BioOne COMPLETE

Effects of a Permanent Soil Cover on Water Dynamics and Wine Characteristics in a Steep Vineyard in the Central Spain

Authors: Marques, MJ, Ruiz-Colmenero, M, Bienes, R, García-Díaz, A, and Sastre, B

Effects of a Permanent Soil Cover on Water Dynamics and Wine Characteristics in a Steep Vineyard in the Central Spain

$\circledS$ SAGE

MJ Marques[1] ID, M Ruiz-Colmenero[2], R Bienes[2] ID, A García-Díaz[2] and B Sastre[2]

[1]Department of Geology and Geochemistry, Autonomous University of Madrid, Madrid, Spain.
[2]Department of Applied Research and Agrarian Extension, IMIDRA, Madrid, Spain.

ABSTRACT: The study of alternative soil managements to tillage, based on the evidence of climate change in the Mediterranean basin, is of great importance. Summer and autumn are critical seasons for soil degradation due to the high-intensity, short-duration storms. Vineyards are vulnerable, especially on steep slopes. The particular effects of storms over the years under different soil conditions due to different management practices are not frequently addressed in the literature. The aim of this study was to examine the differences between runoff and soil moisture patterns influenced by 2 treatments: traditional tillage (Till) and a permanent cover crop. A shallow-rooted grass species *Brachypodium distachyon* (L.) P. Beauv. with considerable density coverage was selected as cover crop. This annual species was seeded once in the first year and then allowed to self-seed the following years. Tillage was performed at least twice in spring to a 10- to 15-cm depth and once in late autumn at a depth of 20 to 35 cm. Rainfall simulation experiments were performed, 1 year after treatments, using high-intensity rainfall on closed plots of 2 m^2, located in the middle strips of the vineyard with different treatments. The effects of simulated rainfall experiments were determined in 3 different moments of the growth cycle of cultivar: (1) in summer with dry soils, (2) in early autumn with moderate soil moisture, and (3) in autumn with wet soils. During the 2-year trial, the soil moisture level in the soil upper layer (0-10 cm) was higher for Till treatment (14.1% ± 2.4%) compared with that for cover crop treatment (12.3% ± 2.0%). However, soil moisture values were more similar between treatments at 35 cm depth (12% ± 1%), with the exception of spring and autumn; in spring, water consumption in *the cover crop treatment* was the highest, and the moisture level at 35 cm depth was reduced (12%) compared with that for Till treatment (13%). In autumn, in cover crop treatment, higher water infiltration rate in soils led to higher soil moisture content at 35 cm (11%) compared with that of Till treatment (10%). The effects of simulated rainfall experiments on runoff and infiltration under different soil conditions and management practices vary seasonally. Runoff was significantly higher in summer for cover crop treatment (11%) as compared with that for Till management (1%), but significantly lower (3%) with wetter soils than for Till treatment (22%) in autumn. Thus, the simulation experiments with wet soils using cover crops produced higher infiltration rates and, consequently, the higher soil moisture content in the following days. The difference between seasons is attributed to the greater porosity of soil under Till treatment in summer, which resulted from the shallow plowing (10-15 cm depth), carried out to reduce moisture competition between weeds. The effect of traditional spring plowing was short-lived. The infiltration of water increased by cover crop treatment as compared with tillage in autumn both before and after ripping. Management practices did not influence wine parameters, as no significant differences were found between wine organoleptic characteristics in the duo-trio wine tastings, similarly, no differences were found for alcoholic degree, acidity, reduced sugars, and pH; however, a trend for a positive increase in polyphenol contents was noticed. Therefore, properly managed to avoid water shortages, cover crops can be recommended for soil protection in semi-arid environments.

KEYWORDS: Groundcover, rainfall simulation, runoff, leaf water potential, sustainable land management

Introduction

It is well known that the characteristics of wine depend mainly on the grape variety, soil, and climate.[1,2] Vines can adapt to different conditions and, therefore, can be cultivated in a wide range of soils with various characteristics such as pH and texture.[3] These variations may provide the basis for establishing the concept of "terroir," originally in France and now in many other countries.[4]

Despite the wide adaptability of vines, according to the 2014 report of the Intergovernmental Panel on Climate Change, future climatic conditions can lead to more extreme weather events, especially in Mediterranean areas,[5] where frequent extreme events and dry spells are expected.[6] The vineyards can be adapted to these new circumstances by selecting the right grape variety and soil management practices.[7] This approach is in accordance with the new strategic plan of the International Organization of Vine and Wine (OIV) for the next 5 years (2020-2024), which addresses the need to encounter climate change through mitigation and adaptation activities.[8] The improvement in the environmental performance of vineyards, the preservation of natural resources, and particularly the study to evaluate the impact of climate change on the microbiome of a vineyard and soil fertility (see http://www.oiv.int/public/medias/7156/en-oiv-strategic-plan-2020-2024-web.pdf) are of great importance.

Soil erosion rates in traditionally managed vineyards are high compared with other land management practices and uses,[9,10] although they show a wide range of variation,

according to the literature.[11] A publication reported great soil losses (70 and 74 t ha⁻¹ yr⁻¹ in Italy[12] and Spain,[13] respectively) due to extreme climate events. Review papers present a clear idea of the methodologies, erosion rates, and limitations associated with soil erosion in vineyards.[9,11,14] In a recent compilation about erosion rates measured on plots, yield values between 8.62 and 23.64 t ha⁻¹ yr⁻¹ were reported in European vineyards, showing high figures compared with the global average rate for sheet and rill erosion rate, which was close to 1 t ha⁻¹ yr⁻¹.[15]

One reason for the variation in soil erosion rates is using different methodological approaches; a few examples cited here are as follows: the variation is based on experimental measurements using erosion plots, without or in combination with simulated rainfall[16,17]; indirect indicators such as root dendrochronology, erosion pins, and poles in the vineyard,[18] unearthed stocks of grafted vines,[19-21] and isotopes[22] are also used. Other approaches involve empirical models such as USLE,[21,23] STREAM,[24] or SWAT,[25] which are the most widely used among others.[26] More recently, remote sensing approaches are usually used in combination with other techniques.[27,28]

Numerous studies have demonstrated the effectiveness of plant cover, particularly woody crops like vineyards,[14] in preventing soil erosion. The study by Garcia et al[29] reviewed the numerous ecosystem services provided by cover crops in vineyards. On one hand, some authors have shown that traditional tillage leads to high erosion rates and can be even more damaging than climate change itself.[30] On the other hand, cover crops can reduce the susceptibility of the soil to sealing by improving soil quality,[31] and can potentially affect the characteristics of must and wine,[32] according to the concept of terroir.

Runoff and soil moisture in vineyards in dry environments, along with an annual rainfall of less than 400 mm and different management practices, have not received much attention. Rainfall simulation experiments are required to analyze arid or semi-arid areas, where it can be difficult to obtain the frequency of natural rainfalls due to low rainfalls. This article summarizes the effects of a protective permanent grass cover crop on soil moisture, vine water stress, and wine composition in a semi-arid area in central Spain. Soil moisture is a critical factor as water scarcity is the most important constraint in vineyard production[33] and an important reason for winegrowers to refuse the adoption of cover crops in this semi-arid area.[34] The data from natural and simulated rainfall experiments were collected to assess the impact of a shallow-rooted species belonging to the Poaceae family, *Brachypodium distachyon* (L.) P. Beauv., on soil moisture content, vine water stress, and wine parameters.

Materials and Methods

Study area

The study site was located in Campo Real, Central Spain, in a 1.4-ha vineyard (UTM 30T X 468169, Y 4467525; KML file in Supplemental Material). The vineyard is in a rolling landscape, with maximum slope of 14% and altitude 780 m above sea level. Average annual temperature was 14°C and accumulated precipitation 386 mm (State Meteorological Agency, AEMET). Rainfalls were recorded with a HOBO gauge system installed in the vineyard, close to the plots.

Vines of Tempranillo grape variety were planted by the year 2000 at 3 × 1.5 m² spacing, vine by row, and trained on a vertical shoot-positioned trellis. During the years of experiments, the vineyard was rainfed. In 2006, a permanent ground cover of *Brachypodium distachyon* (L.) P. Beauv. (hereinafter "Bra") was introduced in the vineyard and was compared with the traditional tillage practice (hereinafter "Till") for soil management. The Bra species is an annual hardy plant, it stands up dry spells and trampling.[35] Its size (about 15 cm tall) and shallow root system (10-15 cm depth)[36] enable using this species for cover cropping in semi-arid areas, as even when withered, it can protect the soil from water erosion (Figure 1A and B). Each 3 consecutive rows in the vineyard had different treatment (Figure 1). To maintain a permanent groundcover of Bra, this species was seeded only once, the first year, in early winter in inter-rows, leaving 0.5 m bare strips under the vine rows (Figure 1A and B). The seeding rate was 40 kg ha⁻¹, the cover was left during the following 2 years of experiment and it was only mowed each year during spring, the height of mowing was 10 to 12 cm to allow self-seeding the next year. The Till treatment consisted of 2 or 3 passes of chisel in spring (10-15 cm depth) to prevent weeds, and one deeper plow (20-35 cm depth in this case) or ripping in late autumn (Figure 1C) performed to enable deep roots development which will supply water during prolonged water stress. Three closed 2 m² plots (0.5 m wide and 4 m long) per treatment were installed in the middle of the inter-rows, distant 1.25 m to the vine rows in both sides of the plot. In this organic vineyard, weeds in the lines of vines were removed by hand.

Methods

Soil parameters. Bulk composite topsoil samples (0-10 cm depth) were obtained by mixing 3 random samples of approximately 300 g and were used to analyze soil parameters, this system enables better gathering soil variability. The thickness of soil is directly affected by the root system development of Bra treatment. These soil samples were air dried, sieved, and prepared for different measurements to determine soil type and condition, especially organic carbon. Intact soil cores of 100 cm³ were taken to measure bulk density, after oven drying and weighing. Electrometric methods were used to measure soil pH and electrical conductivity (EC); soil organic carbon (SOC) was estimated with wet digestion[37]; total nitrogen by Kjeldahl digestion[38]; and available phosphorus by Olsen method.[39] Soil macro- and micronutrients were measured by spectrometry.[40] Cation exchange capacity (CEC) was measured by Bascomb method.[41]

Soil moisture and runoff. The closed soil plots described above were used to measure moisture and runoff. Volumetric water

Figure 1. The vineyard with minimum tillage and *Brachypodium distachyon* cover crops in summer (A) and late autumn (B). In picture "B," 1 erosion plot can be seen in the middle of the strip, on the right the rainfall simulator with windbreaks to prevent wind disturbance effects. Tillage in late autumn is shown in picture "C." Figures "D" and "E" show the progressive decrease in roughness and sealing process experienced by tilled soils over time due to the accumulation of rain events.

content in soils was continuously recorded every hour during the 2 years of experiment in the field using Decagon ECH2O moisture meters, through capacitance technology. Sensors were specifically calibrated prior to use. Each plot was provided with 2 sensors buried at 10 and 35 cm depth. Each daily value is the average of 24 measurements over the day of the 3 replicates.

Runoff. Runoff was measured from simulated rainfall experiments done over the abovementioned closed plots. Three plots were managed with minimum tillage, and another 3 plots were covered by 1-year-old permanent Bra treatment. Simulations started 1 year after the beginning of trials, under 3 different soil conditions: (1) summer, with dry soils close to permanent wilting point; (2) autumn with moderate moisture; and (3) late autumn after deep tillage and moisture conditions close to field capacity. Bra vegetation was withered in summer (Figure 1A) and wrinkled due to the harvest works (Figure 1B) in late autumn; however, the vegetation still covers soils (40%-60% soil cover). The rainfall simulator (Figure 2) consisted of a metal frame with 2 full cone nozzle spraying systems 1/3 HH35W located 1.5 m apart. The nozzles were 2 m high and covered 4 m^2 of rainfall with a Christiansen uniformity coefficient of 86%.[42] The pressure was controlled with a manometer at 1.5 ± 0.2 kg cm^{-2}. The D50 drop size was 1.85 mm. Rainfall intensity was 2.16 mm min^{-1} during 10 minutes, such storm corresponds to rain events with a return period of 10 years.[43]

Methods in vine and wine variables. Leaf water potential (Ψ_1) was measured at the midday by a Scholander et al[44] pressure chamber using an undamaged not sunny leaf on the middle of the vine, which was cut with a sharp knife and sealed in a plastic bag to prevent evapotranspiration. The midday Ψ_1
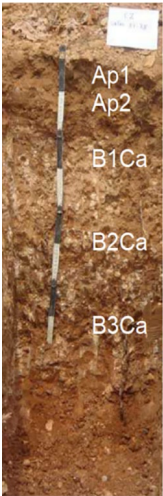
Figure 2. Rainfall simulator. Two full cone nozzles placed in an operating height of 2 m above ground. The windbreaks are partially placed around the simulator in the picture. During the experiment, the windbreaks were unfold completely for preserving rainfall distribution.

measurements were taken within 1 minute after removing leaves from the vines. This parameter was measured for the 3 consecutive years after the beginning of trials. In the winter of the second year, pruning wood weight was measured in situ with a portable weighting scale during the pruning work, which was always carried out by the same expert person. To measure the impact of treatments, 5 vines having different treatments at both sides of the rows were considered. Therefore, there were 5 vines with Till treatments at both sides, 5 vines with Bra at both sides, and 5 vines with Till on one side and Bra on the other side; all these vines were selected by order, discarding the first 2 vines close to the vineyard path.

The wines produced in the different soil treatments were made at the laboratory cellar. The fermentation was carried out

Table 1. Soil characteristics obtained from a pit dug at the starting point of the trials.

	HORIZONS	UNIT	AP1	AP2	B1CA	B2CA	B3CA
	Depth	cm	0-10	10-21	21-39	39-62	62
	Munsell	color	5 YR 4/8	7.5 YR 4/4	6.25 YR 478	7.5 YR 5/4	2.5 YR 3/6
	pH	1:2.5	8.4	8.3	8.0	7.9	7.8
	EC (1:5)	dS m^{-1}	0.20	0.14	0.16	0.15	0.17
	SOC	g kg^{-1}	7.4	1.9	3.0	2.0	1.4
	N	%	0.11	0.06	0.05	0.02	0.01
	P	mg kg^{-1}	36	<4	–	–	–
	CEC	cmol kg^{-1}	16.9	10.3	14.7	9.2	7.3
	Ca	cmol kg^{-1}	19.4	18.4	18.4	21.0	20.1
	Mg	cmol kg^{-1}	1.2	0.9	0.7	0.8	0.9
	Na	cmol kg^{-1}	0.05	0.11	0.15	0.19	0.10
	K	cmol kg^{-1}	1.1	0.9	0.6	0.2	0.3
	Gravel	+2 mm	20	30	33	0	0
	Clay	<2 µm	24	39	18	14	7
	Silt	2-50 µm	18	18	8	10	9
	Sand	0.05-2 mm	58	43	74	76	84
	Texture		Sandy Clay Loam	Clay Loam	Sandy Loam	Sandy Loam	Loamy Sand

Abbreviations: CEC, cation exchange capacity; EC, electrical conductivity; SOC, soil organic carbon.

at a controlled temperature of 25°C in 50 L stainless steel tanks, after cold maceration. The selected yeast was Fermol PB 2033 (AEB, USA). The wines underwent malolactic fermentation and then they were clarified. The following parameters were analyzed in 4 wine samples per treatment: total and volatile acidity, pH, density, alcoholic degree, total dry extracts, reducing sugars, and total polyphenols index (TPI) following standard methods from the OIV.[45] A panel of tasters composed of 8 trained judges examined the finished wines. Several duo-trio tests were performed, and the results were compared with the tables made by Larmond[46] and Roessler et al.[47]

Statistical analysis

Differences between treatments were established by parametric one-way analysis of variance (ANOVA) with normally distributed variables; otherwise, Kruskal-Wallis ANOVA tests were conducted using IBM SPSS Statistics 21.0.0.0. software.

Results and Discussion

Soil

The soils used in this study were classified as Calcic Haploxeralf,[48] according to data presented in Table 1. The data were obtained at the beginning of the research. This soil with a pH of 8.4 in the arable layer and a loamy character has a high available water capacity. It has moderate concentrations of nitrogen, phosphorus, and exchangeable base cations with a good CEC and low EC. Consequently, this soil can be considered suitable for cultivation[49]; however, the SOC content is low (less than 1%).[50]

Soil moisture

Figure 3 shows the effects of treatments on the average monthly soil moisture content at 10 and 35 cm depth during 2 years of experiment. Over the year, the moisture content in the topsoil (0-10 cm) varied from 10% in summer to 16% in spring and late autumn. The annual average was 12.3% ± 2.0% for Bra treatment, which was significantly ($P < .05$) lower than that for Till treatment (14.1% ± 2.3%). The effect of cover crops on water use was previously described in the literature.[51] The evapotranspiration of the herbaceous cover caused this difference in soil moisture at the surface.[52] The root systems of grasses reach the maximum density at a depth of 15 cm and rapidly disappear in the deeper layers.[53] Therefore, in this study, the soil moisture was not affected by the cover crop at deeper layers, as the annual average at a depth of 35 cm was the same for both treatments (12% ± 2%). In the literature, soil moisture
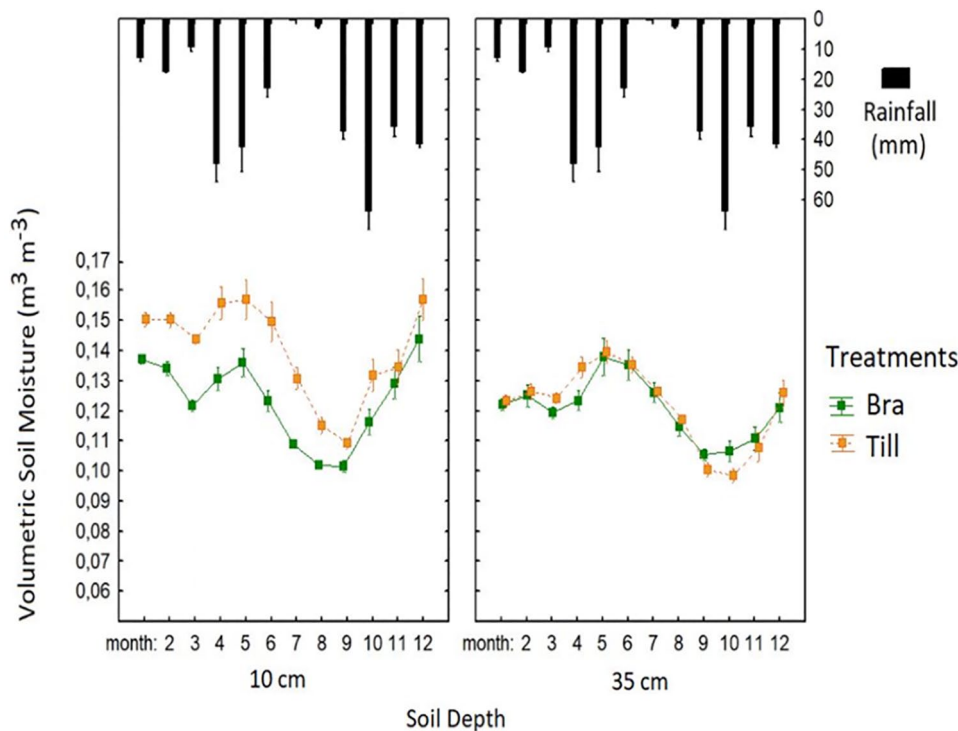
Figure 3. Mean and 95% confidence intervals of monthly volumetric soil moisture for 2 consecutive years in the vineyard (Bra = *Brachypodium distachyon*; Till = minimum tillage).

Table 2. Soil management and relevant soil parameters having an influence on runoff: volumetric soil moisture and bulk density.

	FIRST SIMULATED RAINFALL		SECOND SIMULATED RAINFALL		THIRD SIMULATED RAINFALL	
	TILL	BRA	TILL	BRA	TILL	BRA
Management practice	Plowed 2 months ago	Seeded 8 months ago Cover 60%	Plowed 7 months ago	Undisturbed Cover 90%	Plowed 1 week ago	Undisturbed Cover 90%
Soil moisture (%)	12 ± 1	10 ± 1	14 ± 3	14 ± 2	18 ± 2	21 ± 3
Bulk density (g cm^{-3})	1.19 ± 0.10	1.23 ± 0.08	1.35 ± 0.12	1.29 ± 0.18	1.23 ± 0.07	1.11 ± 0.17
Runoff max (%)	4 ± 6	20 ± 12	40 ± 53	14 ± 17	25 ± 34	11 ± 19
Runoff starting point (minutes)	5-10[a]	3-7	1-4	8-13	1-4	8-15[a]

Runoff coefficient, mean, and standard deviation, maintained at the last minute of the simulated rainfall (N = 3).
[a]One of the 3 plots did not show runoff at all.

has been found to be substantially reduced in the first 40 cm depth in grassed vineyards,[54] but its changes depend mainly on the cover crop species, coverage,[55] and soil texture and structure.[56] Several studies have demonstrated the plasticity of the vine-root system,[57] which tends to modify the vine-root colonization pattern and increase soil exploration in deeper layers to access water if competition occurs.[58] In dry soil conditions, vines can access water from the layers deeper than 90 cm[59]; thus the acclimation is easier for well-established vines.[60]

Even if the Bra treatment caused topsoil moisture shortages, other positive aspects may also be taken into account. The effect of a permanent Bra cover crop treatment on SOC content was significant over time. Compared with its initial value (0.74%), SOC value reached 0.91% ± 0.20%[61] after 3 years

under cover crop treatment. Under traditional tillage, the SOC content showed no significant differences over this period and ranged from 0.7% to 1.04%. In addition, the conservation of soil from water erosion has also been taken into consideration, and a 93% reduction in soil loss was reported in the vineyard of study.[52] The different capacities of erosion control (69%,[62] 76%,[18] 78%,[63] or 83%[64]) have been documented in other vineyards using cover crops.

Runoff

To understand the effects of cover crops in reducing the erosivity of rainfall, 3 sets of rainfall simulation experiments were carried out at different moments in the growth cycle of vine.
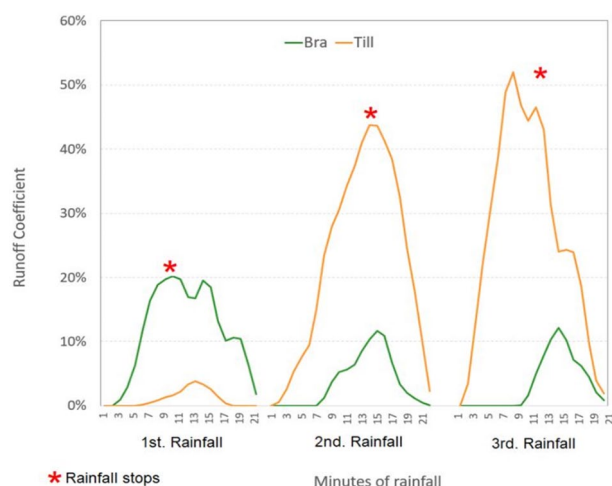
Figure 4. Smooth average runoff (n=3 per treatment) produced during the simulated rainfalls over 2 m² erosion plots. The first simulation was done on dry soil in summer, the second was performed in autumn, and the third over recent tilled soil in the late autumn. Runoff was recorded every minute and measured until the stop of water flow (Bra=*Brachypodium distachyon*; Till=minimum tillage).

Figure 5. Evolution of volumetric soil moisture at 10 and 35 cm depth in *Brachypodium distachyon* and tillage treatments. Average of 3 plots during 20 days after the simulation in the late autumn. Bars represent standard deviation.

The simulations were performed during the maturation and post-harvest stages on the closed plots with different treatments under the varying circumstances of soil moisture and porosity (Table 2). The average runoff in 3 simulations was calculated per plot, as shown in Figure 4.

The difference in runoff response may be due to meteorological conditions[65] and management practices,[66] according to the literature; the maximum runoff rate usually occurs in wet soils in autumn and winter, while the minimum occurs in dry soils that have been recently tilled.[52,67] The initial values of soil moisture and bulk density of soils before the application of simulated rainfalls are shown in Table 2. As expected, soils were dry during summer (10%-12% volumetric soil water content). The low values of bulk density in summer in Till treatments and the higher roughness[68] were the consequences of recent plowing. Soil roughness was measured by the chain method[69] at different moments of the study (data not shown). After tillage operation, chain roughness was 15% ± 4%; however, after rainfalls, soil roughness gradually diminished,[70] as the depressions were filled with sediment deposits. In this study, spring rainfalls resulted in roughness values less than 5%, and the difference between soils due to sealing processes is presented in Figure 1C to E. The different soil conditions throughout the year led to different runoff responses. In summer, the occurrence of higher roughness and porosity in Till treatment, along with low moisture, led to a higher infiltration rate in these rainfall simulation experiments; the average runoff values for Till and Bra treatments were 1% and 11.5%, respectively. The effects of cover crops and roughness in reducing the infiltration rates have been reported by other authors.[71] Under the Bra treatment, soils were left undisturbed since seeding, thus they had significantly higher bulk density, which resulted in a higher runoff in summer as mentioned (Figure 4). Several months
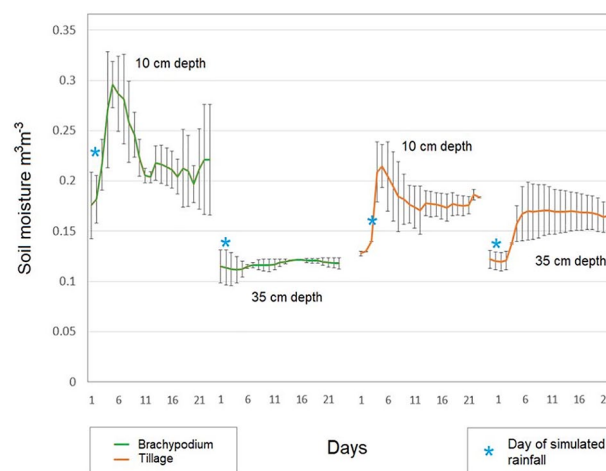
later, in autumn, soils under Till treatment collapsed, and their bulk density increased compared with that for cover crop treatment, and soils were wetter than in summer. The application of the permanent cover crop below and above the ground resulted in higher infiltration rate in the second rainfall experiment; the average runoff values were 22% and 3.5% for Till and Bra treatments, respectively. The third simulation experiment was performed to assess the effect of the autumn farm soil management involving ripping, which is usually higher on moisture. Soils under Till treatment were recently plowed, and the bare surface was not sealed; however, higher runoff with an average of 22% was recorded for Till treatment. The soils under Bra treatment stayed unaltered, as this treatment did not require any labor after the first sowing. The Bra treatment diminished the direct impact of drops, thus reducing its susceptibility to sealing. The application of the permanent cover crop resulted in a higher infiltration rate and an average runoff of 2.7% in the third simulation. Consequently, the results obtained in this treatment were similar to those from the second simulation experiment, confirming that grass covers improved water infiltration[53,72] and increased soil moisture at a depth of 35 cm during the rainy autumn season, as shown in Figure 3. Other authors have also found seasonal differences in runoff coefficients, which increased from summer to winter, on back slopes under the same rainfall intensity due to the higher initial soil moisture condition[73]; they noticed that the vegetation cover as well as organic matter can minimize this effect.

The effects of the last simulation experiment on soil moisture at 10 and 35 cm depth are shown in Figure 5. The changes in volumetric soil moisture after 20 days of the simulation are presented. The treatments showed differences in soil moisture; it was higher for the Bra treatment, probably due to the lower temperature of these soils in the vineyard growth cycle, which prevents evapotranspiration.[74] The green line represents the Bra treatment; after the simulation, the soil moisture sharply
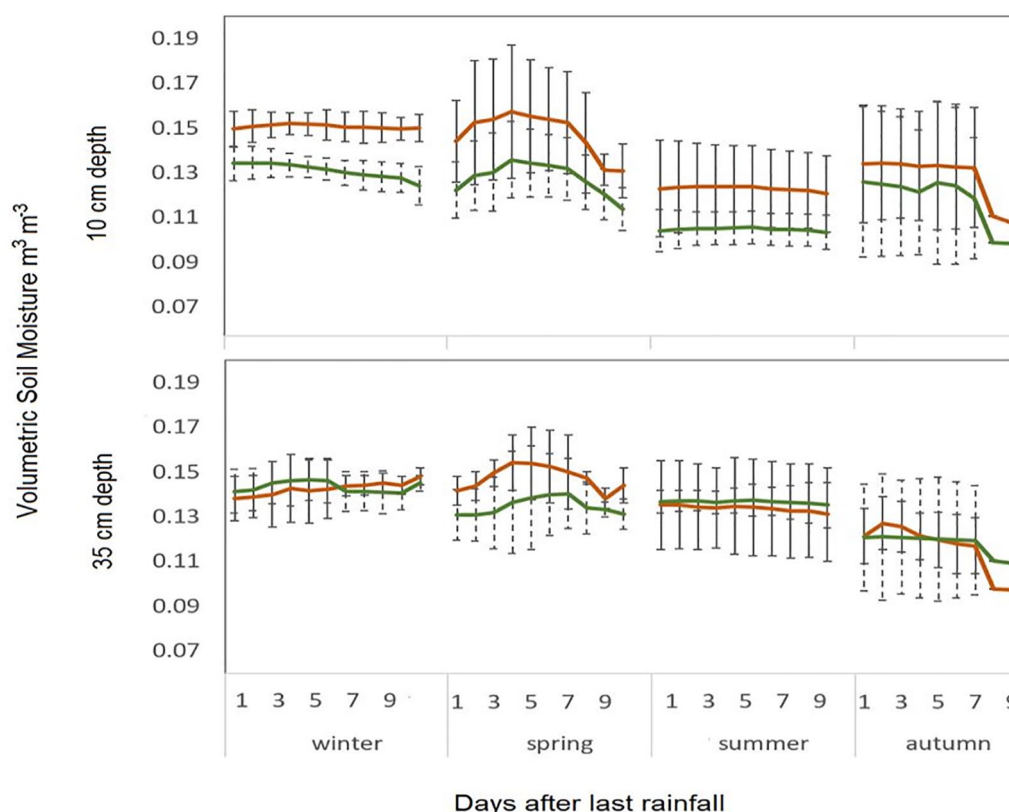
Figure 6. Soil moisture after natural rainfall events, daily average over 10 days. Data obtained during the 2 consecutive years based on 6 rain events in winter, 6 in spring, 3 in summer, and 3 in autumn. The till treatment is represented in orange, and Bra in green color.

increased from 17% to almost 30% in the topsoil (10 cm depth). Similarly, in the Till treatment, represented by orange color, moisture in topsoil increased from 12% to 22%. Both treatments showed similar soil moisture contents (12%) at a depth of 35 cm. At this depth, in Till treatment, the increase in soil moisture was delayed for 3 days. It is suggested that a more direct connection was established between the soil layers for Till treatment, as 3 days after the simulation, there was no difference between moisture, ranging from 14% to 20%, at 10 and 35 cm depth. Although soil tillage temporarily increases the topsoil roughness and favor infiltration, the soil cover also has this effect[75] without breaking the soil structure, and therefore collapsing the macropores and making the soil more susceptible to soil sealing, which are the drawbacks of the tillage (Figure 1E). Highly disturbed soils tend to experience sealing and consequently, higher runoff rates,[76] which can be exacerbated by seasonal changes, leading to a faster runoff in autumn than in summer.[77]

The variability of soil moisture following the natural rainfalls was studied. During 2 years, only rainfall events higher than 2 mm and no new rainfalls during the next 10 days were considered for this study to obtain the soil moisture difference between the top and the deeper layers. This analysis can shed light on the capacity of differently managed soils to retain water for longer periods. Figure 6 shows the evolution of soil moisture changes at 10 and 35 cm depth in both treatments during these 10 days after the last rainfall.

Looking at the chart in the upper part of Figure 6, we can conclude that the differences in moisture between Till and Bra treatments were more obvious in the topsoil (10 cm), especially in winter, when moisture in Till treatment was significantly higher after rainfalls. However, the chart in the lower part of Figure 6 shows that there was no difference in moisture at a depth of 35 cm under both treatments. Only after spring rainfalls, the soils under Till management showed rapid increases in soil moisture at both 10 and 35 cm depths, mimicking the effects of simulated rainfalls. The impact of these differences on vine growth can be limited by the development of vine roots, which are, as previously mentioned, usually deep.[78]

Vine and wine parameters

Vine water status was estimated over 3 consecutive years during the veraison stage (July and August) by the leaf water potential (Ψ_l). Table 3 shows the median values obtained from 12 different leaves per treatment and per year. Although differences could be found between the years, there were no differences between the treatments for the same year. In the second and third years, there were higher values of Ψ_l, but only 25% of leaves had values below –1.5 to –1.6 MPa, which can result in high water stress in plants,[79] as is the lower limit for the matric suction.[80] The Ψ_l increases without irrigation.[81] However, the effect of cover crop on pruning wood weight was significant. This can be due to the fact that vines do not experience immediate signs of water stress

Table 3. Midday leaf water potential (Ψ_l).

YEAR	TREATMENT	Q25	MEDIAN (MPA; N = 12)	Q75
1	Bra	−0.96	−0.85	−0.80
	Till	−0.99	−0.92	−0.90
2	Bra	−1.67	−1.47	−1.35
	Till	−1.60	−1.42	−1.33
3	Bra	−1.59	−1.39	−1.31
	Till	−1.56	−1.50	−1.46

Median and quartiles 25 and 75 for 12 leaves per treatment and year. Kruskal-Wallis test H (1, N = 24) > 0.3; *P* > .3. No significant differences were found between the treatments.

Table 4. Average wine parameters from the 2 vintages (n = 4).

WINE PARAMETERS	TILL	CV (%)	BRA	CV (%)
Alcoholic degree (% vol)	16.0	5	14.4	29
Density	0.99	0	1.0	0
Total dry extract (g L⁻¹)	26.1	9	22.3	66
Volatile acidity (g L⁻¹)	0.38	18	0.4	7
pH	3.8	2	3.7	2
Total acidity (g L⁻¹)	5.4	10	5.7	9
Reducing sugars (g L⁻¹)	1.4	40	1.5	34
TPI (UA)	60.1	59	73.0	29

Abbreviation: TPI, total polyphenols index.

with high values of Ψ_l; however, cumulative water deficit, which was not detected in this study, may have adverse effects on the development of shoots or fruits.[82] Vines under Till treatment on both sides of the row showed 0.55 ± 0.20 kg of pruning weights per vine. However, this parameter for vines under Till treatment on one side and Bra on another side was 0.42 ± 0.18 kg; both values were significantly higher as compared with that for vines under Bra treatment on both sides of the row (0.28 ± 0.08 kg). This indicates that vines are sensitive to soil water availability,[83] which was less in Bra treatment during bud break, flowering, and fruit set, from March to June (Figure 3). Pruning weights can be considered low in the young vineyard. Older vineyards of the same Tempranillo variety and trellis system showed pruning wood weights between 0.75 and 1.25 kg per vine.[84] In this semi-arid climate, cover crops are not used to prevent excessive vigor.[85] On the contrary, attention must be paid to prevent excessive fall in production, as living mulch treatments can reduce vine growth, especially of young ones,[60,86] and restrict the vine vigor.[87]

The results of the analysis of the wine under different soil treatments are shown in Table 4. A trend was observed to less alcoholic degree, total acidity, and total dry extract in cover crop treatment; in addition, higher TPI values were found for this treatment. However, there was a high coefficient of variation between parameters; therefore, no statistical differences were found between the treatments. Similarly, no differences were found between the wine characteristics during the blinded wine tasting practices. However, there has been an interest in these slight differences, as other authors have found positive effects of ground covers on wine quality[88] through an increase in polyphenol contents.

Conclusions

The properly managed *Brachypodium distachyon* cover crop could reduce runoff, therefore improving infiltration in autumn, which can compensate for the competition for soil moisture. Differences in soil moisture were mainly noticed in the topsoil layer (10 cm depth), while no differences were found in deeper layers (35 cm). The cover crop decreased wood pruning weight, attributed to a cumulative water deficit; however, the midday leaf water potential was similar for vines under Tillage or cover crop treatments. Similarly, no differences were found in wine characteristics, although an increasing trend in total polyphenols was observed. However, especial care should be taken while applying cover crops in young vineyards (< 7-10 years), as covers can significantly reduce the growth and yield of the grapevines.

The traditional deep tillage carried out in autumn, which vineyard managers use in an attempt to enhance the infiltration of autumn and winter rainfalls, has the opposite effect, resulting in substantial runoff. In addition to seed prices, the cost of soil erosion must also be taken into account for farmers.

Author Contributions
MJM and RB set up the aims, methods, and drafting of the paper, MR-C, helped in the design and acquisition of data, AG-D, and BS revised critically the versions of the manuscript.

ORCID iDs
MJ Marques ⓘD https://orcid.org/0000-0001-9993-3027
R Bienes ⓘD https://orcid.org/0000-0002-4799-9494

Supplemental Material
Supplemental material for this article is available online.

REFERENCES
1. Vaudour E, Costantini E, Jones GV, Mocali S. An overview of the recent approaches to terroir functional modelling, footprinting and zoning. *Soil.* 2015;1:287-312. doi:10.5194/soil-1-287-2015.
2. Jones VG. The climate component of the terroir. *Elements.* 2018;14:167-172. doi:10.2138/gselements.14.3.167.
3. van Leeuwen C, Roby JP, de Resseguier L. Soil-related terroir factors: a review. *OENO One.* 2018;52:173-188. doi:10.20870/oeno-one.2018.52.2.2208.
4. Deloire A, Vaudour E, Carey V, Bonnardot V, Van Leeuwen C. Grapevine responses to terroir: a global approach. *J Int Sci de la Vigne du Vin.* 2005;39:149-162.

5. IPCC. *Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Pachauri RK, Meyer LA, eds. 2014. https://www.ipcc.ch/site/assets/uploads/2018/05/SYR_AR5_FINAL_full_wcover.pdf

6. Raymond F, Ullmann A, Tramblay Y, Drobinski P, Camberlin P. Evolution of Mediterranean extreme dry spells during the wet season under climate change. *Reg Environ Chang*. 2019;19:2339-2351. doi:10.1007/s10113-019-01526-3.

7. van Leeuwen C, Destrac-Irvine A. Modified grape composition under climate change conditions requires adaptations in the vineyard. *OENO One*. 2017;51:147-154. doi:10.20870/oeno-one.2016.0.0.1647.

8. Lereboullet A-L, Beltrando G, Bardsley DK, Rouvellac E. The viticultural system and climate change: coping with long-term trends in temperature and rainfall in Roussillon, France. *Reg Environ Chang*. 2014;14:1951-1966. doi:10.1007/s10113-013-0446-2.

9. Garcia-Ruiz JM. The effects of land uses on soil erosion in Spain: a review. *CATENA*. 2010;81:1-11. doi:10.1016/j.catena.2010.01.001.

10. Kosmas C, Danalatos N, Cammeraat LH, et al. The effect of land use on runoff and soil erosion rates under Mediterranean conditions. *CATENA*. 1997;29:45-59. doi:10.1016/S0341-8162(96)00062-8.

11. Rodrigo-Comino J. Five decades of soil erosion research in "terroir." The State-of-the-Art. *Earth-Science Rev*. 2018;179:436-447. doi:10.1016/j.earscirev.2018.02.014.

12. Tropeano D. Soil erosion on vineyards in the Tertiary Piedmontese basin (northwestern Italy): studies on experimental areas. *CATENA*. 1983;4:115-127.

13. Ramos MC, Martínez-Casasnovas JA. Nutrient losses from a vineyard soil in Northeastern Spain caused by an extraordinary rainfall event. *CATENA*. 2004;55:79-90. doi:10.1016/S0341-8162(03)00074-2.

14. Prosdocimi M, Cerdà A, Tarolli P. Soil water erosion on Mediterranean vineyards: a review. *CATENA*. 2016;141:1-21. doi:10.1016/j.catena.2016.02.010.

15. Cerdan O, Govers G, Le Bissonnais Y, et al. Rates and spatial variations of soil erosion in Europe: a study based on erosion plot data. *Geomorphology*. 2010;122:167-177. doi:10.1016/j.geomorph.2010.06.011.

16. Arnaez J, Lasanta T, Ruiz-Flano P, Ortigosa L. Factors affecting runoff and erosion under simulated rainfall in Mediterranean vineyards. *Soil Tillage Res*. 2007;93:324-334. doi:10.1016/j.still.2006.05.013.

17. Rodrigo Comino J, Iserloh T, Morvan X, et al. Soil erosion processes in European vineyards: a qualitative comparison of rainfall simulation measurements in Germany, Spain and France. *Hydrology*. 2016;3:6. doi:10.3390/hydrology3010006.

18. Novara A, Gristina L, Saladino SS, Santoro A, Cerdà A. Soil erosion assessment on tillage and alternative soil managements in a Sicilian vineyard. *Soil Tillage Res*. 2011;117:140-147. doi:10.1016/j.still.2011.09.007.

19. Casali J, Gimenez R, De Santisteban L, Alvarez-Mozos J, Mena J, Del Valle de, Lersundi J. Determination of long-term erosion rates in vineyards of Navarre (Spain) using botanical benchmarks. *CATENA*. 2009;78:12-19. doi:10.1016/j.catena.2009.02.015.

20. Rodrigo-Comino J, da Silva AM, Moradi E, Terol E, Cerda A. Improved Stock Unearthing Method (ISUM) as a tool to determine the value of alternative topographic factors in estimating inter-row soil mobilisation in citrus orchards. *Spanish J Soil Sci*. 2020;10:65-80. doi:10.3232/SJSS.2020.V10.N1.05.

21. Barrena-Gonzalez J, Rodrigo-Comino J, Gyasi-Agyei Y, Pulido Fernandez M, Cerda A. Applying the RUSLE and ISUM in the Tierra de Barros Vineyards (extremadura, Spain) to estimate soil mobilisation rates. *Land*. 2020;9:93. doi:10.3390/land9030093.

22. Agata N, Artemi C, Carmelo D, Giuseppe LP, Antonino S, Luciano G. Effectiveness of carbon isotopic signature for estimating soil erosion and deposition rates in Sicilian vineyards. *Soil Tillage Res*. 2015;152:1-7. doi:10.1016/j.still.2015.03.010.

23. Wischmeier WH, Smith DD. *Predicting Rainfall Erosion Losses: A Guide to Conservation Planning. Vol. 537*. Washington, DC: United States Department of Agriculture; 1978. https://naldc.nal.usda.gov/download/CAT79706928/PDF

24. Evrard O, Cerdan O, van Wesemael B, et al. Reliability of an expert-based runoff and erosion model: application of STREAM to different environments. *CATENA*. 2009;78:129-141. doi:10.1016/j.catena.2009.03.009.

25. Ramos MC, Martinez-Casasnovas JA. Soil water content, runoff and soil loss prediction in a small ungauged agricultural basin in the Mediterranean region using the Soil and Water Assessment Tool. *J Agric Sci*. 2015;153:481-496. doi:10.1017/S0021859614000422.

26. Aksoy H, Kavvas ML. A review of hillslope and watershed scale erosion and sediment transport models. *CATENA*. 2005;64:247-271. doi:10.1016/j.catena.2005.08.008.

27. Corbane C, Raclot D, Jacob F, Albergel J, Andrieux P. Remote sensing of soil surface characteristics from a multiscale classification approach. *CATENA*. 2008;75:308-318. doi:10.1016/j.catena.2008.07.009.

28. Rodrigo Comino J, Keesstra SD, Cerda A. Connectivity assessment in Mediterranean vineyards using improved stock unearthing method, LiDAR and soil erosion field surveys. *Earth Surf Process Landforms*. 2018;43:2193-2206. doi:10.1002/esp.4385.

29. Garcia L, Celette F, Gary C, Ripoche A, Valdés-Gómez H, Metay A. Management of service crops for the provision of ecosystem services in vineyards: a review. *Agric Ecosyst Environ*. 2018;251:158-170. doi:10.1016/j.agee.2017.09.030.

30. Luetzenburg G, Bittner MJ, Calsamiglia A, Renschler CS, Estrany J, Poeppl R. Climate and land use change effects on soil erosion in two small agricultural catchment systems Fugnitz—Austria, Can Revull—Spain. *Sci Total Environ*. 2020;704:135389. doi:10.1016/j.scitotenv.2019.135389.

31. Blavet D, De Noni G, Le Bissonnais Y, et al. Effect of land use and management on the early stages of soil water erosion in French Mediterranean vineyards. *Soil Tillage Res*. 2009;106:124-136. doi:10.1016/j.still.2009.04.010.

32. Maigre D, Aerny J. Influence of vineyard management practice on must fermentation and wine quality. *Rev Fr D'oenologie*. 1996;159:46-51.

33. Williams LE, Matthews MA. Grapevine. In: ASA-CSSA-SSA, ed. *Irrigation of Agricultural Crops-Agronomy*. Madison, WI: Agronomy Monograph; 1990;30:1019-1055.

34. Marques MJ, Bienes R, Cuadrado J, Ruiz-Colmenero M, Barbero-Sierra C, Velasco A. Analysing perceptions attitudes and responses of winegrowers about sustainable land management in Central Spain. *L Degrad Dev*. 2015;26:458-467. doi:10.1002/ldr.2355.

35. Saavedra M, Casanova C, Sánchez-Jiménez FJ, Alcántara C. Características de la Gramínea Brachypodium distachyon como Cubierta Vegetal. In: *Protección de Cultivos*. Córdoba, Spain: Consejería de Agricultura, Pesca y Desarrollo Rural; 2016:1-21. https://docplayer.es/55079516-Caracteristicas-de-la-graminea-brachypodium-distachyon-como-cubierta-vegetal.html

36. Ingram PA, Zhu J, Shariff A, Davis IW, Benfey PN, Elich T. High-throughput imaging and analysis of root system architecture in Brachypodium distachyon under differential nutrient availability. *Philos Trans R Soc B: Biological Sci*. 2012;367:1559-1569. doi:10.1098/rstb.2011.0241.

37. Walkley A, Black IA. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Sci*. 1934;37:29-38. doi:10.1097/00010694-193401000-00003.

38. Dewis J, Freitas F. *Physical and Chemical Methods of Soil and Water Analysis*. Rome, Italy: FAO; 1970.

39. Olsen SR, Cole CV, Watanabe FS, Dean JF. *Estimation of Available Phosphorus in Soils by Extraction with Sodium Bicarbonate*. Washington, DC: U.S. Department of Agriculture; 1954.

40. Williams TR. Analytical methods for atomic absorption spectrophotometry (Perkin-Elmer Corp.). *J Chem Educ*. 1972;49:A250. doi:10.1021/ed049pA250.2.

41. Bascomb CL. Rapid method for determination of cation-exchange capacity of calcareous and non-calcareous soils. *J Sci Food Agric*. 1964;15:821. doi:10.1002/jsfa.2740151201.

42. Christiansen JE. *Irrigation by Sprinkling*. University of California Agricultural Experiment Station Bulletin; 1942;670:124.

43. Elías-Castillo F, Ruíz-Beltrán L. *Precipitaciones Máximas En España. Estimaciones Basadas En Métodos Estadísticos*. Madrid, Spain: Ministerio de Agricultura. Monografías; 1979.

44. Scholander PF, Hammel HT, Hemmingsen EA, Bradstreet ED. Hydrostatic pressure and osmotic potential in leaves of mangroves and some other plants. *Proc Natl Acad Sci U S A*. 1964;52:119-125. doi:10.1073/pnas.52.1.119

45. OIV. *Recueil Des Méthodes Internationales d'analyse Des Vins Et Des Moûts. Vol. II. Vol II*. Paris, France: Organisation Internationale de la Vigne et du Vin; 2006.

46. Larmond E. *Méthodes Dáppréciation Sensorielle Des Aliments*. Ottawa, ON, Canada: CRDI; 1969.

47. Roessler E, Pangborn R, Sidel J, Stone H. Expanded statistical tables for estimating significance in paired preference, paired difference, duo-trio and triangle tests. *J Food Sci*. 1978;4:941-947.

48. WRBI. *Reference Base for Soil Resources 2014, Update 2015. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps. No. 106*. Rome, Italy: FAO; 2015.

49. Klingebiel AA, Montgomery PH. *Land Capability Classification. Agricultural Handbook 210*. Office USGP, ed. Washington, DC: USDA; 2010.

50. Loveland P, Webb J. Is there a critical level of organic matter in the agricultural soils of temperate regions: a review. *Soil Tillage Res*. 2003;70:1-18. doi:10.1016/S0167-1987(02)00139-3.

51. Morlat R, Venin G, Jacquet A. Influence du mode d'entretien du sol sur l'alimentation en eau de la vigne en Anjou. Conséquences agronomiques. *Agronomie*. 1987;7:183-191. doi:10.1051/agro:19870305.

52. Ruiz-Colmenero M, Bienes R, Marques MJ. Soil and water conservation dilemmas associated with the use of green cover in steep vineyards. *Soil Tillage Res*. 2011;117:211-223. doi:10.1016/j.still.2011.10.004.

53. Celette F, Gaudin R, Gary C. Spatial and temporal changes to the water regime of a Mediterranean vineyard due to the adoption of cover cropping. *Eur J Agron*. 2008;29:153-162. doi:10.1016/j.eja.2008.04.007.

54. Uliarte EM, Schultz HR, Frings C, Pfister M, Parera CA, del Monte RF. Seasonal dynamics of CO2 balance and water consumption of C-3 and C-4-type cover crops compared to bare soil in a suitability study for their use in vineyards in Germany and Argentina. *Agric For Meteorol*. 2013;181:1-16. doi:10.1016/j.agrformet.2013.06.019.

55. Delpuech X, Metay A. Adapting cover crop soil coverage to soil depth to limit competition for water in a Mediterranean vineyard. *Eur J Agron*. 2018;97:60-69. doi:10.1016/j.eja.2018.04.013.

56. Li T, Hao X, Kang S. Spatiotemporal variability of soil moisture as affected by soil properties during irrigation cycles. *Soil Sci Soc Am J*. 2014;78:598-608. doi:10.2136/sssaj2013.07.0269.

57. Comas LH, Bauerle TL, Eissenstat DM. Biological and environmental factors controlling root dynamics and function: effects of root ageing and soil moisture. *Aust J Grape Wine Res*. 2010;16:131-137. doi:10.1111/j.1755-0238.2009.00078.x.

58. Celette F, Wery J, Chantelot E, Celette J, Gary C. Belowground interactions in a vine (Vitis vinifera L.)-tall fescue (Festuca arundinacea Shreb.) intercropping system: water relations and growth. *Plant Soil*. 2005;276:205-217. doi:10.1007/s11104-005-4415-5.

59. Wilson TG, Kustas WP, Alfieri JG, et al. Relationships between soil water content, evapotranspiration, and irrigation measurements in a California drip-irrigated Pinot noir vineyard. *Agric Water Manag*. 2020;237:106186. doi:10.1016/j.agwat.2020.106186.

60. Klodd AE, Eissenstat DM, Wolf TK, Centinari M. Coping with cover crop competition in mature grapevines. *Plant Soil*. 2016;400:391-402. doi:10.1007/s11104-015-2748-2.

61. Ruiz-Colmenero M, Bienes R, Eldridge DJ, Marques MJ. Vegetation cover reduces erosion and enhances soil organic carbon in a vineyard in the central Spain. *CATENA*. 2013;104:153-160. doi:10.1016/j.catena.2012.11.007.

62. Napoli M, Marta AD, Zanchi CA, Orlandini S. Assessment of soil and nutrient losses by runoff under different soil management practices in an Italian hilly vineyard. *Soil Tillage Res*. 2017;168:71-80. doi:10.1016/j.still.2016.12.011.

63. Biddoccu M, Ferraris S, Opsi F, Cavallo E. Effects of soil management on long-term runoff and soil erosion rates in sloping vineyards. In: Lollino G, Manconi A, Clague J, Shan W, Chiarle M, eds. *Engineering Geology for Society and Territory – Volume 1*. Cham, Switzerland: Springer International Publishing; 2015:159-163.

64. Capello G, Biddoccu M, Ferraris S, Cavallo E. Effects of tractor passes on hydrological and soil erosion processes in tilled and grassed vineyards. *Water*. 2019;11:2118. doi:10.3390/w11102118.

65. Casalí J, Gastesi R, Álvarez-Mozos J, et al. Runoff, erosion, and water quality of agricultural watersheds in central Navarre (Spain). *Agric Water Manag*. 2008;95:1111-1128. doi:10.1016/j.agwat.2008.06.013.

66. Biddoccu M, Ferraris S, Opsi F, Cavallo E. Long-term monitoring of soil management effects on runoff and soil erosion in sloping vineyards in Alto Monferrato (North–West Italy). *Soil Tillage Res*. 2016;155:176-189. doi:10.1016/j.still.2015.07.005.

67. Biddoccu M, Ferraris S, Cavallo E, Opsi F, Previati M, Canone D. Hillslope vineyard rainfall-runoff measurements in relation to soil infiltration and water content. *Procedia Environ Sci*. 2013;19:351-360. doi:10.1016/j.proenv.2013.06.040.

68. Vermang J, Norton D, Marco da Silva A, Huanh C, Gabriels D. *Action of Rain and Wind in Soil Degradation Processes*. Vermang J, Gabriels , Corneils W, eds. Ghent, Belgium: UNESCO Chair of Eremology; 2011:37-43.

69. Saleh A. Soil roughness measurement: chain method. *J Soil Water Conserv*. 1993;48:527-529. https://www.jswconline.org/content/48/6/527

70. Vermang J, Norton LD, Baetens JM, Huang C, Cornelis WM, Gabriels D. quantification of soil surface roughness evolution under simulated rainfall. *Trans ASABE*. 2013;56:505-514.

71. Battany MC, Grismer ME. Rainfall runoff and erosion in Napa Valley vineyards: effects of slope, cover and surface roughness. *Hydrol Process*. 2000;14:1289-1304. doi:10.1002/(SICI)1099-1085(200005)14.

72. Moret D, Arrúe JL, López MV, Gracia R. Influence of fallowing practices on soil water and precipitation storage efficiency in semiarid Aragon (NE Spain). *Agric Water Manag*. 2006;82:161-176. doi:10.1016/j.agwat.2005.07.019.

73. Martínez-Zavala L, López AJ, Bellinfante N. Seasonal variability of runoff and soil loss on forest road backslopes under simulated rainfall. *CATENA*. 2008;74:73-79. doi:10.1016/j.catena.2008.03.006.

74. Bavougian CM, Read PE. Mulch and groundcover effects on soil temperature and moisture, surface reflectance, grapevine water potential, and vineyard weed management. *PeerJ*. 2018;6:e5082. doi:10.7717/peerj.5082.

75. Styczen ME, Morgan RPC. *Slope stabilization and Erosion Control: A Bioengineering Approach*, Morgan RPC, Rickson RJ, eds. London, England: E&FN SPON. 1995:5-58.

76. Ramos MC, Martínez-Casasnovas JA. Soil loss and soil water content affected by land levelling in Penedès vineyards, NE Spain. *CATENA*. 2007;71:210-217. doi:10.1016/j.catena.2007.03.001.

77. Cerdà A. The effect of season and parent material on water erosion on highly eroded soils in eastern Spain. *J Arid Environ*. 2002;52:319-337. doi:10.1016/j.catena.2007.03.001.

78. Richards D. The grape root system. *Hort Rev*. 1983;5:127-168.

79. Romero P, Ignacio Fernandez-Fernandez J, Martinez-Cutillas A. Physiological thresholds for efficient regulated deficit-irrigation management in winegrapes frown under semiarid conditions. *Am J Enol Vitic*. 2010;61:300-312.

80. Ritchie J. Water dynamics in the soil-plant-atmosphere system. *Plant Soil*. 1981;58:81-96. http://www.jstor.org/stable/42933782

81. Williams LE, Baeza P, Vaughn P. Midday measurements of leaf water potential and stomatal conductance are highly correlated with daily water use of Thompson Seedless grapevines. *Irrig Sci*. 2012;30:201-212. doi:10.1007/s00271-011-0276-2.

82. Williams LE, Dokoozlian NK, Wample RL. Grape. In: Shaffer B, Andersen P, eds. *Handbook of Environmental Physiology of Fruit Crops. Volume 1: Temperate Crops*. Boca Raton, FL: CRC Press Inc.; 1994:85-133.

83. White RE. *Understanding Vineyard Soils*. 2nd ed. New York, NY: Oxford University; 2015.

84. Millan B, Diago MP, Aquino A, Palacios F, Tardaguila J. Vineyard pruning weight assessment by machine vision: towards an on-the-go measurement system: this article is published in cooperation with the 21th GIESCO International Meeting, June 23-28 2019, Thessaloniki, Greece. Guests editors : Stefanos Koundouras. *OENO One*. 2019;53. doi:10.20870/oeno-one.2019.53.2.2416

85. Smart R, Robinson M. *Sunlight into Wine: A Handbook for Winegrape Canopy Management*. Underdale, SA, Australia: Winetitles; 1991.

86. Vukicevich E, Lowery T, Hart M. Effects of living mulch on young vine growth and soil in a semi-arid vineyard. *VITIS*. 2019;58:113-122. doi:10.5073/vitis.2019.58.113-122.

87. Karl A, Merwin IA, Brown MG, Hervieux RA, Vanden Heuvel JE. Impact of undervine management on vine growth, yield, fruit composition, and wine sensory analyses in cabernet franc. *Am J Enol Vitic*. 2016;67:269-280. doi:10.5344/ajev.2016.15061.

88. Dry PR, Loveys BR, McCarthy MG, Stoll M. Strategic irrigation management in Australian vineyards. *J Int Sci Vigne Vin*. 2001;35:129-139. http://hdl.handle.net/102.100.100/202263?index=1