



Conducting an in situ evaluation of erodibility in a Mediterranean semi-arid and conventional vineyard in Granada province (Southern Spain) through rainfall simulation experiments

José Parra Ortega¹ · Laura Cambroner¹ · María Alcarria Salas¹ · José Luis Rodríguez¹ · Víctor Hugo Durán-Zuazo² · Saskia D. Keesstra^{1,3,4} · Jesús Rodrigo-Comino¹

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Abstract

Vineyards in Europe has been fundamental for food, drink and cosmetic production, and job creation; however, in recent decades due to increased cultivation intensity, numerous negative consequences, including erosion, have been observed. Erodibility or susceptibility to erosion is a little-studied parameter in vineyards but is crucial for analyzing the vulnerability of this crop. Therefore, in this research, a small portable rainfall simulator was used as a useful tool for assessing erodibility, combined with other methods such as soil analyses or infiltration measurements in a semi-arid vineyard located in the Granada province (Spain) considering 20 different hotspots at diverse hillslope positions along the inter-rows and close to the traffic roads. The experiments were conducted in spring 2022 under dry soil conditions. Our results display susceptibility to erosion, particularly on steeper parts such as the shoulder and backslopes. In these areas, runoff gained momentum, carrying a significant sediment load, diminishing the effectiveness of stone cover, and occasionally leading to its removal, especially near the roads. Nevertheless, it is observed that increased roughness plays a mitigating role by slowing down runoff. Using linear correlation analysis and Spearman rank coefficient, we observed this effect is linked to factors such as stoniness, vegetation, and moderate tillage. Conversely, in the flatter zones, primarily in lower areas, reduced runoff and delayed onset are primarily influenced by factors such as roughness, type of cover, material composition, and organic matter content. We concluded that this study case can demonstrate that erodibility in vineyards can shed light as an extra parameter to inform farmers, rural inhabitants, and policymakers about the extreme problem of the vulnerable soils of vineyards.

Keywords Soil erodibility · Soil erosion · Viticulture · In situ experiments · Hydrological processes

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✉ Jesús Rodrigo-Comino
jesusrc@ugr.es

Laura Cambroner
lauracambro@correo.ugr.es

María Alcarria Salas
mariaalcarria@correo.ugr.es

José Luis Rodríguez
joseluisrl@correo.ugr.es

Víctor Hugo Durán-Zuazo
victorh.duran@juntadeandalucia.es

Saskia D. Keesstra
saskia.keesstra@climate-kic.org

¹ Departamento de Análisis Geográfico Regional y Geografía Física, Facultad de Filosofía y Letras, Campus Universitario de Cartuja, University of Granada, 18071 Granada, Spain

² IFAPA Centro “Camino de Purchil”, Camino de Purchil s/n, 18004 Granada, Spain

³ Climate-KIC Holding B.V. Plantage, Middenlaan 45, Amsterdam, The Netherlands

⁴ Team Soil Water and Land Use, Wageningen Environmental Research, P.O. Box 47, 6700 AA Wageningen, The Netherlands

Introduction

Agriculture has been an essential economic sector in Europe for centuries. It has played a crucial role in providing food for the population as well as creating many jobs. Over the past decades, especially during the 21st century, it has taken on a more commercial and technological focus. For this reason, most of the land is dedicated to agriculture; the area of cultivated and plowed land accounts for approximately 25% of Europe considering the last reports of the European Environmental Agency. Over the years, there has been an attempt to maximize production, which has led to an intensification of cultivation; however, this has been affected by inadequate soil management, resulting in serious environmental consequences such as increased erosion and runoff (Boardman et al. 2003; Cerdà et al. 2009; Kairis et al. 2013). Soil erosion is an environmental issue that affects many countries, including Spain, and can have serious consequences both for agriculture and the local economy (García-Ruiz 2010).

Viticulture is an agricultural activity, especially important in a country like Spain. It is the world's third-largest wine producer, behind countries such as Italy and France, although production is lower compared with previous years (International Organisation of Vine and Wine/Intergovernmental Organisation 2019). Despite being third in production, Spain ranks at the top in terms of the largest vineyard cultivation area globally. In Andalusia, due to its lithology, topography, and climate, vineyards are found on steep slopes, old embankments, or between different levels of embankments and river terraces. Additionally, the soils in these areas are often bare without vegetative cover for much of the year, characterized by a high percentage of rock fragments (Rodrigo-Comino et al. 2017). It is worth noting that these crops often undergo excessive tillage, causing the soils to become bare and exposed to rainfall, leading to raindrops further eroding the soil and triggering surface runoff, displacing the eroded material (Martínez-Casasnovas et al. 2005; Parras-Alcántara et al. 2016; Taguas et al. 2013).

Soil erodibility is a parameter that has been under studied in Spanish vineyards, especially in Andalusia, which is defined as a measure of soil susceptibility to erosion and is influenced by factors such as texture, structure, porosity, and chemical composition (Auerswald et al. 2014; Bryan 2000). Soils with low erodibility are less susceptible to erosion, while soils with high erodibility are more prone to soil and nutrient loss (Choi et al. 2016; Nemetova and Danacova 2019; Parlak et al. 2016). The relationship between erosion in Spanish vineyards and soil erodibility, if further analyzed, would be key to understanding and addressing potential solutions to mitigate it. However, the

scientific and technical literature does not provide clear insights into this, at least not with in situ experiments, especially in vineyards. There is a recent publication at the European scale trying to shed light on it but the resolution is large and is not divided into land uses (Panagos et al. 2014).

In situ measurement of soil erosion is a complex issue, and various techniques exist for its evaluation, but they require long monitoring periods. One of the most used methods is the direct measurement of the amount of soil eroded in a specific area, using techniques such as measuring changes in soil profile height before and after erosion (Rodrigo-Comino et al. 2019) or measuring the amount of sediment and water deposited in boxes or containers placed at the base of the plot along the main slope direction (Biddoccu et al. 2017). In terms of erosion measurement and erodibility modeling, it can also be predicted using mathematical models such as the Water Erosion Prediction Project (WEPP) (Flanagan et al. 2001) or the Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1965) and its revision (RUSLE) (Renard et al. 1991). Another option is to measure erosion in the field using runoff or rainfall simulators, which allow for field experiments to quantify erosion and its activation process (Cerdà 1999).

The portable rainfall simulator is a device used to simulate artificial rainfall in a specific area with controlled conditions such as intensity, duration, kinetic energy, drop size, etc. (Bryan and De Ploey 1983; Cerdà 1998a). Its main purpose is to measure the process of soil erosion activation in the field or under laboratory conditions. Simulators can be of various types, which, according to (Iserloh et al. 2013), are classified on the basis of the nozzle type, such as those developed in Tübingen, Córdoba, or Basel; on the basis of capillary type, developed in Granada and Wageningen; and on the basis of circular plot diffuser type with a base, developed in Almería, Málaga, Murcia, Trier, Zaragoza, Valencia, Zaragoza University, and La Rioja. Mini-rainfall simulators are also a type of portable simulator with a very small analysis area, and the Eijkelkamp model from the Netherlands stands out. This simulator is a very useful tool as it allows for numerous experiments to be conducted in less time, with less water consumption and fewer personnel, reducing costs and effort. However, its representativeness is lower due to its study area and only allows for the estimation of soil erodibility (Danáčová et al. 2017). Nevertheless, for this study, this property is the ultimate research goal. This type of simulator would be the first time it is used to measure erosion and erodibility in Spanish and Andalusian vineyards, making it an innovative method that could provide complementary results for future research and help address the issue of soil erosion and its susceptibility.

To complete these types of studies, it is also common to use other instruments such as infiltrometers, which allow for

measurements of water velocity through the surface horizons of the soil (Naik and Pekkat 2022). Infiltrometers consist of a cylinder subjected to a water load, and the volume of liquid drained per unit of time is measured, known as infiltration capacity. There are different types of infiltrometers, including cylinder or inundation infiltrometers (single or double), closed infiltrometers, or tension infiltrometers (Alagna et al. 2016; Di Prima 2015). Therefore, the main goal of this research is to estimate soil erodibility using a mini-rainfall simulator in a vineyard located in the province of Granada. To achieve this, 20 rainfall simulations and 20 infiltration measurements supported by the analysis of key soil properties were conducted. The specific objectives were as follows: (i) estimate the time the soil is capable of retaining water before mobilizing it as surface runoff; (ii) identify factors related to topography or soil properties that affect the activation of runoff and erosion processes; (iii) propose measures to reduce soil vulnerability to erosion to prevent it from affecting the quality and quantity of grape production; and (iv) lay the foundation for a potential new research topic with data that complements the analysis of environmental degradation and the impact of climate change on Mediterranean vineyards.

Materials and methods

Study area

A total of 20 rainfall simulations and twenty infiltration measurements, supported by the analysis of key soil properties, were conducted between March and April 2023, in a vineyard located in the municipality of Villamena, which belongs to the Valle de Lecrín region, in the province of Granada. The study area is located within the Alpujarride Complex, corresponding to the most recent materials of the mountain chains of Albuñuelas, Almijara, and Guájares, along with the southwestern part of Sierra Nevada. It consists of mica schists, limestone, and dolomite, which are not continuous. The study area is located within the Alpujarride Complex, specifically, it corresponds to the most recent materials of the mountain chains of Albuñuelas, Almijara, and Guájares, along with the southwestern branch of Sierra Nevada. The Alpujarride Beds are classified into two groups, those located to the north of the Pinos del Valle parallel and those to the south; the plot is located in the northern area of Pinos del Valle, between Dúrcal and Jayena. Alcázar Bed, formed by variegated phyllites (violet, gray, green, and reddish colors). The presence of limestones and dolomites is not continuous and is poorly developed. The Cástaras Bed is mainly composed of phyllites alternating with quartzites at the base. The roof exhibits a well-represented carbonate formation.

It has a Mediterranean climate (Padul Meteorological Station—Institute of Agricultural and Fisheries Research and Training), affected by high temperatures and severe drought since 2022. From early February to late May, the average temperature is 13.9 °C, and rainfall has not exceeded 5 mm during these study months (meteorological station installed, which records data from January 2023). The average relative humidity has been 47.1%. Overall, rainfall intensity is moderate, with an absolute maximum in winter, with December being the rainiest month. The second peak in rainfall occurs in spring with little difference from the autumn months. On the other hand, the driest months correspond to summer, with August being the least rainy month.

Rainfall simulation experiments

For the rainfall simulation experiments in the vineyard, a total of 20 different points were selected (Fig. 1) during 4 days of fieldwork involving at least three people. Each day, a total of five experiments were conducted to assess the effects of rain on the soil under known and controlled conditions (intensity, drop size, amount of water applied over an area, and duration of the experiment). In this research, the Eijkelkamp model from the Netherlands was used, which consists of a box with a sprinkler system that simulates rainfall intensity and type. The water sprayed by the sprinklers falls onto a specific area of soil, allowing for the measurement of the amount of sediment lost, runoff, and water absorbed by the soil. This simulator is a very useful tool as it allows for numerous experiments to be conducted in less time, with less water consumption and fewer personnel, reducing costs and effort. However, its representativeness is lower due to its study area being less than 0.0625 m², and in this research, it will allow us to estimate erodibility (Iserloh et al. 2013). The experiment is carried out by discharging an identical volume of water at each point, collecting the resulting water as runoff, and soil loss that flows through the drainage point or outlet. The drop size is 5.9 mm, falling during 360 s with an intensity of 6 mm min⁻¹. The mini-portable rainfall simulator consists of three main parts and some accessories (Fig. 2a, b). The first part consists of the showerhead, which has an internal regulator that generates uniform rainfall through 49 tubes working as capillary pressure flow. The second part is the adjustable aluminum stand on which the showerhead is placed, allowing to use a specific height (in this case, 35–40 cm). Finally, there is a frame to place the adjustable stand on top of it, ensuring its stability and preventing water from escaping from the sides, thus aiding in the flow toward the outlet or channel. To conduct rainfall simulation experiments, it is recommended to carry out them under dry conditions to avoid extreme differences in previous soil moisture content as demonstrated by other authors (Cerdà 1998a, b).

Fig. 1 Localization of the study area and experimental plots

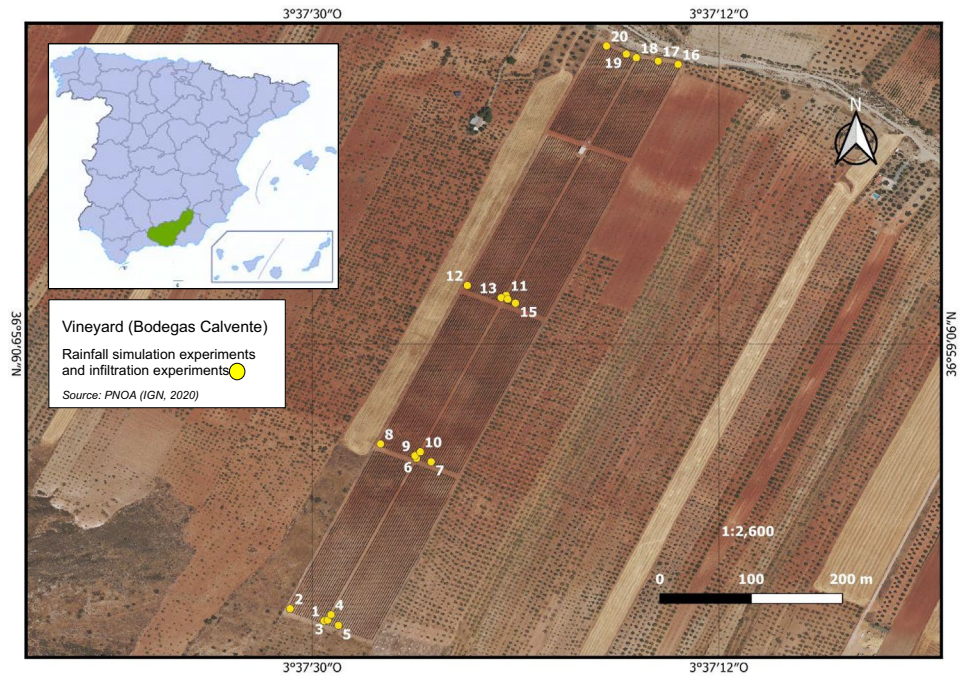
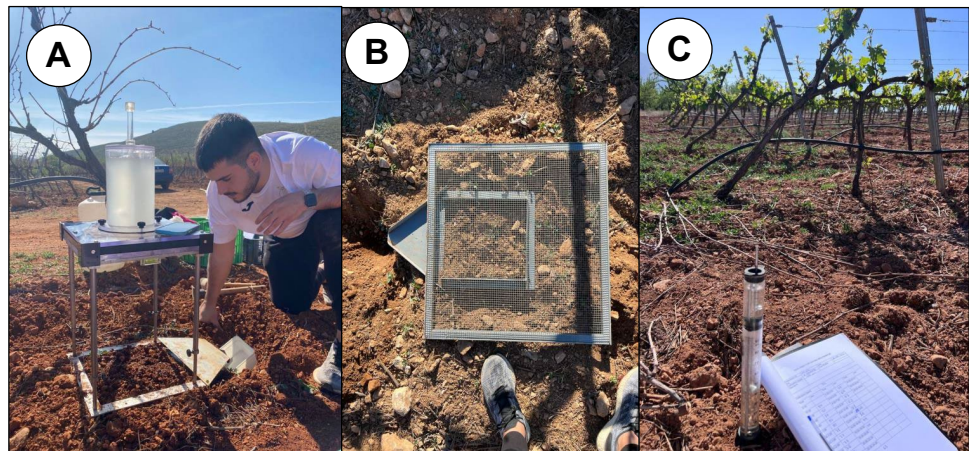


Fig. 2 Field campaign using the mini-rainfall simulator (a, b) and mini-disc infiltrometer (c)



Before starting each experiment, some data were recorded to assess which factors are influencing soil erodibility and runoff activation (Fig. 2b): (i) vegetation cover (%) estimated using a grid cell with vegetation visible in a photograph (Cerdà et al. 1997); (ii) stone cover (%), similar to the previous factor; (iii) surface roughness using the chain method horizontally and vertically; and (iv) slope, measured using a digital clinometer. During each experiment, which lasts approximately 6 min, the same person (to avoid measurement bias) should record the following times in seconds at the beginning and at each 1-min interval: (i) time to ponding (T_p) as the time it takes for the entire plot to become wet from the start of water discharge; (ii) time to outlet (T_o) as the exact moment when the first drop flows through the plot; and, (iii) time to runoff generation (T_r) or the exact time at

which the first drop reaches the outlet and runoff begins. When the experiment finishes, runoff volume (l; total volume of water collected at the end of the outlet at each interval) and sediment yield (g; material detached by drop impact -splash- and transported by runoff) are determined later in the laboratory. The runoff water should be evaporated at 110 °C, and the total solids are then weighted. Finally, sediment concentration can be obtained dividing sediment yield by runoff (g l^{-1}).

Infiltration measurements

At the same time that rainfall simulations are carried out, infiltration measurements were taken using a mini-disc infiltrometer. A total of 20 repetitions were performed in

near areas where the rainfall simulations took place. The experiment results provide data on hydraulic conductivity and infiltration rates. In Fig. 2c, the mini-disc infiltrometer, which consists of an acrylic tube with a semi-permeable disk at the bottom and a tube at the top for regulating suction can be observed. The plastic tank is filled, setting the suction (which in this case was positioned at 4.5 cm), and measurements are taken at regular intervals (10 s, 30 s, 1 min, 2 min, and 5 min) with the help of a stopwatch.

Related key soil properties

Once each rainfall simulation was completed, soil samples (between 0.5 and 1 kg; $n = 20$) were collected from three points near the experiment. All samples were numbered and stored in airtight bags for transportation to the laboratory. In the laboratory, they were sieved, separating the fine material (< 2 mm) from the coarse one (> 2 mm). Subsequently, organic matter analysis was carried out in a muffle furnace at a temperature of 430 °C, following the ignition estimation method (Ball 1964; Rather 1918). Furthermore, pH was calculated by direct measurement using a pH meter. To do this, samples must be prepared by diluting them in distilled water. Once calibrated, the pH of each sample was measured by inserting the electrode into the diluted sample.

Statistical analysis

The data obtained were organized and normalized. Then, the data were encoded in Excel data sheets (Microsoft, USA). Firstly, average values, standard deviations, and maximum/minimum values were estimated. The results were analyzed using scatter plots to observe linear regressions. Subsequently, using SPSS software (IBM, USA), correlations were conducted using the Spearman method to observe if there were statistically significant relationships ($p < 0.001$ and $p < 0.5$) after the normalization of the dataset. This coefficient was used when non-linear relationships are expected instead of other coefficients such as the Pearson correlation.

Results

Soil properties and plot characteristics

In Fig. 3, the key soil properties of the plots are depicted. The experimental area are characterized by more than 54% of gravels (> 2 mm). The overall averages for organic matter and pH are 6.39 and 7.5, respectively. The organic matter values range from 3.86 to 11.13, corresponding to samples 13 (zone 3, road) and 14 (zone 3, inter-row). The pH values

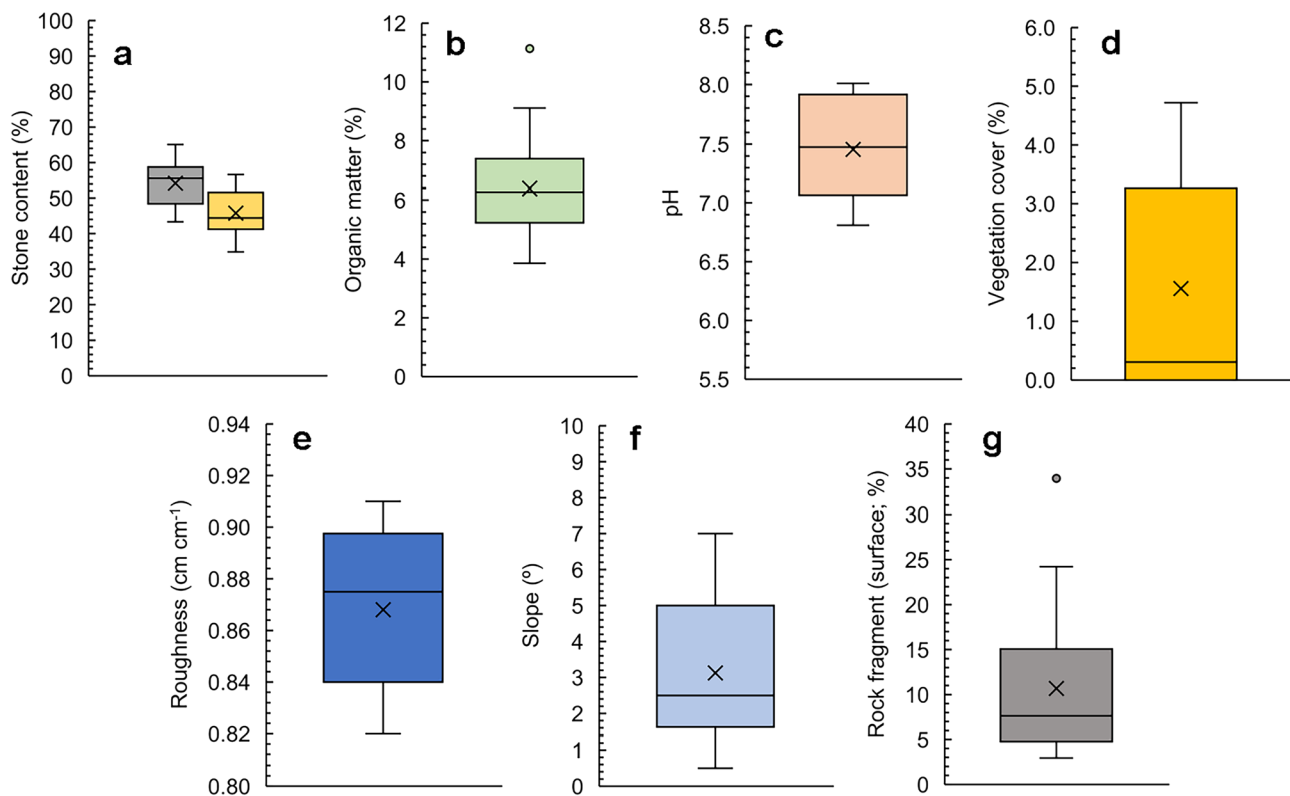


Fig. 3 Soil properties and environmental characteristics of the rainfall simulation plots

vary between 6.8 and 8.0, corresponding with samples 6 (zone 2, road) and 7 (zone 2, inter-row). The average percentage of vegetation cover and rock fragments were 1.6% and 10.7%, respectively. The maximum value for vegetation cover is 4.7%, and for rock fragments at the surface, it is 33.9%. Regarding the minimum values, rock fragments have a minimum of 2.9%, while vegetation was 0%, especially in the roads. As for the slope, the average value was 3.1°, with a maximum of 7° and a minimum of 0.5°. The maximum slope was observed in the upper zone of the vineyard, while the minimum was in the backslope zone. Finally, roughness averaged 0.9 mm mm⁻¹ with minimum values reaching 0.8 mm mm⁻¹.

Infiltration measurements

The measurements conducted with the mini-disc infiltrometer are showed in Fig. 4. Specifically, in Fig. 4a, the results are depicted per intervals and in Fig. 4b per measurement on the field. During the first minute, the average infiltration rates per interval overpassed 7 mm s⁻¹, then, it decreased to less than 4 mm s⁻¹. From the second minute, with wider intervals (30 s), the average rates are 2.5 mm s⁻¹, and then it decreases from the tenth minute to 1.1 mm s⁻¹. Then, the steady state is reached averaging 0.4 mm s⁻¹. The highest infiltration measurements were the sample points 5, 13, and 15, with more than 3 mm s⁻¹, all of them situated in the shoulder and backslope parts within the inter-row areas. On the contrary, the lowest average infiltration rates were recorded at sampling points 1, 10, and 11, corresponding with the same hillslope positions but situated along the roads.

Rainfall simulation results

In Fig. 5, box plots shows the hydrological responses during the initial time of all rainfall simulation experiments. The

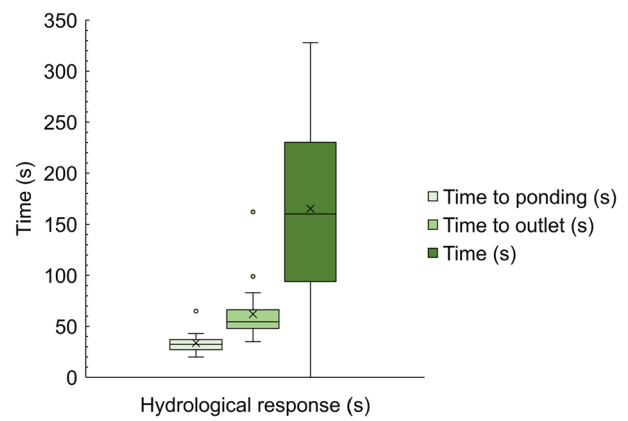
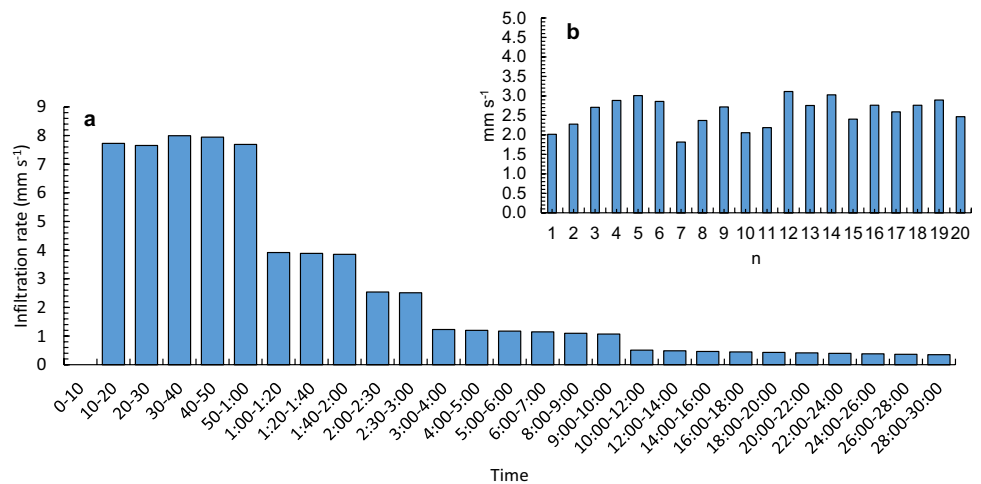


Fig. 5 Hydrological response during the rainfall simulation experiments

average time for *T_p* was 33.7 s, ranging from a maximum of 65 s to a minimum of 20 s. The duration until the first drop reaches the drain (*T_o*) averaged at 62.1 s, with a maximum of 162 s and a minimum of 35 s. Finally, the time it takes for runoff to generate (*T_r*) recorded an average value of 165.1 s, ranging from a maximum of 320 s to a minimum of 0 s, reflecting a case where all the water infiltrated, and no runoff occurred.

In Figs. 6 and 7 scatter plots depict the results of total volume and soil loss in relation to environmental plot characteristics and infiltration measurements. Concerning runoff, the average volume was 0.13 l, with a maximum of 1.17 l (sampling point number 3, on the road) and a minimum of 0 (sampling point number 2, near a vine in the inter-row area), where no runoff occurred in one rainfall simulation. Regarding sediment contribution, the average value was 0.90 g of solids, with a maximum of 9 g and a minimum of 0 g, similar to the patterns observed in the same sampling points (3 and 2). These results corresponded to the highest average sediment concentrations in sampling points 3

Fig. 4 Average infiltration rates per Interval and total values



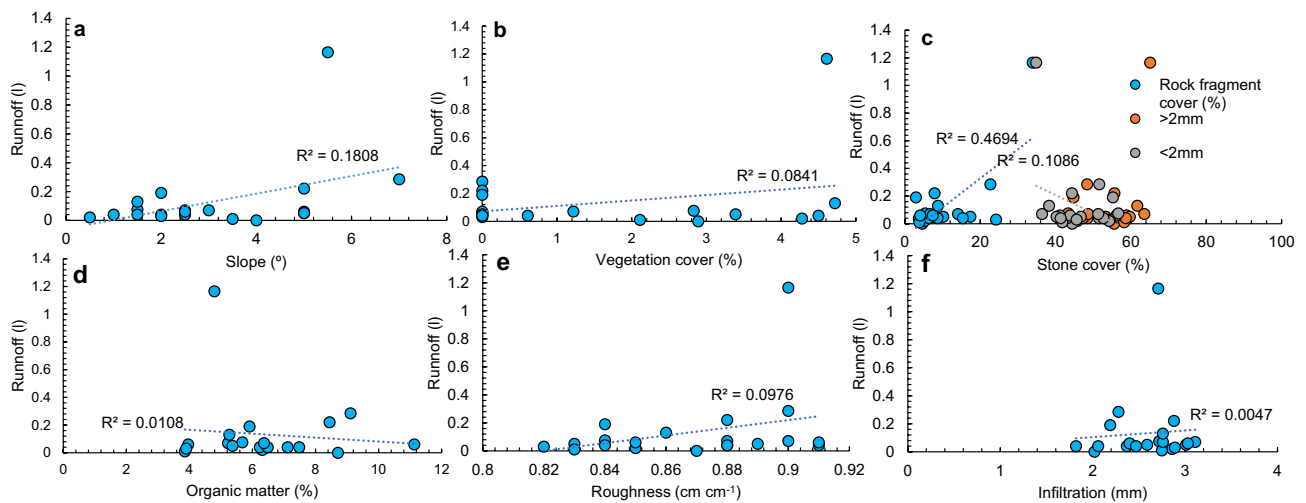


Fig. 6 Scatter plots depicting total runoff volume and conditioning factors related to the plot characteristics

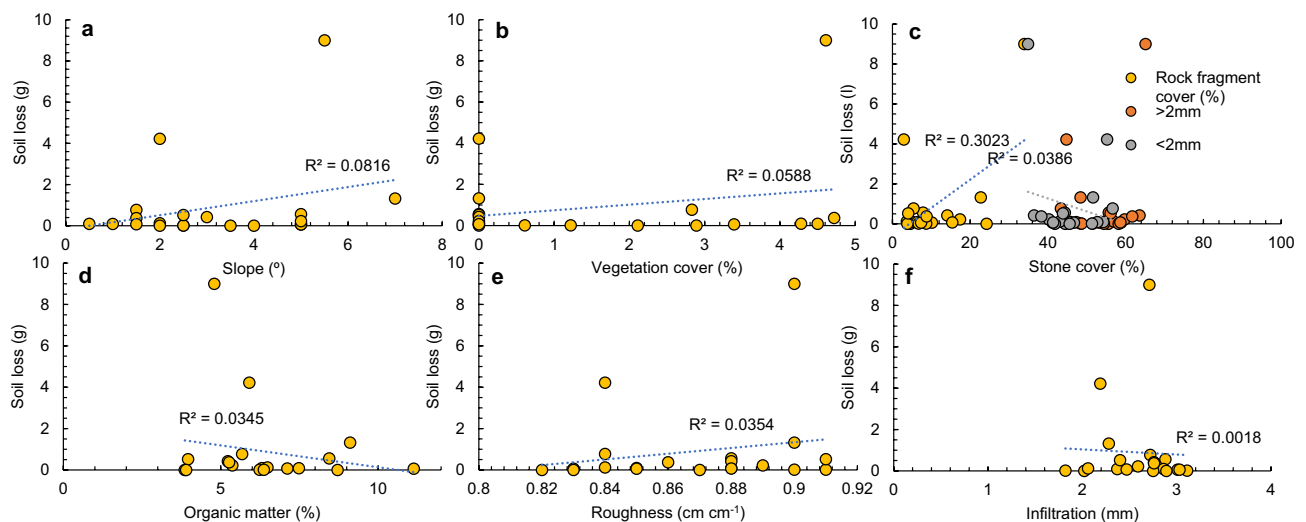


Fig. 7 Scatter plots depicting total soil loss and conditioning factors related to the plot characteristics

(11.3 g l⁻¹) and 11 (22.3 g l⁻¹), both situated along the roads. In the inter-row areas, the highest average sediment concentrations ranged from 8.7 to 8.8 g l⁻¹ in sampling points 15 and 9, respectively. Finally, scatter plot graphs register that an increase in slope (degrees) correlates with an increase in runoff and sediment contribution. There is also an impact of increased stone coverage on overall values in runoff and soil loss. In supplementary material 1, a table summarizing all the results of each simulation can be found.

Correlation among soil erodibility results and environmental plot characteristics

In Table 1 and 2, multiple correlation analyses, specifically Spearman rank coefficients, were conducted. Initially, total

soil erodibility results were considered, showing the highest significant correlations between roughness and stone cover with time to outlet, reaching -0.52 and -0.53 , respectively. In the inter-row areas of the rainfall simulation experiments, the highest correlations were observed between < 2 mm or fine soil grain size fraction and T_p (-0.51) and R (0.50). For experiments conducted on roads, the absence of vegetation cover led to a decrease in T_o (0.61) and T_r (0.74), accompanied by an increase in sediment yield (-0.67) and runoff (-0.79). Additionally, roughness showed a significant correlation with T_o (-0.61) and T_r (-0.57). Moreover, as the slope increased, T_p recorded a reduction (-0.65).

Focusing on correlations per sampling point area, in the shoulder, an increase in stone cover generated a positive correlation with S_y (0.90), R (0.90), and S_c (0.90). Similar

Table 1 Spearman rank coefficient between soil erodibility results and environmental plot characteristics (total and considering inter-row or close to the roads)

	Total	T_p	T_o	T_r	S_y	R	S_c
Total	Vc	0.19	0.09	-0.20	-0.10	-0.09	-0.14
	Rg	-0.02	-0.52*	-0.29	0.28	0.34	0.22
	Scover	-0.09	-0.53*	-0.05	0.09	0.30	0.02
	Sl	-0.02	-0.02	-0.26	0.12	0.35	0.04
	> 2 mm	-0.20	-0.07	0.17	0.10	0.15	0.19
	< 2 mm	-0.28	0.09	0.20	0.08	0.09	0.20
	OM	0.14	0.22	-0.35	-0.07	0.03	-0.17
Inter-row areas Roads	Vc	0.20	0.43	-0.37	-0.26	-0.23	-0.31
	Rg	-0.05	-0.45	-0.05	0.29	0.25	0.19
	Scover	-0.19	-0.25	0.49	-0.01	-0.02	-0.06
	Sl	0.02	0.23	-0.13	0.08	0.29	0.08
	> 2 mm	-0.44	0.07	0.40	0.12	0.26	0.35
	< 2 mm	-0.51	0.01	0.14	0.24	0.50	0.39
	OM	0.34	0.20	-0.43	-0.07	0.04	-0.24
	Vc	-0.35	0.61	0.74	-0.67	-0.79*	0.36
	Rg	0.13	-0.61	-0.57	0.32	0.46	-0.07
	Scover	-0.33	-0.40	-0.16	0.49	0.58	0.11
	Sl	-0.65	0.00	-0.04	-0.25	-0.36	-0.54
	> 2 mm	0.11	0.18	0.18	-0.11	-0.32	0.00
	< 2 mm	-0.35	0.46	-0.21	0.07	0.18	0.21

* $p > 0.5$; ** $p > 0.01$

Vc vegetation cover, Rg roughness, Scover stone cover, Sl slope, > 2 mm gravels, < 2 mm fine material, OM organic matter, T_p time to ponding, T_o time to outlet, T_r time to runoff, S_y sediment yield, R runoff, S_c sediment concentration

results were obtained with an increase in Rg and soil erodibility (0.87). Furthermore, when roughness (-0.90) and slope (-0.95) decreased, T_o increased. In the upper-back-slope part, < 2 mm influenced T_p (-0.90) and S_y (0.90), which also correlated with Rg (-0.98). In the rainfall experiments performed in the low-backslope part, an increase in Sl obtained a significant correlation with an increase in T_p (0.98), and the absence of Vc implied higher S_y and S_c . Finally, in the footslope, the presence of vegetation cover or high contents of organic matter did not reduce runoff and T_r . Only a higher content of stones at the surface and along the first 20 cm showed any influence on S_y and R .

Discussion

The theme addressed in this research is under explored in Spanish vineyards and, to a lesser extent, in Andalusia. Hence, we have attempted to go further into the relationship between erosion in vineyards and soil erodibility. Understanding and addressing this understudied parameter would be crucial in mitigating erosion and finding effective solutions (Al-Hamdan et al. 2017; Ayoubi et al. 2018).

In the experiments conducted in Bodegas Calvente's vineyard plot, rainfall simulations showed relatively

homogeneous values throughout the parcel, but also it was indicated specific vulnerable points in the vineyard. Factors influencing vulnerability include stone cover and soil roughness, both of which slow down the runoff generation process (Seeger 2007). An increase in slope also results in higher runoff volumes. According to traditional studies conducted under laboratory conditions (Aksoy and Kavvas 2005; Bryan 2000; De Ploey 1991), erosion is more pronounced on steeper slopes due to increased water velocity and particle movement. This effect is even more pronounced on roads (Salesa et al. 2019). While slope has been studied for decades as a trigger for erosion, the influence of roads, especially in vineyards, remains to be thoroughly evaluated, as also mentioned by Rodrigo-Comino et al. (2015) in German vineyards close to steep vineyards and the taluses. Regarding stoniness, Poesen et al., (1998) suggest that rock fragments increase the time of runoff concentration and decrease its volume compared to bare soil surfaces. A stony surface may promote faster infiltration and deeper penetration of applied water due to the contact between stones and soil matrix, facilitating quicker and deeper flow (Jomaa et al. 2013, 2012). However, rock fragments may reduce infiltration rates and increase runoff generation if embedded in the upper layer. However, in some parts of the hillslope, rock fragments even increased soil erodibility, which totally

Table 2 Spearman rank coefficient between soil erodibility results and environmental plot characteristics considering sampling plot areas (hillslope positions)

Sampling points	T_p	T_o	T_r	S_y	R	Sc
1–5						
Vc	−0.39	0.03	0.56	0.15	0.15	0.15
Rg	0.29	−0.90*	−0.21	0.87	0.87	0.87
Scover	−0.36	−0.87	0.50	0.90*	0.90*	0.90*
Sl	−0.13	−0.95*	0.21	0.87	0.87	0.87
> 2 mm	−0.56	−0.15	0.70	0.20	0.20	0.20
< 2 mm	−0.41	−0.15	0.50	0.10	0.10	0.10
OM	0.72	0.10	−0.80	−0.30	−0.30	−0.30
6–10						
Vc	0.20	−0.50	−0.10	−0.20	−0.22	0.10
Rg	0.72	−0.10	0.41	−0.98**	−0.34	−0.82
Scover	0.50	−0.60	−0.10	−0.70	0.22	−0.60
Sl	0.20	0.10	−0.10	−0.20	0.45	−0.50
> 2 mm	−0.50	0.30	−0.20	0.60	0.45	0.30
< 2 mm	−0.90*	0.00	−0.30	0.90*	0.45	0.80
OM	0.70	0.40	0.10	−0.30	−0.45	−0.40
11–15						
Vc	0.34	0.67	0.45	−0.89*	−0.46	−0.89*
Rg	−0.20	−0.70	−0.30	0.30	0.21	0.30
Scover	0.70	0.20	0.30	−0.30	−0.21	−0.30
Sl	0.98**	0.72	0.87	−0.62	−0.76	−0.62
> 2 mm	−0.20	0.20	0.30	0.00	−0.36	0.00
< 2 mm	−0.70	−0.20	−0.70	0.20	0.67	0.20
OM	0.30	0.00	−0.30	0.20	0.46	0.20
16–20						
Vc	0.18	−0.18	−0.71	0.35	0.71	0.00
Rg	−0.53	−0.53	−0.21	0.36	0.21	0.67
Scover	0.56	0.36	0.90*	−0.80	−0.90*	−0.50
Sl	−0.03	0.39	0.05	0.21	−0.05	0.56
> 2 mm	−0.36	0.36	−0.80	0.90*	0.80	0.80
< 2 mm	0.15	0.05	−0.80	0.60	0.80	0.50
OM	−0.36	−0.98**	−0.10	0.00	0.10	0.10

* $p > 0.5$; ** $p > 0.01$ Vc vegetation cover, Rg roughness, Scover stone cover, Sl Slope, > 2 mm gravels, < 2 mm fine material, OM organic matter, T_p time to ponding, T_o time to outlet, T_r time to runoff, S_y sediment yield, R Runoff, Sc sediment concentration

contradict the results of other investigations conducted in Mediterranean vineyards characterized by similar environmental conditions and using small portable rainfall simulations (Rodrigo-Comino et al. 2017).

In the results obtained by vineyard hillslope parts, various parameters stand out. In the shoulder, the highest and steepest part of the vineyard, both roughness and stone cover play significant roles. Higher roughness delays runoff, aligning with general results. With increased slope, the time for runoff initiation decreases. Stone cover enhances concentration, especially when coupled with high roughness, which correlates with the slope. In the rest of the parts, roughness, vegetation cover, and stone cover are closely related.

In these flatter areas, both vegetation and stone cover reduce runoff, delaying its onset, and decreasing sediment contribution. This happens because, in flat vineyard areas, runoff moves more slowly, and higher roughness and greater cover percentage slow down its surface movement (Bagagiolo et al. 2018). These factors can be linked to erodibility, i.e., the susceptibility to erosion (Wang et al. 2019). To reduce erodibility in the vineyard, increasing soil roughness and coverage with either vegetation or stones would be essential to minimize runoff and, consequently, erosion. The challenge with vegetation cover is potential competition with the grapevines for nutrients and water (Marques et al. 2021; Ruiz-Colmenero et al. 2011), although water may be less

of an issue due to drip irrigation localized to each plant. However, the scientific literature related to drip irrigation and erosion is scarce. Regarding stone cover, a technique using it as mulch could be employed to enhance crop productivity in semi-arid areas. Stones reduce soil erosion and shield the soil surface against raindrop impact, detachment, and flow (Poesen et al. 1998). However, protective effects against soil erosion may reduce the transport of soil particles. Soil samples show organic matter levels ranging from a minimum of 3.9% to a maximum of 11.1%. Generally, organic matter is crucial, influencing various soil properties (Kabelka et al. 2019; Novara et al. 2011). Soils rich in organic matter, especially clay–humus soils, are less suitable for grape cultivation. Organic matter is indispensable for grape cultivation, but excess is detrimental. Also, soil pH is fundamental in biochemical balance, and deviation from neutrality can limit plant growth. Vineyard soils generally exhibit varying pH values, ranging from 4.5 to 8.5 in highly calcareous areas. In this case, pH values range between 6.81 and 8.01, likely due to the vineyard being situated on calcareous soils. While caution is advised against excessively high pH values to prevent gradual alkalization, the recorded pH falls within the recommended range for grape cultivation; however, an excess of runoff could wash the minerals and decrease these values.

As a potential solution and for future research, studying the effect of rainfall on areas with higher coverage, whether vegetation or rock fragments, could provide insights into mitigating soil erosion in vineyards. Additionally, continuing treatments to maintain organic matter levels could be proposed. In certain vineyard areas, the addition of winery by-products, such as pomace and prunings, could be explored to observe potential benefits and reducing soil erodibility.

Conclusions

After considering all of the results obtained from the study, it can be affirmed that there is a susceptibility to erosion in the studied vineyard plot. The differences between vineyard zones are significant and depend greatly on slope, roughness, and the type of soil cover. Rainfall simulations in the vineyard, one of the most direct tests that can be conducted, prove to be highly practical due to their versatility. The insight they provide into understanding how rainfall behaves and its potential impact on the soil is confirmed as valuable. The studied semi-arid Mediterranean vineyard showed vulnerability to erosion, especially in the shoulder and backslopes where the inclination is steeper. In this area, runoff moves at a higher velocity, carrying a greater amount of sediment, rendering stone cover ineffective, and at times, even washed away, especially close to the roads. However, it has been observed that roughness helps slow down runoff,

which is related to stoniness, vegetation, and moderate tillage. In the flatter zones studied, which are mainly in the lower parts, it has been noted that roughness, type of cover, material, and organic matter are the main factors contributing to reduced runoff and delayed onset. This makes the soil less susceptible to erosion. Regarding the analyzed soil samples, it has been observed that the pH is somewhat alkaline, and monitoring is needed to prevent further decrease if runoff increases, although it is currently within values that are not concerning for grape cultivation. Organic matter is within acceptable values, suggesting that continuing the treatments applied in the plot is ideal. In conclusion, after the study in Bodegas Calvente's vineyard, it is evident that improvements can be implemented to reduce or eliminate soil erodibility. With the aid of soil cover techniques preferably close to the roads, the degradative processes persistent in the vineyard could be mitigated.

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Data availability Data will be shared upon request.

Declarations

Conflict of interest The authors declare there are not conflict of interest in the manuscript.

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