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Role of rock fragment cover on runoff generation and sediment yield in tilled vineyards

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Summary

The soil in conventional Mediterranean vineyards is an active and non-sustainable source of sediment and water. Lack of vegetation cover, small soil organic matter content and intense ploughing result in large rates of erosion in a millennia-old tillage system. There is a need for soil conservation strategies that enable sustainability of wine and grape production; therefore, it is essential to measure the rates and to investigate the processes and factors of soil erosion. This study evaluated factors that can reduce soil losses in traditional Mediterranean vineyards. The investigation was carried out with 96 rainfall simulation experiments at the pedon scale (0.24 m^2) to measure soil detachment and runoff yield under low frequency–high magnitude rainfall events of 1 hour at 55 mm $hour^{-1}$. On average, runoff was 40.6% of the rainfall, and the rate of soil erosion (i.e. amount of soil lost) was 71.5 g m^{-2}. The key factor controlling erosion was the rock fragment cover. There was a clear decrease in soil losses with increased rock fragment cover on the soil surface, but an increase in surface runoff. The results of our study showed that rock fragments at the pedon scale reduced soil erosion in Mediterranean vineyards, but when a layer of embedded rock fragments developed, large rates of runoff were triggered.

Highlights

- We investigated soil erosion factors in Mediterranean vineyards.
- Rainfall simulation at the pedon scale achieved accurate measurements.
- Rock fragment cover reduces soil losses.
- Embedded rock fragment cover will trigger large runoff rates.

Introduction

Soil erosion results in soil degradation and losses in crop production (Zhang *et al.*, 2016). Orchards and vineyards around the world are active sources of sediments and water, and are characterized by non-sustainable rates of soil erosion (Martínez-Casasnovas *et al.*, 2016). Large rates of erosion and economic loss from soil erosion are not unusual in agricultural areas, especially after intense rain events (Fernández-Raga *et al.*, 2017). They are rather common in Mediterranean regions where management types, land use, climate and geomorphological conditions enhance erosion. There is a need to reduce sediment delivery and to achieve sustainable agriculture with smaller rates of soil erosion (Cerdà *et al.*, 2016). Within traditional agricultural areas, vineyards are one of the most degraded environmental landscapes (Rodrigo-Comino *et al.*, 2016a). Several studies confirm that the main causes of this degradation include lack of vegetation cover because of widespread

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use of herbicides and compaction by heavy machinery, suggesting the use of organic amendments and management of vegetation cover such as catch crops as solutions (Arnáez *et al*., 2007; García-Díaz *et al*., 2016; Rodrigo-Comino *et al*., 2016a).

Prosdocimi *et al*. (2016) reported large rates of erosion in Mediterranean vineyards after a literature review. Rodrigo-Comino *et al*. (2016a,b) homogenized data from different rainfall simulation experiments in European vineyards and also reported large rates of erosion. Different viticulture zones show the same response: large rates of erosion. Penedés (Catalonia, northeastern Spain) had an average rate of erosion of 13.27 g m^{-2} $hour^{-1}$ (0.13 Mg ha^{-1} $hour^{-1}$) and La Rioja (northern Spain) an average soil loss of 10.4 g m^{-2} $hour^{-1}$ (0.1 Mg ha^{-1} $hour^{-1}$). However, some types of management result in small rates of erosion. Vineyards under organic farming in the Saar valley (Germany) and Champagne region (France) showed negligible soil loss and rates of runoff. This confirms that the management in Mediterranean vineyards is a key factor affecting large rates of soil erosion. Recently, Cerdà *et al*. (2017) found that the largest rates of erosion occurred during planting of the vines, and then a few years after.

Vegetation cover is the most efficient strategy to control soil and water losses at different scales (Keesstra, 2007; Rodrigo-Comino *et al*., 2017). However, farmers from Mediterranean agricultural areas generally prefer bare soil because (i) it reduces the amount of water used by weeds and catch crops and (ii) bare soil is perceived as tidy and therefore seen by farmers as the way their orchards should look (Marques *et al*., 2015). Because of this perception, there is a need to find another efficient strategy that contributes to reduced soil losses that is accepted by farmers. Straw mulch has been used successfully (Cerdà *et al*., 2016), but it is quite expensive, can introduce undesirable plant and animal species, and farmers typically see straw as untidy in the field. One potential option for this might be to use rock fragments as a mulch to reduce soil losses because it is a local (*in situ*) natural cover (Martínez-Zavala & Jordán, 2008; Martínez-Zavala *et al*., 2010). Other researchers have already found rock fragments to be effective in reducing erosion (Poesen & Lavee, 1994; Cerdà, 2001; Follain *et al*., 2012). To achieve sustainability, we also need to find economically viable management strategies; some of those that have been investigated previously such as straw mulch, catch crops and geotextiles are expensive. Local and inexpensive materials are easier to manage, less costly to apply and more sustainable if already in the soil, such as rock fragments.

Rock fragments can improve soil conditions by conserving the temperature, such as the slates in German vineyards (Rodrigo-Comino *et al*., 2015), or by contributing to the afforestation of degraded ecosystems (Jiménez *et al*., 2016), but no information exists from tilled vineyards. Previous research on soil erosion and rock fragment cover has been carried out under laboratory conditions, in forest soil or at archaeological sites, but not in vineyards. Therefore, rock fragments from the local parent materials could be a good option to reduce soil losses, and improve soil physical properties (van Wesemael *et al*., 1995), soil biology (Certini *et al*., 2004), soil moisture (Jiménez *et al*., 2016), soil porosity and productivity (Nyssen *et al*., 2001) at a low cost. Rock fragments may increase infiltration when not embedded and reduce soil losses because they can act as a protective cover (Nearing *et al*., 2017). Most of the current research has been carried out under laboratory conditions with disturbed soil (Poesen *et al*., 1990; Poesen & Lavee, 1994) or on forest and rangeland soil (Cerdà, 2001); however, we do not know the effect of rock fragment cover and disturbance in a managed vineyard setting. By applying rainfall simulations with small portable rainfall simulators in the field to *in situ* soil under different rock fragment covers we can assess the role that various factors (e.g. vegetation, slope angle or rock fragment cover) have on water and soil losses (Rodrigo-Comino *et al*., 2016a). Rainfall simulation experiments can provide accurate measurements under controlled conditions.

Therefore, the main aim of this research was to determine the effect of soil cover and soil properties (slope, soil organic matter, vegetation cover, soil water content and rock fragments) on soil erosion in tilled vineyards. To achieve this goal, simulated rainfall experiments were applied to avoid the spatial and temporal variability of natural rainfall and to speed up the generation of data because the study site is a semiarid region. To reduce the variation in soil properties, such as soil moisture during the fieldwork campaign from possible rain, the experiments were carried out during the summer drought after ploughing. After the field experiments with rainfall simulation and the results of statistical analysis, our interest was focused on the effect of rock fragment cover because the results showed strong correlations with runoff (positive) and sediment yield (negative).

Materials and methods

Study area

The study area is in a traditional Spanish viticulture region, Terres dels Alforins in the Valencia province (eastern Spain), and Les Alcusses valley in the Moixent municipality of La Costera District (Figure 1; 38°48′30.33″N, 0°48′57.88″W). These vineyards belong to the Celler del Roure winery and have Monastrell vines that are 25 years old and cover 40 ha. The study site is in the watershed of the upper Canyoles River and parent materials are Cretaceous limestones and Tertiary marl deposits. These lithological characteristics generate *terric Anthrosols* with colluvic materials (IUSS Working Group WRB, 2014). The observed soil profiles are 50-cm deep and are homogeneous after the millennia of ploughing, have small organic matter content ($\approx 1\%$) and are basic (pH = 8). Soil texture is sandy loam with 7.5% rock fragment content by volume in the upper 20 cm. Slope is relatively gentle in the area ($< 10\%$) (Tables 1, 2).

The main climatic conditions are typically Mediterranean: (i) between 3 and 5 months without rain (June–September), (ii) mean annual rainfall of 350 mm $year^{-1}$, (iii) maximum peak rainfall intensities during autumn are more than 100 mm day^{-1}, although spring and summer thunderstorms can produce large amounts of intensive rain over short periods of time, and (iv) a mean annual temperature of 13.8°C, with a maximum average of

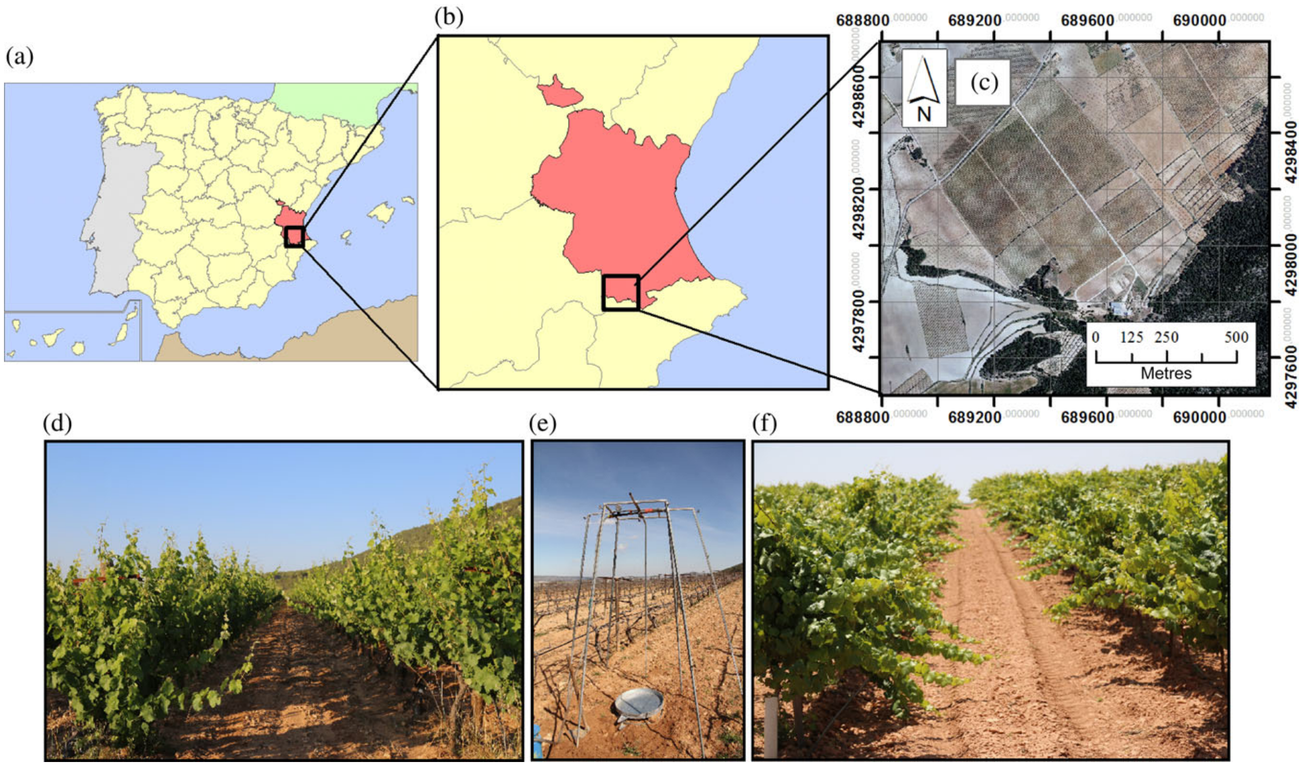

Figure 1 The location and general characteristics of the study area. Note the bare exposed soil between the vines. (a) Spain, (b) Valencia region, (c) Moixent (experimental area), (d) shows clear signs of rill formation from tillage and a splash effect on bare soil, (e) is the rainfall simulator used and (f) one inter-row with clear signs of compaction from tractor passes.

23.2°C in August. Recurrent rain events of more than 100 mm day^{-1} or 30 mm hour^{-1} make extreme rain events a key factor in soil erosion processes in this region (Cerdà *et al*., 2016). Rain events of 250 mm day^{-1} were recorded three times in the last 50 years, with intensive rain for 5 minutes that exceeded 100 mm hour^{-1} (Elías Castillo & Ruiz Beltrán, 1979).

Rainfall simulation experiments

Ninety-six rainfall experiments were carried out at different plots during July 2012 under dry conditions with soil moisture contents ranging from 4.3 to 8.3% in the top soil layer (0–2-cm depth). A sprinkler rainfall simulator was used to reproduce typical rainstorms in Valencia at 55 mm hour^{-1} rainfall intensity (Elías Castillo & Ruiz Beltrán, 1979) for 1 hour on circular plots of 0.24 m^2. Storms of this intensity have a 10-year return period on average and are mainly responsible for surface runoff and soil erosion in the study area (Cerdà *et al*., 2016). The rain simulator used was the one described by Cerdà (1997) because it has been shown to be effective in rugged terrain conditions and to provide good results in semiarid environments. We were interested in the detachment of material by rain and the initiation of runoff. Circular plots of 55-cm diameter were used because they avoid potential water and soil losses in the corners of square or rectangular plots and enable accurate measurements to be made. The main components of the rainfall simulator consist of a nozzle, a structure to hold the nozzle, a wind protector, a pumping system and connections to the water supply. With the nozzle at 2 m above a plane surface, the area wetted was slightly larger than 1 m^2. To avoid border effects, the central 0.24 m^2 part only of the sprinkled area is recommended to be used for measurements, with 0.76 m^2 used as a buffer area. Soil surface cover was determined with vertical point frames of 10 sliding pins spaced about 5 cm apart. This led to a total of 100 points within each 0.24 m^2 plot at which to record bare soil, vegetation and rock fragments. The measurements with the simulated rain over the 55-cm plot length are representative of inter-rill pedon-scale soil erosion processes and illustrate the effect of runoff initiation and sediment detachment. Detailed information on the distribution of rainfall properties can be found in Cerdà (1997).

Runoff was collected and volume (l) was determined at each minute. Runoff coefficients (Rc/%) were calculated as a proportion of rain water volume. Runoff samples were desiccated in the laboratory, and sediments in the runoff water were determined gravimetrically. This allowed the calculation of sediment yield (Sy/g), sediment concentration in runoff (Sc/g l^{-1}), and rates of soil erosion for larger scales (g m^{-2} hour^{-1} and t ha^{-1} hour^{-1}). Units transformed into t ha^{-1} hour^{-1} are included to help readers understand the magnitude of the data better because these are units that are used much more widely in soil erosion studies.

Other hydrological characteristics related to runoff times were also determined. Time to ponding is the time between rain initiation and when 40% of the surface shows ponds on flat or concave micro-surfaces (Tp, s). This has been widely used by other authors since the 1980s. Furthermore, this will make our data and results comparable with those from previous research. Time to the initiation of runoff (Tr, s) (i.e. the runoff in the plot) and time to runoff at the outlet of the plot (Tro, s) were also determined. When the ponded water moves, it runs off as overland flow from one pond to another. There is a delay between Tr and Tro that explains the connectivity of water flow within the plot. Time between ponding and time to runoff initiation (Tr – Tp), and time to runoff at the outlet minus time to runoff (Tro – Tr), were also measured and calculated in seconds. The values Tr – Tp and Tro – Tr are important for understanding the mechanisms of the generation of Hortonian runoff because they represent the delay in runoff and the velocity of overland flow, and they provide information about the connectivity of flows (Masselink *et al*., 2017). Local slopes were measured with a digital clinometer in the plot.

Soil samples (0–2-cm depth) were collected before the rainfall simulations. Part of the field-moist soil samples was weighed, oven dried (105°C, 24 hours) and then weighed again. Soil water capacity (SWC, %) was determined as the difference between field-moist and oven-dry weights. Soil organic matter content was determined by oxidation with acid-dichromate potassium and titration of dichromate excess with ferrous sulphate. Soil organic matter (SOM, %) content was calculated by multiplying soil organic matter content by 1.7 (Walkley & Black, 1934).

Data analysis

We carried out the data analysis at different stages. First, we determined descriptive statistics in the form of box plots to identify the maximum, minimum, median and outlier values with SigmaPlot 12.0 (Systat Software Inc., San Jose, CA). Rainfall simulation results were calculated per hour to determine the averages and their standard deviations (SDs).

Two Spearman's rank correlation analyses (r_{Sp}) were carried out with SPSS 23 (IBM, USA) to aid interpretation; the first to relate site features to temporal variables of runoff (Tp, Tr, Tr – Tp, Tro and Tro – Tp) and the second to relate site features to erosion variables (Rc, Sc and Se). We used r_{Sp} instead of the Pearson correlation coefficient because r_{Sp} measures the strength and direction of a monotonic relation between ranked variables because we cannot assume that the relations between soil erosion variables are linear. Correlations were considered significant at the 0.01 level. Finally, we plotted the data as scatter plots to investigate the relations between rock fragments and rainfall simulation variables.

Results

Environmental characteristics of the plots

The environmental characteristics of the plots studied had a direct effect on soil loss and runoff, and they were measured before the simulated rain was applied (Figure 2). On average, slope inclination was 2.8% (SD, 1.4) and SOM content was 1.2% (0.3). Rock fragment content was 48.3% (27.6) (range of 2–98%). Vegetation cover was negligible, with a maximum value of 5%. Finally, SWC had an average value of 4.4% (1.2).

The results of the rain simulations are represented in the box plots (Figure 3). An average of 5.6 (2.5) l of surface flow was collected; it ranged from 10.5 to 1.27 l. The runoff coefficient (Rc) averaged 40.6% (17.9), with a maximum value of 76.3% and minimum value of 9.2%. The average of Tp was 72.1 s (29.9), and Tr and Tro averaged 186.5 s (111.1) and 355.7 s (198), respectively. The sediment yield (Sy) averaged 17.9 g (11.7), and the average rate of soil erosion was 71.5 g m^{-2} hour^{-1} (46.8).

Effect of environmental plot characteristics on soil erosion

Spearman's rank correlation coefficients (r_{Sp}) were used to determine the factors that affected soil and water losses the most (Table 1). The strongest correlations between the variables recorded in the rainfall simulations were between the percentage of rock fragment cover and sediment yield and runoff. A decrease in total Se depended strongly on rock fragment cover; the correlation coefficient was −0.870. Rock fragments also resulted in a marked decrease in the sediment concentration (Sc), and the correlation coefficient, r_{Sp}, was −0.977. In contrast, an increase in rock fragment cover resulted in an increase in the runoff coefficient, Rc, and the correlation coefficient was 0.956. The other variables, such as slope, SOM, vegetation cover and soil water capacity, did not have strong correlations with the runoff and rates of soil loss.

Spearman's rank correlation coefficients computed for the runoff times also showed strong relations with the rock fragment cover (Table 2). An increase in the percentage of stone cover at the soil surface resulted in a marked reduction in the runoff times. The time to ponding, Tp, has a strong correlation (r_{Sp}) with stone cover, with a correlation of −0.885, and time to the initiation of runoff in the plot, Tr, with a correlation of −0.962. The correlation coefficients between the percentage stone cover and the connectivity of water flow (Tr – Tp, Tro and Tro – Tr) within the plot were also strong and negative: they were −0.965, −0.965 and −0.883, respectively.

Effect of rock fragment cover on runoff initiation and runoff rates

The previous analyses revealed that rock fragments are a strong controlling factor for soil erosion and the hydrologic processes at this site. Consequently, it was necessary to investigate the relations between rock fragments and hydrological and erosional responses. Scatter plots between rock fragments and Tp, Tr, Tro – Tr, Sc, Rc and Se are shown in Figure 4. Figure 4(a–c) shows similar relations with rock fragments. The greatest effect of the rock fragments consisted of a reduction in the time variables (Tp, Tr, Tro – Tr) for rock fragment covers ranging between 0 and 30%. Rock fragment cover greater than 30% resulted in smaller changes in the values of Tp, Tr and Tro – Tr. This effect was particularly marked with Tr,

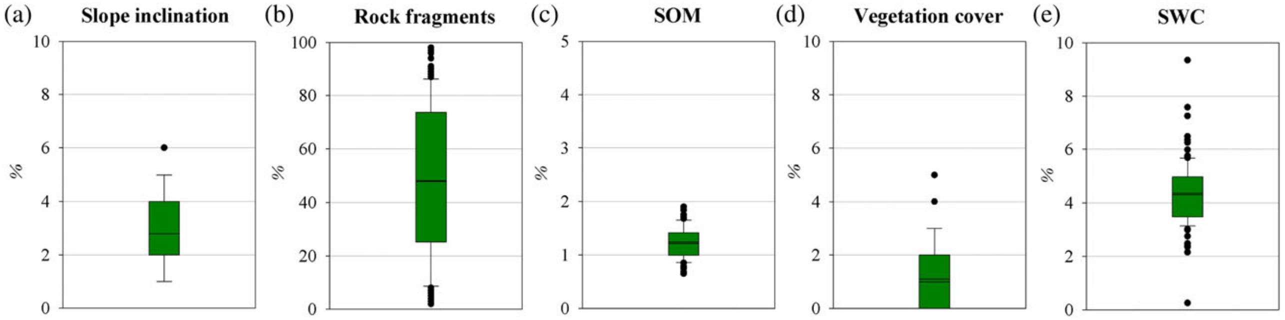

Figure 2 Box plots of the environmental characteristics of the study plots (%). The horizontal bar represents the median of each variable; the whiskers represent the 5th and 95th percentiles of each variable. SOM, soil organic matter; SWC, soil water capacity.

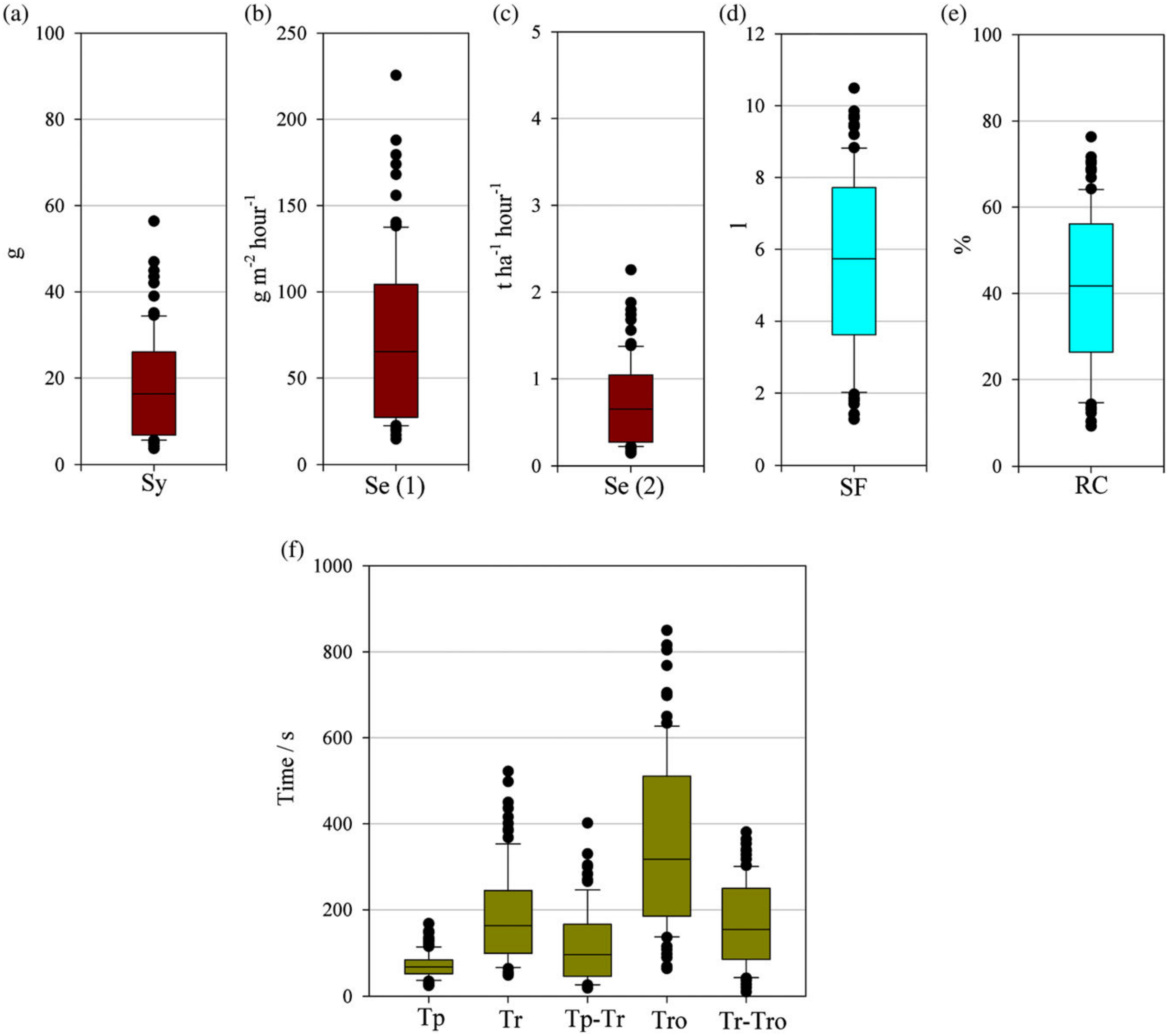

Figure 3 Results of the rainfall simulation experiments. The horizontal bar represents the median of each variable; the whiskers represent the 5th and 95th percentiles of each variable. (a) Sediment yield (Sy), (b) Se (1) represents soil erosion in $\mathrm{g\,m^{-2}\,hour^{-1}}$, (c) Se (2) means soil erosion in $\mathrm{t\,ha^{-1}\,hour^{-1}}$, (d) surface flow (SF), (e) runoff coefficient (RC) and (f) the runoff time variables such as time to ponding (Tp), time to runoff (Tr), time to ponding minus time to runoff (Tr – Tp), time to runoff outlet (Tro) and time from runoff to outlet (Tro – Tr), which is a measure of the runoff velocity.

Table 1 Spearman's rank correlation coefficients for the rainfall simulation results

Variable	Rc / %	Sc / g l^{-1}	Se / g ha^{-1} $hour^{-1}$
Slope	−0.180	0.160	0.112
Rock fragment cover	*0.956*	*−0.977*	*−0.870*
SOM	0.241	−0.244	−0.221
Vegetation cover	−0.106	0.120	0.148
Soil water capacity	−0.059	0.044	0.022

SOM, soil organic matter; Rc, runoff coefficient; Sc, sediment concentration; Se, soil erosion. Correlations significant at the 0.01 level (two-tailed) are in italic.

Table 2 Spearman's rank correlation coefficients for the hydrological times

Variable	Tp / s	Tr / s	Tr – Tp	Tro	Tro – Tr
Slope	0.150	0.193	0.194	0.153	0.075
Rock fragment cover	*−0.885*	*−0.962*	*−0.965*	*−0.968*	*−0.883*
SOM	−0.150	−0.201	−0.229	−0.230	−0.201
Vegetation cover	0.024	0.094	0.115	0.123	0.160
Soil water capacity	0.049	0.059	0.043	0.058	0.061

SOM, soil organic matter; Tp, time to ponding; Tr, time to runoff; Tr – Tp, time to runoff minus time to ponding; Tro, time to runoff in the outlet; Tro – Tr, time to runoff in the outlet minus time to runoff. Correlations significant at the 0.01 level (two-tailed) are in italic.

time to runoff generation (Figure 4b); the negative relation between Tr and rock fragment cover is particularly strong with a value of −0.965. Time required for runoff flow to move out of the plot (Tro – Tr) decreased with increasing rock fragment cover from about 800 (rock fragment cover ∼0%) to 100 s (∼100%).

Figure 4(d) shows that the effect of rock fragments on Sc is similar to the time variables (Tp, Tr and Tro – Tr) because the decrease in Sc tended to be asymptotic. On the other hand, Rc is the only variable that had a positive correlation with rock fragments. The slope of the scatter plot indicates a clear increase in Rc with increasing rock fragment cover. Soil erosion decreased with increasing cover by rock fragments (Figure 4e), but its trend was slightly different from that in the previous figures. Despite the scatter in the data, the points show that from 0 to 10% rock fragment cover the decrease in Se is small.

Discussion

Soil erosion in Mediterranean vineyards is characterized by being recurrent and considerable during intense rainfall events. The main factors responsible for the large rates of erosion in Les Alcusses are the lack of vegetation cover on the soil and intense tillage, which are common in vineyards (Prosdocimi *et al*., 2016). The recurrent planting of new vineyards increases the rates of erosion because the plantation operations result in a larger sediment detachment in vineyards (Cerdà *et al*., 2017).

A common strategy to control erosion is the use of straw mulches, catch crops or geotextiles, which result in an immediate reduction of sediment and water losses, as shown by Giménez-Morera *et al.* (2010), Prosdocimi *et al*. (2016) or Cerdà *et al*. (2016), and also improve other soil properties (Jordán *et al*., 2010). Nevertheless, the main environmental concern when straw, geotextiles or seeds for catch crops are used is the potential change in species composition and invasion of plants that can modify the environmental conditions. Moreover, all of these strategies commonly used to reduce soil erosion are expensive because of the treatment and origin of the materials, which often need to be transported or manufactured (i.e. mulches or geotextiles). Farmers also have to handle these materials in operations such as spreading, sowing and laying them over their vineyards, and have to determine the optimal rates of application (Jordán *et al*., 2010). In addition to environmental issues, these operations add to farmers' costs.

Our research has shown that rock fragment cover has a large effect on soil erosion and hydrological processes in a tilled vineyard soil at the pedon scale. We applied a high rainfall intensity thunderstorm during a dry period with a rainfall simulator, and by doing so we showed that soil losses and runoff coefficients depended on a key factor: the rock fragment cover.

The study site was characterized by slopes of between 1 and 10%, where theoretically low runoff discharges would be expected. However, maximum values of 76.3% (40.6%, on average) confirmed the large runoff delivery in this vineyard, which has also been reported by other authors in Mediterranean viticulture areas such as the Penedés-Anoia region in Catalonia (Martínez-Casasnovas *et al*., 2016), La Rioja (Arnáez *et al*., 2007) or Italy (Novara *et al*., 2011). Our results indicate that farmers should not remove rock fragments from their soil because they contribute to reducing soil losses, although the runoff rates increase. Other authors have confirmed that large rates of runoff would increase nutrient and fine particle losses (Danalatos *et al*., 1995; Jordán *et al*., 2010) and concentrated flow in the form of rills and ephemeral gullies in footslope areas (Follain *et al*., 2012).

Our rainfall simulation experiments in eastern Spain have demonstrated that there was an increase in rates of runoff, rapid ponding and the generation of runoff when the surface area covered by rock fragments was increased. This was because the rock fragments are embedded in the soil and act as a crust, as described by Poesen *et al*. (1990). It has been reported that rock fragments resting on the soil surface channel runoff water, which generates more efficient flow and also facilitates infiltration through macropores and cracks (Cerdà, 2001; Martínez-Zavala & Jordán, 2008). The rock fragments act as a protection in relation to sediment detachment and reduce soil losses when the rock fragment cover increases. This is contrary to the findings of Cerdà (2001) from research on a forest soil, where the rock fragments were not embedded and favoured infiltration and reduced particle detachment. This contrast in response between forest and agricultural land is a consequence of tillage. Forest soil develops a network of macropores that conduct the runoff deep into the soil, but tillage reduces the formation of macropores and encourages the formation of a crust because of the bare soil.

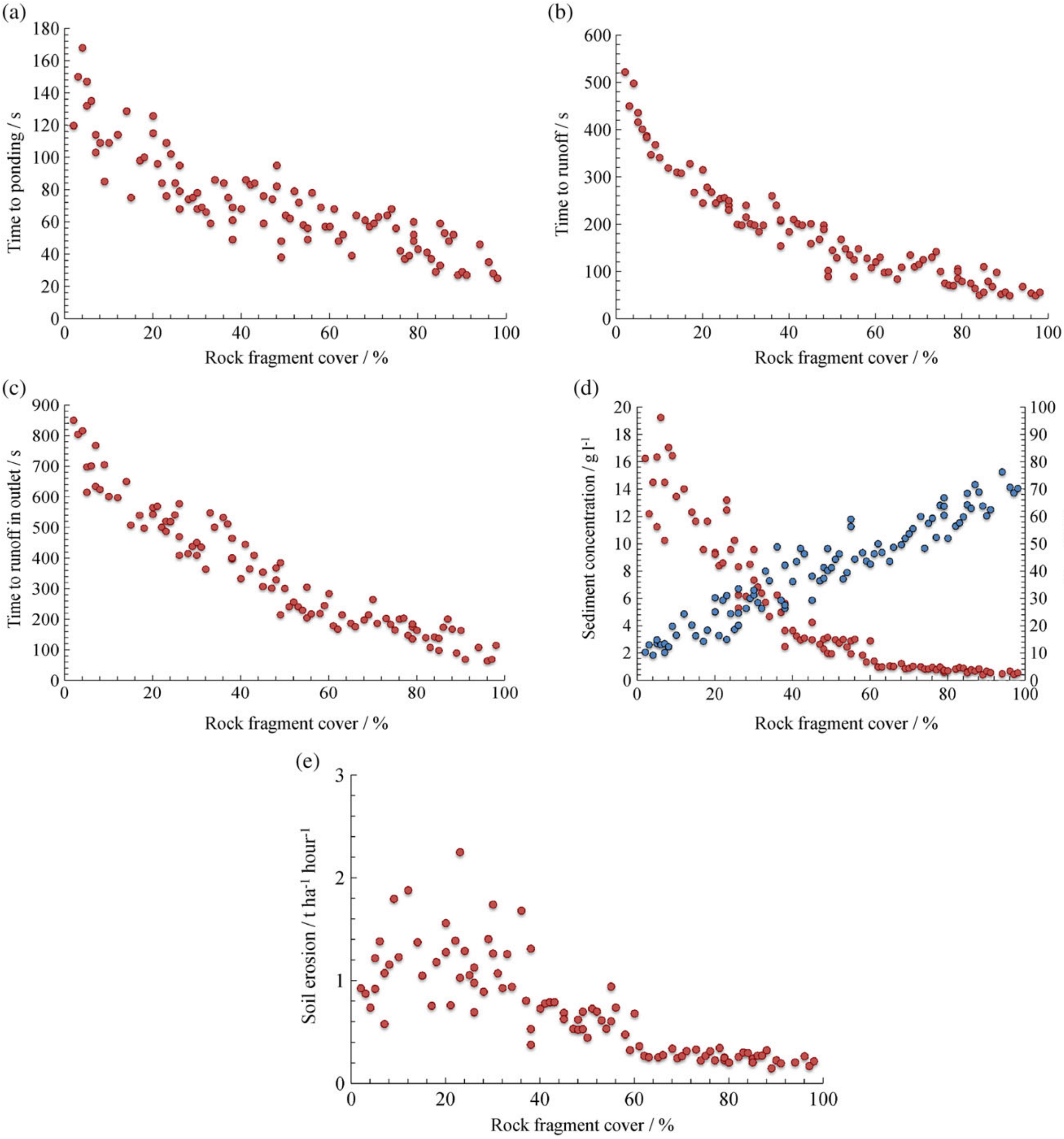

Figure 4 Relations between rock fragments and time variables: (a) time to ponding, (b) time to runoff, (c) time to runoff in the outlet. In (d), the runoff (blue) and the sediment concentration (red) are plotted against the rock fragment cover.

As a next step, methods should be developed to canalize the overland flow if the surface is covered with stone fragments to manage the water for other uses (e.g. irrigation), which would be particularly valuable in this semiarid environment (Rodrigo-Comino *et al.*, 2017).

After observing the negative relation between the stone fragment cover and soil loss, it appears that between 30 and 60% cover by rock fragments provided acceptable protection against soil losses because below these proportions of cover there was a clear and steep increase in soil erosion (sediment yield and sediment concentration) with decreasing rock fragment cover. These possible thresholds are in accord with previous results from uncropped soil (Martínez-Zavala *et al.*, 2010).

Slope angle was not the most important factor affecting soil erosion at this site, although Cerdà *et al.* (2009) and Keesstra *et al.* (2016) observed that both runoff and soil loss may increase considerably with slope in similar types of soil planted with citrus and apricot trees. Lack of vegetation cover and small SWC increase the relevance of rock fragments in controlling soil erosion. We emphasize that the activation of runoff in bare soil is strongly affected by tillage in vineyards, which leads to a lack of vegetation cover; this is accepted as the primary factor affecting soil erosion at different scales (Cerdà *et al*., 2009; Prats *et al*., 2016).

Rock fragments were the main factor controlling soil erosion in the Mediterranean vineyards studied when there was little or no vegetation cover as a result of tillage. Danalatos *et al*. (1995) observed that soil below rock fragments on the soil surface or partially embedded in it provide favourable micro-environments for biotic activity, resulting in the growth of herbaceous plants at their margins. This might contribute to breaking up water connectivity and decrease the intensity of runoff flow. Increasing rock fragment cover contributed to a decrease in the time required to ponding (Tp) and for runoff generation (Tr). With little rock fragment cover, longer times to ponding contributed to less generation of runoff, especially during short storms (Martínez-Zavala & Jordán, 2008). A large proportion of embedded rock fragments delayed infiltration (even when soil conditions were favourable), which accelerated ponding and, therefore, the formation of runoff (small $Tr - Tp$). Therefore, it could be suggested that rock fragments enhance water connectivity at the scale of our study and should also be considered at other scales (López-Vicente *et al*., 2015).

In Spain, farmers used to remove rock fragments because they considered them to be a problem when ploughing. In other regions farmers might be reluctant to remove rock fragments because they believe that they improve soil moisture and structure, and plant nutrient absorption and root protection (Nyssen *et al*., 2001), but other studies have reported negative effects from rock fragments (Zhang *et al*., 2016). This research presents information that is relevant for farmers and policy makers because we have shown the effect of rock fragments at different percentages of cover and this can help to design the cover to either reduce or increase the soil losses or runoff discharge.

Knowledge of the effects of rock fragments on geomorphological and hydrological soil processes at different scales is key to understanding soil systems and soil–landscape relations. On the one hand, future research should focus on the study of microscale processes to elucidate the behaviour of infiltration and runoff processes at the interface between rock fragments and fine soil particles. On the other hand, research on the effects of rock fragments at hillslope and catchment scales will help to explain and model water and sediment connectivity (Masselink *et al*., 2017). Future research into intra-plot differences in soil erosion processes in vineyards of different ages could include other measurement techniques such as SfM (structure from motion) or remote sensing (Prosdocimi *et al*., 2017).

Conclusions

Mediterranean vineyards are one of the most active sources of sediment and water on agricultural land, which we have shown by our results. There is a need to find sustainable management techniques to achieve tolerable soil losses. We found that rock fragments can be managed to reduce soil and water losses. Two main conclusions were reached: (i) a clear increase in runoff discharge occurred when rock fragment cover increased and (ii) a large percentage cover of rock fragments resulted in a small rate of soil erosion. To use rock fragment cover as a mulch it is necessary to reduce the runoff discharges or to harvest the runoff for irrigation. A large rock fragment cover reduced the rates of soil erosion effectively, but greater cover increased rates of runoff.

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