.3	1.2	7.6	3.3	26.1
		CV	58%	48%	56%	50%	59%	75%
Long-lasting	15	Mean	65.6	82.0	0.8	9.3	8.7	178.2
		CV	82%	43%	72%	124%	121%	283%
Intense	15	Mean	55.6	22.5	4.0	29.6	10.1	424.5
		CV	95%	100%	117%	60%	107%	156%
Extreme	1		485.2	240.3	2.0	14.0	64.2	737.3

No., number of events; P, rainfall depth (mm); D, rainfall duration (hrs); Imed, medium rainfall intensity (mm h^{-1}); Imax30, maximum rainfall intensity over a 30-min period (mm h^{-1}); E, rainfall energy; EI30, rainfall erosivity (MJ mm ha^{-1} h^{-1}).

Table 2. Summary of mean values and coefficient of variation at event scale of runoff, runoff coefficient and soil loss variables at the experimental site. Extreme event is not considered in all events.

Type	No.		CT				GC				
			n RO	RO (mm)	RC	n SL	SL (Mg ha^{-1})	n RO	RO (mm)	RC	n SL	SL (Mg ha^{-1})
All	59	Mean	47	4.32	5.6%*	21	0.08220	41	1.50	1.5%*	20	0.02338
		CV		244%	190%		392%		328%	222%		400%
Normal	29	Mean	20	1.26	3.2%*^{a}	5	0.00172^{a}	18	0.45	0.9%*^{a}	5	0.00016^{a}
		CV		255%	188%		490%		338%	246%		453%
Long-lasting	15	Mean	12	10.01	11.8%^{a}	7	0.05396^{b}	11	3.60	3.1%^{a}	7	0.02378^{b}
		CV		165%	150%		327%		246%	174%		373%
Intense	15	Mean	15	4.84	4.4%*^{a}	9	0.27151^{b}	12	1.53	1.2%*^{a}	8	0.06943^{b}
		CV		226%	132%		219%		221%	162%		230%
Extreme	1		1	427.95	88.2%	1	NA	1	205.98	42.5%	1	NA

CT, conventional tillage; GC, controlled grass; No., number of events; n RO, number of events generating runoff higher than 0.03 mm; RO, runoff depth (mm); RC, runoff coefficient; n SL, number of events generating soil loss; SL, soil loss (Mg ha^{-1}). *Significant differences between treatments (CT and GC); ^{a,b} different letters in the same column indicate significant differences between event types, according to Kruskal-Wallis Test at P=0.05 level.

which are higher than the 20-years mean.

The difference between treatments is statistically significant ($P<0.05$) only for RC also when compared within the type of events: mean values of RC are 3.6 (normal) to 3.8 (intense and long-lasting) times higher in CT than in GC, however differences due to long-lasting events result not statistically significant. Only in CT, intense events have generated runoff in all the considered events. In terms of SL, no significant differences between treatments are found even though mean SL in GC is only 10% of CT during normal events, 26% during intense events and 44% during long-lasting events.

Analysing the events by their type, long-lasting events result in the highest RC in both CT and GC, but this difference was not statistically significant compared with other types of events. The largest statically significant difference observed among types of event is in terms of SL were: mean values of normal events are 31 and 144 times lower than long-lasting in CT and GC, respectively, and 157 and 421 times lower than intense in CT and GC, respectively. Intense events result in the highest SL in both CT and GC, as expected considering the highest mean erosivity for this category of events. This suggests that, in response to a rainy event, the runoff volume is principally affected by the soil management, while the sediment yield is influenced by the type of event.

During the three observed years, which were characterized by contrasting meteorological conditions from very warm and dry to exceptionally rainy, the grass cover always assured a significant reduction of the runoff, and at least 56% reduction of soil losses for each category of events, despite low runoff in CT was observed after the execution of tillage operations, according to Biddoccu *et al*. (2013).

The highest RC value was associated to long-lasting events, with high amount of precipitation and long duration, that usually produces saturation excess runoff (Castillo *et al*., 2003) likely favoured by the reduced grass cover during autumn and winter, since the grass usually slows down the overland flow and protects the soil (Fernández-Ragaa *et al*., 2017). The absence of grass cover or litter in both vineyards can also explain why this is the only type of event in which there is no statistical difference between the two treatments. Even if not significant, the mean runoff reduction in the plot with grass cover during long-lasting events is 65%, which means more water available for infiltration during those events that typically occur in late autumn, winter, and spring.

Furthermore, in another study carried out in the period 2013-2014 in the same vineyard, Biddoccu *et al*. (2017) found that the main runoff and erosive events, especially in the GC, were related to the saturation excess mechanism, which was observed particularly in late autumn and in long-duration winter precipitation events, usually associated with high P. In fact, the tilled soil is characterized by the presence of a plough pan, with reduced hydrological conductivity of and the hydrological connectivity between the surface and deep soils (Horn and Smucker, 2005). The water, after having infiltrated the upper soil part and saturated it, can flow by gravity below the surface and then re-emerge downstream, therefore giving origin to a subsurface lateral flow (Wang and Zang, 2017).

The highest SL value associated to intense events, usually spring and summer storms, which showed the highest Imax30, Imed, E, and EI30 is related to infiltration excess overland flow (Horton, 1933): the water initially fills the macropores, attracted by capillarity. Subsequently, the clays present in the soil, becoming wet, can expand, reducing the size of the pores. In addition, the impact of the drops, especially on bare soil of CT, can move fine particles (splash erosion) that can be transported by runoff (Fernández-Raga *et al*., 2017). Furthermore, particles previously detached by splash erosion can obstruct the soil pores, contributing to increase the soil crusting, reducing even more the soil hydraulic conductivity (Terry and Shakesby, 1993). The results show how the use of grass cover is particularly efficient in reducing runoff and soil losses during both intense and long-lasting rainfall events, that generate most of runoff and erosion and contribute to the conservation of water and soil, and was effective in halving the runoff volume also during the extreme event occurred in October, 2019.

Tractor traffic

Considering soil compaction conditions, due to the traffic over the soil, in CT both RC and SL are significantly higher in Comp than NComp (2 and 11 times, respectively). Although this difference also exists in GC, it is smaller and not statistically significant. This suggests that GC is less influenced by traffic and is more resilient than CT: the presence of grass lets the soil recover its characteristics more quickly after the transit of an off-road vehicle (Matthews *et al*., 2010). Reduced compaction, indicated by lower bulk density, and higher soil volumetric content were also measured in grassed inter-rows, rather than tilled by Bogunovic *et al*. (2017) in a Croatian vineyard. In a previous study, Capello *et al*. (2019a) found that the number of tractor passages strongly influences the bulk density only in the tilled soil and not in the grassed one, affecting negatively the soil hydraulic conductivity, and soil penetration resistance.

Analyzing the effects of traffic in combination with the different types of event, there are significant differences only for SL in CT (Table 3): the highest SL is produced by intense events over a compacted soil (Comp). This result confirms that the soil compaction, induced by tractor traffic, causes evident reduction of hydraulic conductivity, and favours infiltration excess overland flow (Horton, 1933) and consequent soil transportation. Indeed, during intense events, Imax30 can reach 30 mm h^{-1}, but in the CT inter-rows after some tractor passages, the soil hydraulic conductivity in correspondence of the track was very low, up to less than 1 mm h^{-1}, as measured by Capello *et al*. (2019b). On the opposite, the same type of event occurring on a NComp soil generates a lower SL because of the higher soil hydraulic conductivity. Confirming what previously stated, lower - but not statistically different - values of SL are also generated by long-lasting events, both in NComp and Comp conditions: saturation excess runoff is less affected by reduced hydraulic conductivity induced by compaction, but it is more predisposed by initial soil water content, being linked to the previous rainfall events.

The lowest values of SL are generated by normal events (both in Comp and NComp) and are statistically different from those due to intense events over Comp soil conditions and long-lasting events on NComp soil conditions (Figure 1).

The highest soil loss at event scale was observed in CT during an intense summer storm event (2.0 Mg ha^{-1}), occurred on July 16, 2018, with Comp soil conditions. During the same event, 0.38 Mg ha^{-1} of soil was lost in GC. As it is possible to notice in Figure 2 the 61.4 mm of rain were concentrated in a few hours (Imax30>70 mm h^{-1}). The field saturated hydraulic conductivity, measured in that month by Capello *et al*. (2019b), was only 4 mm h^{-1} in the Track position (T), and 74 mm h^{-1} in the less disturbed inter-row (NT), while in GC it was higher than 100 mm h^{-1}. These conditions favoured the formation of infiltration excess runoff and explain why runoff was higher in CT than GC. The high intensity of the rain produces splash erosion, that can move fine particles, transported by runoff, increasing the soil losses. Considering the soil water content, it is evident how in GC (blue and green lines) it

had risen rapidly, even at greater depths, as evidence of the infiltration of water into the soil, while in CT it was not so quick and did not reach -20 cm depth, without effect on the available soil water content.

However, certainly, the extreme event occurred in autumn 2019, which SL data are not available yet, will show higher value: RO generated by this single event, with high intensity rainfall and long duration, is much higher than the sum of all other events occurred during the investigated period. This extreme event shows also the highest RC value in both the treatments. Capello *et al.* (2017) highlighted that in both CT and GC the highest runoff coefficients were obtained in wet soil conditions, but in the present study the soil moisture condition (dry or wet) at rainfall occurrence did not result in significantly different runoff amounts.

Table 3. Summary of mean values and coefficient of variation at event scale of runoff coefficient and soil losses variables at the experimental site. Extreme event is not considered in all events.

Type	Soil condition	No.		CT		GC	
				RC	SL	RC	SL
All	Comp	19	Mean	8.4%*	0.220*	2.0%	0.055
			CV	133%	243%	150%	263%
All	NComp	40	Mean	4.4%*	0.019*	1.3%	0.009
			CV	236%	575%	270%	600%
Intense	Comp	11	Mean	5.7%	37.0%[a]	1.4%	9.4%
			CV	111%	183%	150%	194%
Long-lasting	NComp	12	Mean	9.0%	5.8%[a]	3.1%	2.9%
			CV	186%	340%	193%	341%
Long-lasting	Comp	3	Mean	23.0%	3.7%[ab]	3.2%	0.3%
			CV	89%	95%	93%	87%
Intense	NComp	4	Mean	0.9%	0.2%[ab]	0.4%	0.2%
			CV	76%	122%	112%	172%
Normal	NComp	24	Mean	2.6%	0.2%[b]	0.5%	0.0%
			CV	207%	446%	195%	411%
Normal	Comp	5	Mean	5.8%	0.0%[b]	2.5%	0.0%
			CV	142%	-	190%	-

CT, conventional tillage; GC, controlled grass; No., number of events; RC, runoff coefficient (%); SL, soil loss (Mg ha^{-1}); CV, coefficient of variation. *Significant differences between soil condition (in all events); [a,b]different letters in the same column indicate significant differences between event types over different soil conditions, according to Kruskal-Wallis Test at P=0.

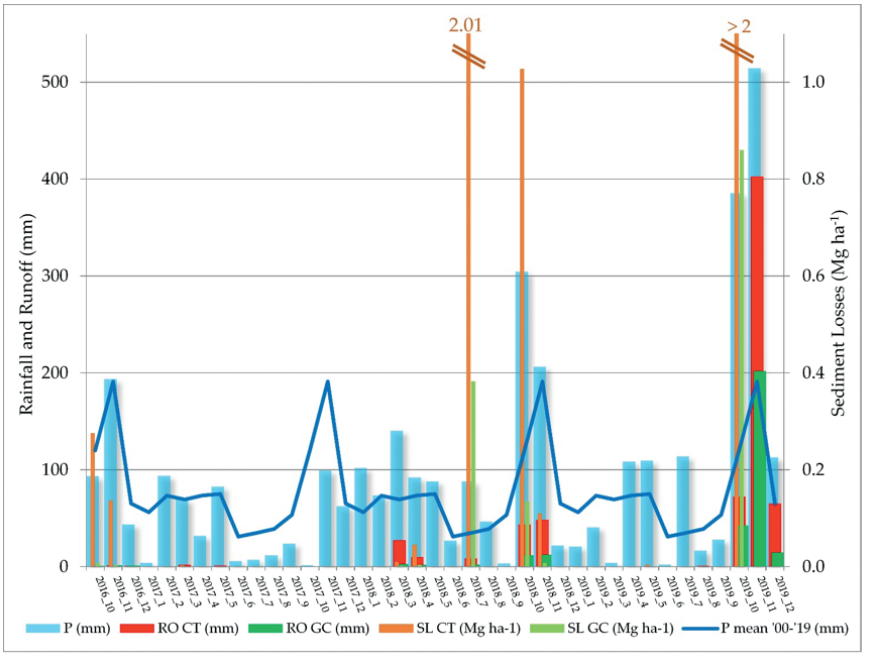

Figure 1. Monthly precipitation (P) and mean precipitation in 2000-2019 period (P mean), runoff (RO) and soil losses (SL) in CT and GC (SL value of November, December, and partially October 2019 are not available yet).

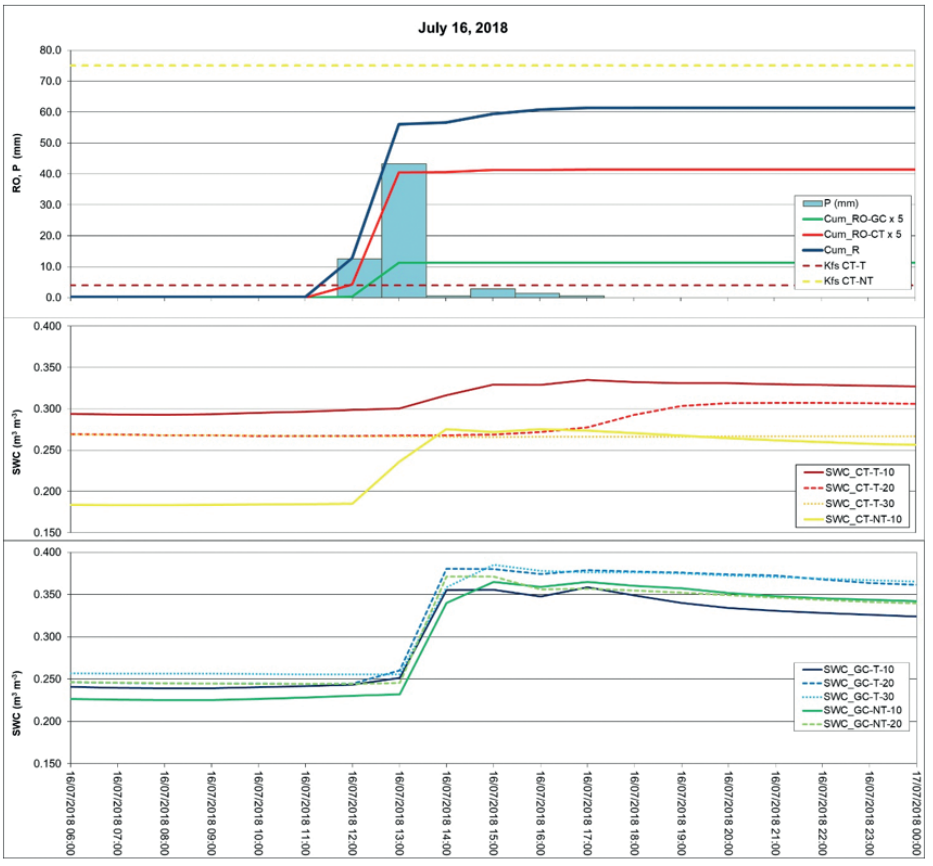

Figure 2. Analysis of the event occurred on July 16, 2018: in the first graph are represented hourly precipitation (P), Cumulated rainfall (Cum_P) and runoff (RO) in comparison to the hydraulic conductivity (Kfs) in CT and GC. Below, the soil water content (SWC) measured in the track (T) and no-track (NT) positions of the two treatments (CT and GC) is shown.

Conclusions

This paper presents the results of a study case in Piedmont during three-years characterized by contrasting meteorological conditions (2016-2019). Very different yearly precipitation characterized the observed period: 2017 was the less rainy of the last 20 years with runoff lower than 1% of precipitations and very low soil losses while, on the opposite, 2019 was the rainiest year, with more than 99.5% of the annual runoff, concentrated in October, November, and December. The year 2018, as well as the end of 2016, was similar to the mean annual rain distribution. All long-lasting rainfall events occurred in late autumn and winter, on the contrary, intense events occurred from spring to early autumn.

Runoff volume was principally affected by soil management, while sediment yield was influenced by the type of event. Intense events resulted in the highest SL in both CT and GC: the highest SL value was produced by intense events over a compacted soil and related to infiltration excess overland flow. This result confirms that the soil compaction, induced by tractor traffic, causes evident reduction of hydraulic conductivity, and favours infiltration excess overland flow, and consequent soil transportation. The compaction due to repeated passage of agricultural machinery could cause a significant reduction of water that can infiltrate into the soil and that is potentially available for the vine's needs.

Grass cover reduced by 65% the runoff, with the highest efficiency during intense events. Soil losses were reduced on average by 72%, with 74% efficiency during the most erosive intense events and the lowest protection (56%) during long-lasting rainfall. Moreover, the response of grass cover plot was less influenced by traffic and was more resilient.

With this study, we demonstrate the efficiency of grass cover in reducing water and soil losses also during extreme events: the increasing frequency of extreme events, both with high intensity or long duration precipitation, due to climate change, makes it necessary to protect the soil and adopt adequate soil management to preserve water and soil in the different times of the year.

The great variability observed during these years of study, evidences the need for an adequate assessment in adopting soil protection techniques through soil management (cover crop: total, alternating, permanent, temporary, *etc.*) and an adequate programming of the activities in the field, in particular for off-road traffic.

Highlights

- Runoff volume was principally affected by soil management.
- Sediment yield was influenced by the type of event.
- Intense events result in the highest sediment losses.
- Grass cover reduced by 65% the runoff, with the highest efficiency during intense events.
- Tractor traffic caused a significant reduction of water that could infiltrate into the soil, recharging it.

References

Aguilera E, Lassaletta L, Gattinger A, Gimeno B S, 2013. Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: a meta-analysis. Agr. Ecosyst. Environ. 16825-36.

ARS-USDA, 2015. RIST Rainfall Intensity Summarization Tool. Available online: http://www.ars.usda.gov/Research/docs.htm?docid=3251 Accessed: 04/04/2020.

Bagagiolo G, Biddoccu M, Rabino D, Cavallo E, 2018. Effects of rows arrangement, soil management, and rainfall characteristics on water and soil losses in Italian sloping vineyards. Environ. Res. 166:690-704.

Biancotti A, Bellardone G, Bovo S, Cagnazzi B, Giacomelli L, Marchisio C, 1998. Distribuzione Regionale di Piogge e Temperature. Collana Studi Climatologici del Piemonte, vol 1. Regione Piemonte, Torino, Italy.

Biddoccu M, Ferraris S, Cavallo E, Opsi F, Previati M, Canone D, 2013. Hillslope Vineyard Rainfall-Runoff Measurements in Relation to Soil Infiltration and Water Content. In: Four decades of progress in monitoring and modeling of processes in the soil-plant-atmosphere system: applications and challenges. Procedia Environ. Sci. 19:351-60.

Biddoccu M, Ferraris S, Opsi F, Cavallo E, 2016. Long-term monitoring of soil management effects on runoff and soil erosion in sloping vineyards in Alto Monferrato (North-West Italy). Soil Till. Res. 155:176-89.

Biddoccu M, Ferraris S, Pitacco A, Cavallo E, 2017. Temporal variability of soil management effects on soil hydrological properties, runoff and erosion at the field scale in a hillslope vineyard, North-West Italy. Soil Till. Res. 165:46-58.

Bogunovic I, Bilandzija D, Andabaka Z, Stupic D, Comino JR, Cacic M, Brezinscak L, Maletic E, Pereira P, 2017. Soil compaction under different management practices in a Croatian vineyard. Arab. J. Geosci. 10:340.

Brown LC, Foster GR, 1987. Storm erosivity using idealized intensity distributions. Trans. ASAE 30:379-86.

Capello G, Biddoccu M, Cavallo E, 2019a. L'influenza della gestione del suolo e del traffico agricolo sulla conservazione dell'acqua e del suolo: un caso studio in Piemonte. pp 38-43 in Atti del XXII Convegno Nazionale di Agrometeorologia - Ricerca ed innovazione per la gestione del rischio meteo - climatico in agricoltura, Bologna: Dipartimento di Scienze Agrarie - Università di Bologna, Italy.

Capello G, Biddoccu M, Ferraris S, Cavallo E, 2019b. Effects of tractor passes on hydrological and soil erosion processes in tilled and grassed vineyards. Water 11:2118.

Capello G, Biddoccu M, Ferraris S, Pitacco A, Cavallo E, 2017. Year-round variability of field-saturated hydraulic conductivity and runoff in tilled and grassed vineyards. Chem. Engine. Trans. 58:739-44.

Castillo V M, Gomez-Plaza A, Martínez-Mena M, 2003. The role of antecedent soil water content in the runoff response of semiarid catchments: a simulation approach. J. Hydrol. 284:114-30.

CEC, 2006a. Communication from the Commission to the Council, the European Parliament, the European economic and social Committee and the Committee of the Regions. Thematic Strategy for Soil Protection. Brussels, 22.9.2006, COM, 231 final.

CEC, 2006b. Proposal for a directive of the European Parliament and of the Council establishing a framework for the protection of soil and amending Directive 2004/35/EC. Brussels, 22.9.2006, COM, 232 final.

CEC, 2009. Council Regulation (EC) No 1782/2003 of 19 January 2009 Establishing Common Rules for Direct Support Schemes for Farmers under the Common Agricultural Policy and Establishing Certain Support Schemes for Farmers, Amending Regulations (EC) No 1290/2005, (EC) No 247/2006, (EC) No 378/2007 and repealing Regulation (EC) No 1782/2003. European Union, Brussels. Available from: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32009R0073 Accessed: 29/04/2020.

Celette F, Gaudin R, Gary C, 2008. Spatial and temporal changes to the water regime of a Mediterranean vineyard due to the adoption of cover cropping. Eur. J. Agron. 29:153-62.

Celette F, Ripoche A, Gary C, 2009. WaLIS - a simple model to simulate water partitioning in a crop association: the example of an intercropped vineyard. Agric. Water Manage. 97:1749-59.

Corti G, Cavallo E, Cocco S, Biddoccu M, Brecciaroli G, Agnelli A, 2011. Evaluation of erosion intensity and some of its consequences in vineyards from two hilly environments under a mediterranean type of climate, Italy. Soil Erosion Issues in Agriculture, Danilo Godone and Silvia Stanchi, IntechOpen. Available from: https://www.intechopen.com/books/soil-erosion-issues-in-agriculture/evaluation-of-erosion-intensity-and-some-of-its-consequences-in-vineyards-from-two-hilly-environment

Dolšak D, Bezak N, Šraj M, 2016. Temporal characteristics of rainfall events under three climate types in Slovenia. J. Hydrol. 541:1395-405.

FAO, ITPS, 2015. Status of the World's Soil Resources (Main Report), No. 608. FAO, Rome, Italy.

FAO, 2020. Sustainable Development Goals. Available from: http://www.fao.org/sustainable-development-goals/mdg/en/

FAO/ISRIC/ISSS, 1998. World reference base for soil resources. World Soil Resources Report, No. 84. FAO, Rome, Italy.

Fernández-Raga M, Palenciaa C, Keesstrab S, Jordánd A, Frailea R, Angulo-Martíneze M, Cerdàb A, 2017. Splash erosion: A review with unanswered questions. Earth-Sci. Rev. 171:463-77.

Ferrero A, Usowicz B, Lipiec J, 2005. Effects of tractor traffic on spatial variability of soil strength and water content in grass covered and cultivated sloping vineyard. Soil Till. Res. 84:127-38.

Foronda-Robles C, 2018. The territorial redefinition of the vineyard landscape in the sherry wine region (Spain). Misc. Geogr. 22:95-101.

Gaál L, Molnar P, Szolgay J, 2014. Selection of intense rainfall events based on intensity thresholds and lightning data in Switzerland. Hydrol. Earth Syst. Sci. 18:1561-73.

Garcia L, Celette F, Gary C, Ripoche A, Valdés-Gómez H, Metay A, 2018. Management of service crops for the provision of ecosystem services in vineyards: a review. Agric. Ecosyst. Environ. 251:158-70.

Gómez JA, Vanwallenghem T, De Hoces A, Taguas EV, 2014. Hydrological and erosive response of a small catchement under olive cultivation in a vertic soil during a five-year period: implications for sustainability. Agr. Ecosyst. Environ. 188:229-44.

Guzmán G, Cabezas JM, Sánchez-Cuesta R, Lora Bauer T, Strauss P, Winter S, Zaller JG, Gómez JA, 2019. A field evaluation of the impact of temporary cover crops on soil properties and vegetation communities in southern Spain vineyards. Agric.

Ecosyst. Environ. 272:135-45.
Hamza MA, Anderson WK, 2005. Soil compaction in cropping systems: a review of the nature, causes and possible solutions. Soil Till. Res. 82:121-45.
Horn R, Smucker A, 2005. Structure formation and its consequences for gas and water transport in unsaturated arable and forest soils. Soil Till. Res. 82:5-14.
Horton RE, 1933. The role of infiltration in the hydrologic cycle. Trans. Am. Geophys. Union. 14th Ann. Mtg: 446-60.
IPCC, 2014. IPCC Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Geneva, Switzerland.
Lagacherie P, Coulouma G, Ariagno P, Virat P, Boizard H, Richard G, 2006. Spatial variability of soil compaction over a vineyard region in relation with soils and cultivation operations. Geoderma. 134:207-16.
Li Z, Fang H, 2016. Impacts of climate change on water erosion: a review. Earth-Sci. Rev. 163:94-117.
Matthews GP, Laudone GM, Gregory AS, Bird NRA, Matthews AGD, Whalley WR, 2010. Measurement and simulation of the effect of compaction on the pore structure and saturated hydraulic conductivity of grassland and arable soil. Water Resour. Res. 46:1-13.
Millennium Ecosystem Assessment, 2005. Ecosystems and human well-being: synthesis. Island Press, Washington, DC, USA.
Nicholls CI, Altieri MA, Ponti L, 2008. Enhancing plant diversity for improved insect pest management in Northern California organic vineyards. Acta Hortic. 785:263-78.
OIV (Organisation Internationale de la Vigne et du Vin), 2019. State of the vitiviniculture world market; April 2019. Available from: http://www.oiv.int/en/technical-standards-anddocuments/statistical-analysis/state-of-vitiviniculture Accessed: Mar 23, 2020.
Panagos P, Ballabio C, Borrelli P, Meusburger K, Klik A, Rousseva S, Tadić M P, Michaelides S, Hrabalíková M, Olsen P, Aalto J, Lakatos M, Rymszewicz A, Dumitrescu A, Beguería S, Alewell C, 2015a. Rainfall erosivity in Europe. Sci. Total Environ. 511:801-14.
Panagos P, Borrelli P, Poesen J, Ballabio C, Lugato E, Meusburger K, Montanarella L, Alewell C, 2015b. The new assessment of soil loss by water erosion in Europe. Environ. Sci. Policy. 54:438-47.
R Core Team, 2020. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available from: https://www.R-project.org/ Accessed: 29/02/2020.
Raclot D, Le Bissonais Y, Louchart Y, Andrieux P, Moussa R, Voltz M, 2009. Soil tillage and scale effects on erosion from fields to catchment in a Mediterranean vineyard area. Agr. Ecosyst. Environ. Catena. 66:198-210.
Raffelli G, Previati M, Canone D, Gisolo G, Bevilacqua I, Capello G, Biddoccu M, Cavallo E, Deiana R, Cassiani G, Ferraris S, 2017. Local and plot-scale measurements of soil moisture: time and spatially resolved field techniques in plain, hill and mountain sites. Water 9:706.
Regione Piemonte, 2015. Programma di Sviluppo Rurale PSE 2007-2013. Available from: https://www.regione. piemonte.it/web/sites/default/files/media/documenti/2019-03/psr2007_2013_piemonte_11_25set2015_dic15.pdf Accessed: 01 July 2020.
Renard K G, Foster G R, Weesies G A, McCool D K, Yoder D C, 1997. Predicting soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). US Department of Agriculture Agricultural Handbook No. 703, USDA Washington, DC, USA.
Rodrigo-Comino J, Brevik E C, Cerdà A, 2018. The age of vines as a controlling factor of soil erosion processes in Mediterranean vineyards. Sci. Total Environ. 616-17:1163-73.
Ruiz-Colmenero M, Bienes R, Marques MJ, 2013. Soil and water conservation dilemmas associated with the use of green cover in steep vineyards. Soil Tillage Res. 117:211-23.
Sansom J, Thomson PJ, 1992. Rainfall classification using breakpoint pluviograph data. J. Climate. 5:755-64.
Servizio Geologico d'Italia, 1969. Carta Geologica d'Italia alla scala 1:100.000. Available from: http://193.206.192.231/carta_geologica_italia/cartageologica.htm Accessed: 28 December 2019.
Sohne W, 1953. Druckverteilung im Boden und Boden-verformung unter Schlepper Reifen. Grundlagen der Landtechnik. 5:49-63.
Soil Survey Staff, 2010. Keys to Soil Taxonomy, 11th ed. USDA-Natural Resources Conservation Service, Washington, DC, USA.
Spinelli R, Magagnotti N, Cavallo E, Capello G, Biddoccu M, 2019. Reducing soil compaction after thinning work in agroforestry plantations. Agroforest Syst. 93:1765-79.
Taguas EV, Peña A, Ayuso J L, Pérez R, Yuan Y, Giráldez J V, 2010. Rainfall variability and hydrological and erosive response of an olive tree microcatchment under no-tillage with a spontaneous grass cover in Spain. Earth Surf. Process. Landf. 35:750-60.
Terry JP, Shakesby RA, 1993. Simulated rainfall and photographic evidence. Earth Surf. Process. Landf. 18:519-25.
Tropeano D, 1984. Rate of soil erosion processes on vineyards in Central Piedmont (NW Italy). Earth Surf. Process. Landf. 9:253-66.
UNESCO, 2020. Vineyard landscape of Piedmont: Langhe-Roero and Monferrato. Available from: http://whc.unesco.org/en/list/1390 Accessed: 29/02/2020.
van Leeuwen C, Friant P, Choné X, Koundouras S, Dubourdieu D, 2004. Influence of climate, soil, and cultivar on terroir. Am. J. Enol. Vitic. 55:207-17.
Verheijen FGA, Jones R JA, Rickson RJ, 2009. Tolerable versus actual soil erosion rates in Europe. Earth Sci. Rev. 94:23-38.
Wang Y, Zhang B, 2017. Chapter Four - Interception of subsurface lateral flow through enhanced vertical preferential flow in an agroforestry system observed using dye-tracing and rainfall simulation experiments. In: S.A. Banwart, D.L. Sparks (Eds.), Advances in agronomy. Academic Press, 142:99-118.
Winter S, Bauer T, Strauss P, Kratschmer S, Paredes D, Popescu D, Landa B, Guzmán G, Gómez JA, Guernion M, Zaller JG, Batáry P, 2018. Effects of vegetation management intensity on biodiversity and ecosystem services in vineyards: a meta-analysis. J. Appl. Ecol. 55:2484-95.
World Meteorological Organization (WMO), 2016. Guidelines on the definition and monitoring of extreme weather and climate events; December 2015. World Meteorological Organization, 62 pp.