Geoderma 296 (2017) 47–59

http://dx.doi.org/10.1016/j.geoderma.2017.02.021

Understanding soil erosion processes in Mediterranean sloping vineyards (Montes de Málaga, Spain)

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ABSTRACT

Sloping vineyards in the Mediterranean cultivated on bare soils show several types of evidence of soil erosion processes. However, little is known about the key factors that condition and enhance these processes at the intra-plot scale. There is a need to assess soil conservation methods to reach sustainability of vineyards and high grape quality, and for this it is necessary to investigate the factors and rates of soil erosion processes under natural conditions. The main goal of this research, conducted in traditional Mediterranean vineyards in Los Montes de Málaga (South Spain), was to carry out a precision analysis of the patterns of soil erosion and the soil surface components at the intra-plot scale. The analysis was performed after monitoring soil erosion processes during 25 natural rainfall events. Soil loss, overland flow, and runoff threshold were calculated using six Gerlach troughs. Fine soil particles and rock fragments were also assessed after each natural rainfall event and tillage practice. The research showed an example of sloping vineyards in a Mediterranean environment with bare soils that are associated with high soil losses and an uneven spatiotemporal distribution of hydrological and geomorphological processes. Key factors enhancing soil erosion processes are: i) extreme rainfall events and ii) management practices (pruning, ploughing and trampling). The runoff threshold reached very low values (between 4.55 mm and 8.5 mm) and the highest soil loss and overland flow rates were obtained from a few rainfall events during the rainiest period, coinciding with times that the surface was covered by vines that had dropped their leaf cover. Finally, we demonstrated that the runoff threshold, soil loss and overland flow showed high variability depending on the stoniness, soil texture, and antecedent conditions of tillage.

KEY WORDS

Vineyards; rock fragments; soil texture; soil erosion; overland flow; soil surface components.

1. INTRODUCTION

Soil is a key component of the Earth system as it controls biological, hydrological, erosional and geochemical cycles (Keestra et al., 2012; Brevik et al., 2015; García-Díaz et al., 2016; 2017) and provides a wide range of resources, goods and services (Cerdà et al., 2016; Mol and Keesstra, 2012; Smith et al., 2015). Soil horizons are constantly changing, losing and transforming energy and matter due to the effect of raindrops, runoff, wind, gravity (Grismer, 2016; Zemke, 2016), and other soil forming processes (Khaledian et al., 2017). Within this complex system, human impacts also cause changes to the soil, including negative inputs that are generating hazardous outputs including soil erosion (Gonzalez-Hidalgo et al., 2012; Keesstra et al., 2016; Ochoa-Cueva et al., 2015; Romero-Díaz et al., 2016).

Vineyards are one of the most exposed agricultural systems damaged by soil erosion processes (Cerdan et al., 2010; Prosdocimi et al., 2016a). Within the viticultural agroecosystem, soils play a major role in providing mineral nutrients to plants, and soil characteristics also affect vine water status which is a key factor determining grape quality potential (van Leeuwen et al., 2009). The alteration of natural hydrological dynamics and increased sediment transport create several problems related to uncontrolled solute and nutrient transport (Gruber and Kosegarten, 2002; Manandhar and Odeh, 2014; Navel and Martins, 2014), soil loss (Hacisalihoglu, 2007; Novara et al., 2011; Prosdocimi et al., 2016b; Quiquerez et al., 2014), formation of rills and ephemeral gullies (Kosmas et al., 1997; Martínez-Casasnovas et al., 2003; Rodrigo Comino et al., 2015), degradation of roots, biodiversity and carbon storage (Bruggisser et al., 2010; Eldon and Gershenson, 2015; Francone et al., 2010; Gagnarli et al., 2015; Zsófi et al., 2011), and quality of the product and productivity (García-Díaz et al., 2016; Likar et al., 2015; Lorenzo et al., 2012; Marqués et al., 2015; Terrón et al., 2015). To understand the soil erosion processes in vineyards will bring solutions for a sustainable agriculture (Novara et al., 2013) and this is related to the income of the farmers due to payments for ecosystem services (Galati et al., 2016) and the soil erosion rates (Novara et al., 2016a), and the soil carbon sequestration (Novara et al., 2016b).

Traditionally, Mediterranean vineyards are located in semi-arid sloping areas and the soils are kept bare to eliminate water competition from weeds and to increase the strength and taste of the final product (Leeuwen et al., 2009). However, it is evident that new worldwide trends of mean temperature increases and the impact of extreme rainfall events are observable and, in some cases, dangerous for ecosystem health in these areas (Adams et al., 2001; Blanco-Ward et al., 2015; Chuine et al., 2004).

Changes in seasonal rainfall distribution have been observed and quantified in Mediterranean areas (Ramos et al., 2008); however, the inter-annual variability and universal patterns continue to be difficult to calculate (Ruiz Sinoga et al., 2011, 2010). Nevertheless, the most crucial issue from the erosion point of view may be the increased extreme events (Ramos and Durán, 2014), which can cause high levels of soil erosion over short periods (Cerdà et al., 2016). This has been found in semiarid land (Vaezi et al., 2016) and in fire affected land (van Eck et al., 2016; Keesstra et al., 2017).

The Axarquía region is studied in this research as an example of these changing areas. Despite the increasing temperatures and the concentration in a short period season of the rainfall events, Axarquía has preserved high quality wine production since the Muslim centuries. However, Rodrigo Comino et al. (2016a, 2016b) detected three main causes of land degradation processes in this region using soil analysis, a small portable rainfall simulator, and a Guelph permeameter: i) extremely steep slopes (26-76%); ii) silty soils (>60%) and high rock fragment content (>40%), and iii) traditional hand tillage that removed vegetation cover under and around the vines. It is relatively common to observe that many farmers and wineries prefer to choose high productivity for short-term periods (leading to a continuous decrease of the grape quality and topsoil layers) against sustainable production for long-time periods.

The spread of knowledge of research about economic damages generated by soil erosion processes on- and off-site (Vanmaercke et al., 2011) should increase the awareness of the problem by farmers and enterprises (Marques et al., 2015; Sastre et al., 2016). Galati et al. (2015) calculated an annual cost of soil erosion in Sicily (Italy) at about 1575.37 €/ha^{-1} in conventional tillage fields and only 487.51 €/ha^{-1} in agri-environment areas (a difference of 1087.86 €/ha^{-1}). Martínez-Casasnovas and Ramos (2006) documented nitrogen and phosphorus losses for northern Spanish vineyards due to erosion of 14.9 kg/ha^{-1} N and 11.5 kg/ha^{-1} P respectively, with economic costs between 1.2% and 2.4% of the annual income from the sale of the grapes.

To promote research about the economic costs of soil erosion processes between farmers and enterprises, it will be mandatory to assess the role that tillage practices and rainfall events (García Díaz et al., 2016; Novara et al., 2011; Prosdocimi et al., 2016d; Zaimes et al., 2012) play in the mobilisation of rock fragments and fine particles downslope (Follain et al., 2012; Lasanta, 1985; Ortigosa and Lasanta, 1984; Rodrigo Comino et al., 2016c). In the Axarquía region, there is a lack of precision analysis of soil erosion rates (amounts, intensities, variations…) (Ferre Bueno et al., 2009; Martínez-Casasnovas et al., 2013) and its geomorphologic and pedological consequences under natural conditions. Therefore, the main goal of this research was to carry out an analysis of the spatial and temporal patterns of soil erosion processes related to the soil surface components in a chosen hillslope in this region. To reach this main goal, we performed: i) soil analyses and soil surface components (textural and rock fractions) characterization at four different slope positions (summit, shoulder, backslope and footslope) and two sides (west and east); ii) a quantification of soil erosion processes (soil and water losses) under natural rainfall events and tilled conditions using Gerlach troughs; and iii) a measurement of mobilized fine soil particles and rock fragments after each natural rainfall and tillage event.

2. MATERIALS AND METHODS

2.1. Study area

The vineyards studied are in the Axarquía viticulture region, within the Montes de Málaga range (Andalucía, Spain), close to the village of Almáchar (36.8 N; −4.2167 W) (Fig. 1), between 300-350 m a.s.l. The average annual temperature is 17.2 ºC, with maximum average values in July and August (24.5-24.9ºC) and minimum average values in December, January and February (11.3-11.5ºC). The average annual rainfall is 520 mm and its highest concentration is distributed between October and January during a few rainfall events. Recurrence periods using the Poisson method (Mays, 2010; Senciales González, 1999) show high inter-annual rainfall variability. The probability of days without rain calculated with this method is about 89.1-89.7% while 0.8-0.9% of rainfall events during the year exceed 40 mm.

Estévez González and Chamón (1978) described two different geological facies in this area. The first is composed of mica schists with well-developed schistosity, small garnets (1-2 mm), and intercalations of lenticular levels of white quartz. The second one is characterized by quartz and mica schists without garnets, which have less developed schistosity, showing higher resistance than the first facie.

Soils are typically *Eutric Leptosols* (IUSS Working Group WRB, 2014; Rodrigo Comino, 2014). These soils were characterized by Rodrigo Comino et al. (2016c): i) silt loam texture; ii) very low electrical conductivity values (0.1 dS m^{-1}); iii) general soil pH values of about 7.1, but, on several occasions less than 7; iv) bulk density up to 1.5 g cm^{-3} v) carbonate contents less than 1% because the main lithology is schist; and vi) a total organic carbon content lower than 3% due to the use of herbicides and tillage to eliminate vegetation growth.

Land use management practices are conducted to produce raisins and wine with the *Muscat of Alexandria* grape variety registered by a Spanish DO (Designation of Origin) “Málaga, Sierras de Málaga and Pasas de Málaga”. Soil tillage is followed by handwork using hoes and shovels and the use of herbicides to control the re-vegetation of the slope and organic additions (cow and goat manure) to limit erosion by water. Historically, due to high soil erosion rates during short period season of the rainfall events and steep slopes, the vine growers have developed rudimentary protection measures in some places (Rodrigo Comino et al., 2016c). “Sangría” or “desaguadero” (Fig. 2a), is a soil erosion control strategy, which consists of handmade rills or agri-spillways (Rodrigo Comino et al., sub.) that collect and interrupt the surface flow and channelize water directly to another principal rill. The second traditional technique is stony walls (“albarrada” or “balate”) situated along the upper slope to collect the soil across the slope (Fig. 2b). The second protection measure is included in the experimental area of this research and is similar to the trapping strategies used in other regions (Mekonnen et al., 2015).

2.2. Methods

2.2.1. Stoniness and soil texture analysis

Soil samples were collected in April 2016 under dry conditions at four different slope positions (summit, shoulder, backslope and footslope). They were collected along a longitudinal profile of 5 meters (Fig. 2c) and from the surface to 0.5 m depth (Fig. 2d) from each slope position (about 15 kg per sample). Samples were transported to the laboratory and air dried.

Particle size distribution of the fine material (between 0.002 mm and 2 mm) was calculated using a Coulter LS230 particle size analyser, which combines different diffraction patterns from a light beam. Soil particles larger than 0.2 cm were sieved and divided into six intervals using an adjustable sieve of our own design (Fig. 2g, 2h): 0.2-0.5 cm, 0.5-2 cm, 2-4 cm, 4-6 cm, 6-8 cm and >8 cm.

2.2.2. Soil erosion patterns and runoff thresholds

Six Gerlach troughs (Gerlach, 1967) were used in this research. Each sediment collector had a width of 100 cm (Fig. 2d, 2f) and was situated in the inter-rows of the vineyards. Two-paired troughs were situated on the shoulder, backslope and footslope. They were provided with a slanted front edge to prevent scouring or undercutting of the trough. Troughs were connected to collecting tanks (60 L) to be prepared for extreme rainfall events, which can exceed the total storage capacity of each sediment collector (50 L up to the spillway). A Hellmann-rain gauge was placed close to the experimental plot to measure rainfall amounts after each event. The main limit of this tool is that the open soil erosion plots give information about soil and water losses but the contributing area is uncertain. This is why the soil erosion rates are shown in g m^{-1} and L m^{-1}. Maintenance of the equipment, emptying sediments and overland flow, was performed after each rainfall event.

All samples were taken to the laboratory for drying, weighing and quantifying soil loss (g), overland flow (L) and sediment concentration (g L^{-1}). Particle size distribution of fine materials and rock fragments were calculated for all rainfall events and each Gerlach trough by applying the same method described above.

To calculate the runoff threshold, lineal estimations using data from every recorded overland flow and rainfall event by slope position were adjusted to get the correspondent values for overland flows of about 0.1 L m^{-1}, 1 L m^{-1} and 10 L m^{-1}. For every Gerlach trough, an R^2 higher than 0.985 was found.

Finally, to characterize the type of overland flow, a scatter plot was developed using the recorded soil samples. We avoided outliers such as the 200.1 mm event (number 5, Table 1) to obtain a trend without uncommon rainfall events. Moreover, results were verified with field observations when some of the recorded rainfall events were occurring.

2.2.3. Climatic extrapolation, tillage monitoring and statistical analysis

Rainfall was measured with a Hellmann-rain gauge. The data was compared and completed with the extrapolated data from the nearby climatic stations of IFAPA (Instituto de Investigación y Formación Agraria y Pesquera), Red Hidrosur and REDIAM (Red de Información Ambiental de Andalucía). Due to the lack of a complete climatic data record in the study area, values of rainfall (all with more than 30 years of data) were extrapolated from latitude, longitude and altitude above sea level: Colmenar-Torrijos (718 m; 36.828N, -4.357W), Contadoras (758 m; 36.811N, -4.382W), Olías (421 m; 36.776N, -4.323W), Rincón de la Victoria (7 m; 36.722N, -4.279W), Moclinejo (433 m; 36.772N; -4.251W), Comares (731 m; 36.851N, -4.247W), Benamargosa (96 m; 36.837N, -4.191W), Benamocarra (126 m; 36.792N, -4.159W) and Vélez-Málaga (60 m; 36.78N, -4.099W). Calculations were carried out by applying linear estimations and intersections with the axis, using rainfall and elevation data with Excel 2010 software (Rodrigo Comino, 2013; Senciales and Ruiz Sinoga, 2013). Furthermore, the different tillage practices applied in the studied vineyards were monitored and described during the study period through interviews with the vine-growers.

The results of soil loss and overland flow from the paired-Gerlach troughs in different slope positions were compared using a Mann-Whitney Rank Sum Test and between side pairs applying an ANOVA-analysis with the SigmaPlot 13 statistical software. Finally, the Spearman rank coefficient was calculated to analyse the statistical significance between soil erosion (soil loss, overland flow and sediment concentration), particle grain size distribution, and different types of rainfall events (amount, intensity, and maximum intensity) using the SPSS 23 software (IBM, USA). When rainfall did not activate overland flow but soil loss occurred, anthropogenic factors such as trampling or tilling by hand were catalogued as the main cause that initiated the soil erosion events.

3. RESULTS

3.1. Soil surface characteristics: rock fragments and soil fine particles

Rock fragments and fine soil particle distributions from different slope positions (summit, shoulder, backslope and footslope) were measured (Fig. 3). Every slope position had a higher proportion of rock fragments than fine materials (<0.2 cm). The highest rock fragments content was measured on the shoulder (77%). On the other parts of the slope, rock fragments had values between 64% and 68%.

In general, the most abundant rock fragment fraction was 0.5 cm to 2 cm, with the highest values on the summit and shoulder parts (38%) and the lowest on the footslope (28.7%). The second highest fraction corresponded to the interval between 0.2-0.5 cm. Maximum values ranged from 20.7% on the summit to 16.3% on the shoulder slope. After that, rock fragment sizes between 2 cm and 4 cm (10.4%) and up to 6 cm to 8 cm (6.1%) reached relatively high values only on the shoulder slope. Finally, materials larger than 8 cm were found only on the footslope (4.2%).

Several differences were observed in fine materials (<2 mm) between slope positions. Very coarse sand (1.25-2mm) was not recorded at any sampling point and coarse sand (1.25-0.63 mm) was recorded only on the summit (23.2%). The medium sand fraction (0.63-0.2 mm) was most abundant on the summit (16.7%) in comparison with other slope positions, which ranged between 0.7% on the shoulder and about 4% on the backslope and footslope. The proportion of fine sands showed similar results on the summit and shoulder (4.1% and 6.2%, respectively) and on the backslope and footslope (3%). Very fine sands (0.125-0.063 mm) had their highest content on the shoulder (17.9%) with little difference compared to the backslope and footslope positions (15%). The summit only had 10% very fine sand particles. Silt particles reached their maximum values at the shoulder to footslope positions. Coarse silts (0.063-0.02 mm) and fine silts (0.02-0.002 mm) oscillated around about 35% and 37%, respectively. The summit had a lower silt fraction characterized by 14.9% coarse silt and

17.2% fine silt. Finally, clay contents were similar from the shoulder to footslope (6%) and lowest on the summit (2.6%).

3.2. Rainfall and tillage practice descriptions

Recorded rainfall events during the study period totalled 683.8 mm divided into 25 events (Table 1). The seasonal and inter-annual variations were very high. From October until November in 2014 (from rainfall event 1 to 5), 248.8 mm were recorded, with 80.6% in only one event that lasted two days. In 2015, from October until November (from rainfall event 17 to 20), rainfall totalled 139.3 mm. In summer, between June and August, 4% of the total average annual rainfall was received. However, during the period between May and August no precipitation was recorded.

Depending on the yearly and seasonal meteorological conditions, the vine-growers carried out different soil tillage practices. A prototype calendar for the study period (2014-2016) is shown in Table 2. During January and February herbicides (to avoid weeds competing for water) and organic fertilizer were applied, combined with an early pruning, removing of the soil around the grapevines, and raking the aggregates with shovels and hoes to enhance infiltration (March). After that, during spring (April-May), phytosanitaries was used to protect against fungus and, non-selected buds were pruned. During the dry period, the vintage was carried out with animals during the middle of July and beginning of August. Soil was unprotected during the first rainfall events because stems and leaves were pruned and immediately removed for burning. In November, during the rainiest period of the year, phytosanitaries were applied. Finally, during December-January hand tillage was carried out using hoes to eliminate herbs, and aerating and raking of aggregates was performed.

3.3. Overland flow and soil loss during the study period

Recorded rainfall, soil loss and overland flow for every event are shown in figure 4 and summarized to show the accumulated frequencies in figure 5. After that, all the events were compared with ANOVA and Mann-Whitney rank sum tests. Statistically significant differences ($P < 0.001$) in soil loss and overland flow rates were found between the east and west parts of the study area.

On the shoulder, statistical tests showed similarities in soil loss and overland flow between Gerlach troughs ($P = 0.596$ and $P = 0.492$, respectively). A total of 4980.9 g m^{-1} (28.6% of the total was collected during only one event) and 33.3 L m^{-1} were obtained from the east side. The recorded soil loss was higher (5534.3 g m^{-1}) on the west side, but not the overland flow (649.4 L m^{-1}). On the backslope, both Gerlach troughs obtained samples with statistically significant differences ($P = <0.001$). The Gerlach trough on the east part recorded the lowest soil loss (1408.2 g m^{-1}) and overland flow (31.3 L m^{-1}) values in the study area. On the west side a total soil loss of 4336.9 g m^{-1} was registered and overland flow showed the highest rates, ranging up to 440.7 L m^{-1}, of which 110 L m^{-1} were obtained during one event in November 2014 (rainfall event 5, Table 1).

On the footslope, the difference in the median values were greater than would be expected by chance; therefore, statistically significant differences were obtained (soil loss: $P = <0.004$ and overland flow $P = <0.001$). On the east part, the total soil loss rates reached 5247.6 g m^{-1} and the overland flow 69.7 L m^{-1}. The highest total rates of soil loss were found on the west part, ranging up to 14,133.9 g m^{-1}, of which 2296.35 g m^{-1} came from one event (rainfall event 5, Table 1) and represented 16.2% of the total. With respect to the overland flow, amounts up to 410 L m^{-1} were recorded. Figure 1 in the Supplementary materials shows the results obtained per rainfall event in each Gerlach trough.

3.4. Threshold runoff and characterisation of overland flow.

All the events were represented in a scatter plot and linear estimations were calculated for each Gerlach trough (Fig. 6). On the backslope and footslope of the west side, a high coefficient of determination was found (0.94 and 0.66, respectively), while the lowest correlation between parameters was found on the east side, where R^2 values of 0.34 (footslope) and 0.34 (backslope) were obtained, respectively. Both data sets collected on the shoulder showed similar R^2 values (0.73 and 0.77).

By applying lineal estimations and intersection with the axis, the runoff threshold values for each Gerlach trough were calculated for getting an overland flow of 0.1 L m^{-1}, 1 L m^{-1} and 10 L m^{-1}. To get some runoff (0.1 L m^{-1}) in the east, rainfalls between 4.55 mm (footslope) and 8.5 mm (backslope) must occur. At the same slope positions on the west part, the runoff threshold may be exceeded with the first drops. Similar runoff thresholds were found for upper slope positions on both sides, ranging from 5.9 mm in the east to 6.3 mm in the west. Reaching 1 L m^{-1} of overland flow would be possible for every slope position but would be more difficult on the backslope on the east side, because it would require up to 78 mm of rainfall. Reaching 10 L m^{-1} of overland flow would be relatively probable on the back- and footslopes on the west part, but would be much more unlikely on the east part and almost impossible on the backslope due to the amount of rainfall that would be required.

Based on this and corroborated with field observations, three different hydrological processes related to the runoff threshold and activation of the overland flow could be defined: i) laminar overland flow; ii) concentrated overland flow; and iii) a combination between laminar and concentrated overland flow. In the eastern part on the back- and footslopes, the lowest statistical significance between overland flow and rainfall amounts and the highest expected rainfall to reach the runoff threshold indicated higher infiltration rates and more obstacles to water following a lineal trend. Therefore, laminar overland flow could be identified. On the contrary, in the west part, at the same slope positions, the highest statistical correlation between rainfall and amount of water and the lower runoff threshold could show that a concentrated overland flow forms with little to no capacity for water retention. Finally, from the shoulders, a combination of laminar and concentrated overland flow could be observed, because statistical significances and amounts are situated halfway between the other two.

3.5. Rock fragment and fine particle mobilisation

After sieving the collected sediment samples after every natural rainfall event and tillage practice, descriptive statistics of the mobilized rock fragments and fine particles were calculated and are shown in Tables 4 and 5. Information about each percentage of rock fragment and fine particle transported during each recorded rainfall event can be found in figures 7 and 8.

Descriptive statistics showed elevated standard deviations and non-symmetric distribution (skewness and kurtosis) with values. Soil particles < 2 mm (Table 4) showed a higher presence in the Gerlach troughs from the footslopes to the shoulders in both parts. However, on both backslopes the concentration broke the trends, being higher on the east side and lower on the west side. The first gravel size interval in the collected sediments (0.2-0.5 cm) showed an increase in mobilisation from the shoulder to the footslope on both sides. Rock fragments between 0.5 cm and 2 cm were the largest component transported, with results that reached up to 30%. However, it was not a continuous behaviour from the shoulder to the footslope; both trends, the increase in the east part and the decrease in the west part from the shoulder to footslope were interrupted at the backslope on both parts. Rock fragments between 2-4 cm and 4-6 cm were mobilized from the summit to shoulder, with the percentage of mobilisation decreasing from the back- to footslopes. Materials larger than 6 cm and 8 cm were transported only from the summit to the shoulder (1.9%). Particles of this size were registered in June-July after harvesting and April and October after pruning.

Descriptive statistics for the fine soil particles on different slope positions are presented in Table 5. Standard deviations were lower than for the mobilized rock fragments because the results were more homogeneous after the erosive events. Moreover, skewness and kurtosis obtained positive values and, on several occasions, values that were nearly 0, showing non symmetric distribution close to the smallest percentages. Total averages showed that the most mobilized soil particles belonged to the sand fraction (very coarse sand, coarse sand and medium sand), with similar values being obtained between slope positions and sides (between 16.4% and 20.9%). The next most mobilized materials were coarse silt and fine silt (between 10.5% and 14.6%), showing a mobilisation from the shoulder to the footslope. The least transported fine particle fraction was the clays with values less than 2%.

Finally, Spearman rank coefficients between the rainfall characteristics and soil particle distribution were applied (Table 6). On the west side, an increase of total rainfall, rainfall intensity, and maximum rainfall intensity showed the highest significance on the shoulder and backslope with the very coarse sand and gravels between 0.2-0.5 cm ($p<0.01$). A correlation with the coarse sand was also found with a lower significance ($p<0.05$). On the footslope, the silt fraction obtained the highest significance ($p<0.01$) with the increase of variables related with the rainfall (fine silt = 0.494; coarse silt = 0.49). In the east part, high significant differences at level $p<0.05$ were obtained between rainfall and materials smaller than 0.2 cm and rock fragments between 0.2 and 0.5 cm.

4. DISCUSSION

4.1. Key factors that enhance soil erosion processes in Mediterranean sloping vineyards

Mediterranean sloping vineyards represent some of the most degraded orchards due to soil erosion processes, which are characterised as being recurrent and intense (Prosdocimi et al., 2016a, 2016d). In this research, overland flow and soil loss rates were the highest during the rainiest season and after tilling practices (ploughing and pruning) and only on one side (west). Results showed that using this methodology would make it relatively easy to detect spatiotemporal patterns of soil erosion and the intensity of the process. Similar results showing high variability with a clear pattern have been obtained using other methodologies in different croplands such as fruits in the Western Mediterranean (Cerdà et al., 2016, 2009; Keesstra et al., 2016) or USA (Atucha et al., 2013) and in olive orchards in Andalucía (Di Stefano et al., 2016; Vanwalleghem et al., 2010) and South America (Bravo-Espinosa et al., 2014).

The main common factors between Mediterranean conventional agricultural lands and the studied area are the bare soils, which are due to: i) pruning during the rainiest season, eliminating the leaf cover (Kosmas et al., 1997); and, ii) the use of herbicides, which also modify chemical and physical pedological characteristics (Calleja-Cervantes et al., 2015). During the most erosive events (October-December), soils are totally unprotected (Biddoccu et al., 2016; Rodrigo Comino et al., 2015) and as a consequence erosion reaches accelerated rates (Cerdà et al., 2009).

In this research, the measurements showed in 2 of 6 monitored slope positions that only a low amount of rainfall is necessary to activate overland flow (the lowest recorded rainfall amount was 4.55 mm), with precipitation amounts of about 20 mm leading to overland flow rates of up to 10 L m^{-1}. By comparing different European vineyards, Rodrigo Comino et al. (2016a; 2016c) also showed that activation of runoff increases soil loss.

Seasonal variation of rainfall events and intensities was observed and quantified as has been done in several Mediterranean areas (Ramos et al., 2008; Senciales González and Ruiz Sinoga, 2013). However, as Ramos and Durán (2014) highlighted, the most crucial climatic factor from the erosion point of view may be the number of extreme events (in this study area up to 100 mm during a few days). Moreover, coupled with the negative effects of steep slopes (Bryan, 2000; Fox and Bryan, 2000; Nadal-Romero et al., 2014) and silty texture (Bodner et al., 2013; Ramos et al., 2000; Rodrigo Comino et al., 2016a) in our studied vineyards, one or two events supplied more than 80% of the total rain over a period of several months and more than 25% of the total eroded material at the back and foot slope positions. These areas represented clear hot spots where farmers should focus their remediation plans. During these erosive episodes, which other studies in vineyards have also documented, there is the possibility of generating rills (Novara et al., 2011; Rodrigo Comino et al., 2015) and ephemeral gullies (Fox and Bryan, 2000; Martínez-Casasnovas et al., 2013), landslides (Richter, 1980), and degradation of roots that leads to decreased productivity (Bruggisser et al., 2010).

During ploughing and harvesting at the same landscape positions (intensity increased from shoulders to footslopes) other key erosive factors were encountered: the trampling of the farmers and animals. Since Morgan and Smith (1980), very little research has been conducted related to the impact of human trampling on erosion in agricultural areas. Over the last few decades, much of the research has focused on animal trampling in grasslands (Pulido-Fernández et al., 2013; Schnabel et al., 2013), recreational trails (Williams and Brevik, 2010; Svajda et al., 2016) and campsites (Tibor and Brevik, 2013). In vineyards, some studies were carried out in intensive plantations that investigated the effect of heavy machinery on the soil (Arnaez et al., 2007; Blavet et al., 2009; Ferrero et al., 2005).

4.2. Spatiotemporal variation of soil surface components and runoff threshold

As Rodrigo Comino et al. (2016b) observed the total amount of rock fragments (summits and shoulders) and their schistosity facilitate the weathering of the soil materials, which acquire a laminar morphology and high angularity. This dynamic was observed on the west side of our studied hillslope, where overland flow was higher than the east part. On the contrary, on the east part the aspect of the stones offered higher resistance to movement of the fine sediments (clays and fine silts) down the slope and caused hydrological variations, so the sediments did not necessarily accumulate at the footslope shoulder or backslope positions. In this way, a mixed Hortonian-Hewlettian model (Rodrigo Comino et al., 2016c), combining surface and sub-surface flow, irregular sediment transport, and differential impacts of rainfall on the soil at the micro-scale was observed, such as Gabarrón-Galeote et al. (2013) and Ruiz Sinoga and Martinez Murillo (2009) showed in Southern Spain. The studied vineyards showed clear mechanisms of connectivity between rock fragments, fine particles, and type of overland flow (laminar and concentrated flow), appearing and disappearing at different slope positions and sides (east and west). All together they created a pattern from the shoulder to the footslope that developed a continuous feedback system.

This research also demonstrated that the number and length of pathways for runoff threshold varied with the slope and the side (aspect), the volume of rock fragments, and the textural class as well as with the antecedent conditions of tillage and type of runoff. We observed that during low rainfall events, runoff sources and main pathways were disconnected in the east part, but in a larger event, the network of pathways for runoff threshold and sediment yield became fully connected (Masselink et al., 2016a; 2016b). The importance of the connectivity of the flows has been found in recent researches (López-Vicente et al., 2015; 2016; Marchamalo et al., 2016).

The results related to sediment transport showed three different textural mobilization phases, highly demonstrated on the west side, as Lasanta (1985) and Ortigosa and Lasanta (1984) showed in La Rioja for tilled vineyards. First, silt particles (fine and medium) were transported due to low rainfall intensities and amounts. Second, the mobilization of sands (fine and very fine sands) occurred finally followed by the clays, which confirms that solid aggregates that are difficult to destroy were detached and transported. For their part, non-embedded rock fragments (larger than 4 cm) followed a gravitational redistribution, with the largest sizes at the summit (with the lowest surface inclinations) and footslope positions (where there are rock fragments larger than 8 cm). On the other hand, embedded stones (between 0.5 cm and 2 cm) had a non-regular distribution along the hillslope due to the continuous top layer remobilization by the vine grower and natural weathering.

4.3. Is it necessary to include soil protection measurements?

It is definitely necessary to include soil protection measurements. Mitigation systems should be designed to restrict runoff generation, or at least, canalize the water for other uses. To address this situation, the winegrowers from Málaga plough the soil to modify the surface component distribution, removing and generating micro-topographical changes under and between the grapevines in the form of little sinks (improving the infiltration), walls and agri-spillways (channelizing the overland flow) by removing the stone cover (Rodrigo Comino et al., sub).

Proposed solutions to avoid high erosion rates often include the use of legumes or herbaceous plant covers during the rainiest period (Galati et al., 2015; Novara et al., 2011; Prosdocimi et al., 2016a). However, in the driest Mediterranean environment areas, the long dry periods between May and August (Nadal-Romero et al., 2015; Ruiz Sinoga et al., 2011, 2010) may generate excessive competition for depleted water storage and become deleterious for the vines and grape quality (Lorenzo et al., 2012; Ramos et al., 2008). Therefore, seasonal mulching with straw that results in an immediate reduction of sediment and water losses (Cerdà et al., 2016; Prosdocimi et al, 2016c) or using vine pruning and organic wastes from the agricultural production process (Parras-Alcántara et al., 2016) could be possible solutions.

Moreover, our findings demonstrate that the farmers should not remove the rock fragments as they contribute to reduced soil losses, although the runoff rates can be increased (Follain et al., 2012; Poesen et al., 1997). But it is necessary to find the right forms to avoid high sediment yield and to channelize runoff losses into deposits, for example, on the west side.

Perhaps it would be interesting to promote research about the economic cost of soil erosion processes that included vine- and wine-growers (Galati et al., 2015). Demonstrating the economic impact of erosion would be very important, and maybe, farmers may be more concerned about potential economic impacts than about the loss of the soil itself (Osterman and Hicks, 1988).

4.4. Further research in the future

In the future, when looking deeper into the intra-plot differences in soil erosion processes at the pedon scale (Chevigny et al., 2014; Quiquerez et al., 2014), two types of studies would be interesting to carry out. First, by including other measurement techniques such as Sf3M 3-D (Hänsel et al., 2016; Prosdocimi et al., 2017)) or remote sensing (Carrasco-Benavides et al., 2014; Desprats et al., 2013; Taylor et al., 2009), we could compare micro-topographical changes by making maps at different times, such as after tilling (pruning, ploughing and harvesting) or extreme rainfall events. Such maps have the potential to supply critical information for precision farming purposes (Brevik et al., 2016). Moreover, there is no research on agricultural land, and especially in vineyards, addressing human trampling. Therefore, there is a need to research how human trampling changes soil compaction, soil aggregate stability, and influences erosion so plans and strategies can be developed to reduce its effects and negative impacts.

After performing this research, we would know the important role that tillage practices and rainfall events play in the mobilisation capacity of the soil (rock fragments and fine particles) downslope, which can also remove valuable products such as herbicides, fertilizers, fungicides, and nutrients.

5. CONCLUSIONS

This research reported that sloping vineyards in a Mediterranean environment on bare soils can experience high soil erosion rates and that the spatiotemporal distribution of hydrological and geomorphological processes is uneven. The extreme rainfall events, agricultural practices, and bare soils were key factors that enhanced the soil erosion processes in the west part of the study area, especially at back- and footslope positions. The measurements showed that the runoff threshold ranges from 4.55 mm to 8.5 mm). The highest soil loss and overland flow rates occurred in a few extreme rainfall events during the rainiest period, when the soil was bare, without cover after tillage practices.

We demonstrated that the number and length of pathways for runoff varies with the slope, the volume of rock fragments, and the textural class and also with the antecedent conditions of tillage. We observed that during low rainfall events, runoff sources and main pathways were disconnected, and during extreme events, the network of pathways of runoff threshold and sediment yield became fully connected.

AKNOWLEDGMENTS

We acknowledge the farmer's syndicate UPA (Unión de Pequeños Agricultores) and wine-grower Pepe Gámez (Almáchar) for providing access to the study area and the technicians from Instituto de Geomorfología y Suelos (University of Málaga) María Pedraza and Rubén Rojas of for the soil analysis.

We also thank Ministerio de Educación, Cultura y Deporte from Spain for the financial support with the FPU15/01499 to J. Rodrigo Comino.

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