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Rainfall-simulated quantification of initial soil erosion processes in sloping and poorly maintained terraced vineyards - Key issues for sustainable management systems

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ABSTRACT

In the context of the Sustainable Development Goals (SDG), understanding landscape evolution is essential to design long-term management plans. In agricultural fields, such as the vineyards on steep slopes, the terraces offer one of the most important morphological changes. However, it is not clear if the poorly managed agricultural terraces are optimal to reduce soil erosion and overland flow, although the trafficability is improved. Therefore, the main aim of this research is to compare the differences between initial soil erosion processes on poorly managed terraced vineyards and sloping vineyards at the pedon scale, considering the key role of the SSC (Soil Surface Components). To achieve this goal, twenty-six rainfall simulations were performed, considering the inclination, vegetation and stone covers, and surface roughness. Our research was carried out in the sloping vineyards (>20°) of the Almáchar municipality, in the Montes de Málaga (Spain). Those vineyards are characterized by bare soils, low organic matter and high rock fragment contents. Our results showed that higher soil losses (42.2 g m^{-2} *vs* 9.4 g m^{-2}) and runoff (4.91m^{-2} *vs* 1.61m^{-2}) were detected in the plots of the poorly managed terraced vineyard than in the sloping one. Moreover, the time to runoff generation was lower in the poorly conserved terraces (232 s) than in the sloping vineyard (679 s), showing a faster saturation capacity. The SSC considered as the key factors were the reduction of the stone cover and an increase of roughness. As a conclusion, we confirm that the imminent transformation from sloping vineyards into terraced fields could lead several land degradation processes if a poor management is carried out, and no control measures are applied during the process, such as the conservation of stone walls or vegetation cover above the embankment, which is not in compliance with the SDG.

1. Introduction

Understanding landscape evolution and morphological changes is essential for the successful development of land management plans (Cunha et al., 2017; Ferro-Vázquez et al., 2017). In agricultural fields, terracing has proven to be one of the most important morphological interventions that directly affect runoff and soil erosion processes (Arnáez et al., 2015). Agricultural terraces have traditionally been designed for territories characterized by steep slopes and for crops with a high productivity (Chen et al., 2012; Tarolli and Sofia, 2016). And yet, in some regions, and for some crops, terracing is the only option for crop production, although the productivity is not always high, especially when compared with the same crops in plains (Lasanta et al., 2013; Veeck et al., 1995).

For wine-making, in particular, the micro-climate on terraces and the lower yields can produce better quality wine, as some authors have confirmed in cases in Southern Europe (Fraga et al., 2014; Ramos and Porta, 1997). The implementation of terraced slopes also allows the enhancement of water retention capacity (Kosmowski, 2018) and trafficability (machinery and animal movements) along steep surfaces (Li et al., 2014). However, land degradation processes such as soil erosion can also be activated, sometimes with dramatic consequences, after extreme rainfall events (Brandolini et al., 2016) or substandard practices such as a poor maintenance of the embankments, elimination of vegetation cover, and failure to maintain stone cover (Chapagain and Raizada, 2017; Treacy, 1987). These negative effects are not due to terracing *per se*. When terraces are constructed correctly, they can function as sediment traps and may directly reduce erosion (Kosmowski, 2018). The dramatic negative consequences are; however, a result of non-sustainable practices such as too much tillage, excessive use of herbicides, land abandonment, and unmaintained/non-vegetated terraces (Cossart and Fressard, 2017; Londoño et al., 2017).

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A fundamental question is why should some crops and orchards be planted on steep hillslopes at all? In most of the cases, as some authors confirmed, this kind of occupation is not related to land capability or sustainability, because terracing generates an inadequate land occupation accompanied by critical environmental land use conflicts, and threatens short- and medium-term soil erosion (Pacheco et al., 2014; Valle Junior et al., 2014).

Soil erosion is a well-known process that drastically increases desertification rates (Martínez-Valderrama et al., 2016). This is firmly recognized in goal 15 of the Sustainable Development Goals (SDGs). Combating land degradation processes and desertification should be considered a primary concern because the loss of soils directly affects human and ecosystem health (Faccioli et al., 2016; Keesstra et al., 2016). As regards land degradation and desertification, Pacheco et al. (2018) paid special attention to the role of the environmental land use conflicts on land degradation, in the context of SDG 15, including the non-common term “land degradation neutrality”, which is not currently applied to vineyards.

In terraced vineyard systems, SDG goal 15 is sometimes violated. For example, in Troodos Mountains of Cyprus, Camera et al. (2018) measured on a terraced vineyard a soil erosion rate from 2.4 to 3.2 $\mathrm{Mg\,ha^{-1}\,yr^{-1}}$, highlighting that the degradation of dry-stone walls increased soil loss by 3.8 times. Still, terraces can actually control erosion if they are well constructed and maintained. In the Priorat region (Pènedes, Spain), Ramos et al. (2007) noticed that the farmers only consider the positive advantages of the trafficability along the terraces, but not if an extreme rainfall event shortly after terrace implementation can generate mass movements, and damage for the plants, irrigation and training systems. According to Cots-Folch et al. (2006), in the mentioned region, the costs of building the terraces can reach up to 30% of the total costs for a new terraced vineyard, exhausting the maximum EU subsidies. In Spain and Italy, the destruction of the grapevine plantation or the loss of soil fertility used to encourage grape growers to build new plantations (Martínez-Casasnovas et al., 2005; Tarolli et al., 2014), which introduced a new key factor of soil erosion risk: the age of the plantation (Rodrigo-Comino et al., 2017a).

In the vineyards of the Axarquía region (Montes de Málaga, southern Spain) with steep slopes higher than 20° and bare soils, terraces are not very common, but when they are introduced, they are usually poorly managed (Martínez-Murillo and Ruiz-Sinoga, 2003; Ruiz-Sinoga, 1987). Currently, the vineyards are being removed throughout this region and substituted by mango (*Mangifera indica*) and avocado (*Persea americana*) orchards, using poorly managed terraces and irrigation systems, because of their increased productivity and incomes. However, no study has been conducted to decipher if soil erosion processes will be enhanced or not. To date, studies have been carried out in sloping vineyards in this region which indicate several spatiotemporal differences in soil and water losses and high erosion rates in sloping systems (Rodrigo-Comino et al., 2016). For example, Rodrigo-Comino et al. (2017d) registered with paired Gerlach troughs differences up to 1000 $\mathrm{g\,m^{-1}}$ after the same extreme rainfall event (>100 mm in a few hours). In another study, under dry soil conditions, two extreme runoff events (1 $\mathrm{m^3}$ of water) were simulated in rills designed to canalize the excess of runoff along the hillslope (agri-spillways). The results showed that sediment concentration can reach amounts up to 1500 $\mathrm{g\,l^{-1}}$ (Rodrigo-Comino et al., 2017c). These results were much higher than other runoff experiments carried out using the same method on badlands or abandoned grazing areas in Andalusia (Spain) (Wirtz et al., 2012a, 2012b). One of the most important key factors highlighted in these studies was the main role of the soil surface components (SSC), which coincided with other studies conducted in Mediterranean areas (Ruiz-Sinoga and Martinez Murillo, 2009). Arnau-Rosalén et al. (2008) defined SSC as specific elements on the soil—such as vegetation, rock fragment cover, rock outcrops, bare soil, and soil surface crust—whose spatial patterns play a key role in understanding the hydrological behaviour of hillslopes. However, there is a lack of studies that infer the role of the soil surface components in the hydrodynamics of either poorly managed terraced or sloping vineyards.

Therefore, the main goals of this research were: i) to assess the initial soil erosion processes at the pedon scale in two paired vineyards cultivated under sloping and poorly managed terraced systems; and; ii) to detect which role the SSC plays in terms of hydrodynamics. We consider that, as stated the Sustainable Development Goals, research must be conducted to show the farmers and policymakers the possible environmental consequences to moving from sloping plantations to poorly managed terraces. To achieve this goal, 26 rainfall simulations using a rainfall intensity of 40 $\mathrm{mm\,h^{-1}}$ were conducted to compare soil loss, runoff coefficient, time to runoff generation, and sediment concentration.

2. Materials and methods

2.1. Study area

The experimental study site is situated in the Axarquía region in the Montes de Málaga relief (Andalusia, Spain). The vineyard is planted in the Almáchar municipality. In Fig. 1a and b, the specific location can be noted (36.8 N; −4.2167 W).

The main parent materials were Palaeozoic dark schists, which have less developed schistosity, showing higher resistance than the first facies (Rodrigo-Comino et al., 2017a). Soils are typically *Eutric* Leptosols (IUSS Working Group WRB, 2014). These soils are characterized by Rodrigo-Comino et al. (2016): i) silt loam texture; ii) very low electrical conductivity values (0.1 $\mathrm{dS\,m^{-1}}$); iii) general soil pH values of about 7; iv) bulk density up to 1.5 $\mathrm{g\,cm^{-3}}$; v) carbonate contents 1% because the main lithology is schist; and vi) a total organic carbon content between 1 and 2% due to the use of herbicides and tillage to eliminate vegetation growth.

The average rainfall depth is 520 $\mathrm{mm\,yr^{-1}}$, distributed between October and January (78%) in a few extreme events, but with a high inter-annual variability (Rodrigo-Comino et al., 2016).

The experimental plots are characterized by conventional and traditional grape production with an irregular distribution of the vines along with steep hillslopes. The main grape variety is *Muscat of Alexandria*, registered by a Spanish DO (Designation of Origin) with the name “Málaga, Sierras de Málaga and Pasas de Málaga”, which has been named the first Globally Important Agricultural Heritage System in Europe. The 2014 and 2015 harvests were carried out at the beginning of July by hand due to the high temperatures and the fast maturation of the grapes. The land management is characterized by i) non-mechanical tillage which is performed using hoes and shovels before (April–May) and after the harvest (October–December); ii) the application of herbicides to avoid the competition for water with other plants (November–December); and iii) the application of natural and organic soil fertilisers of domestic cows and goats (February–March). The utilization of animals to collect the grape production is required. The main goal of terrace construction is to improve the animal trafficability, although substandard practices such as the elimination of vegetation cover and replacement of stones preclude their important potential benefits as soil conservation measures.

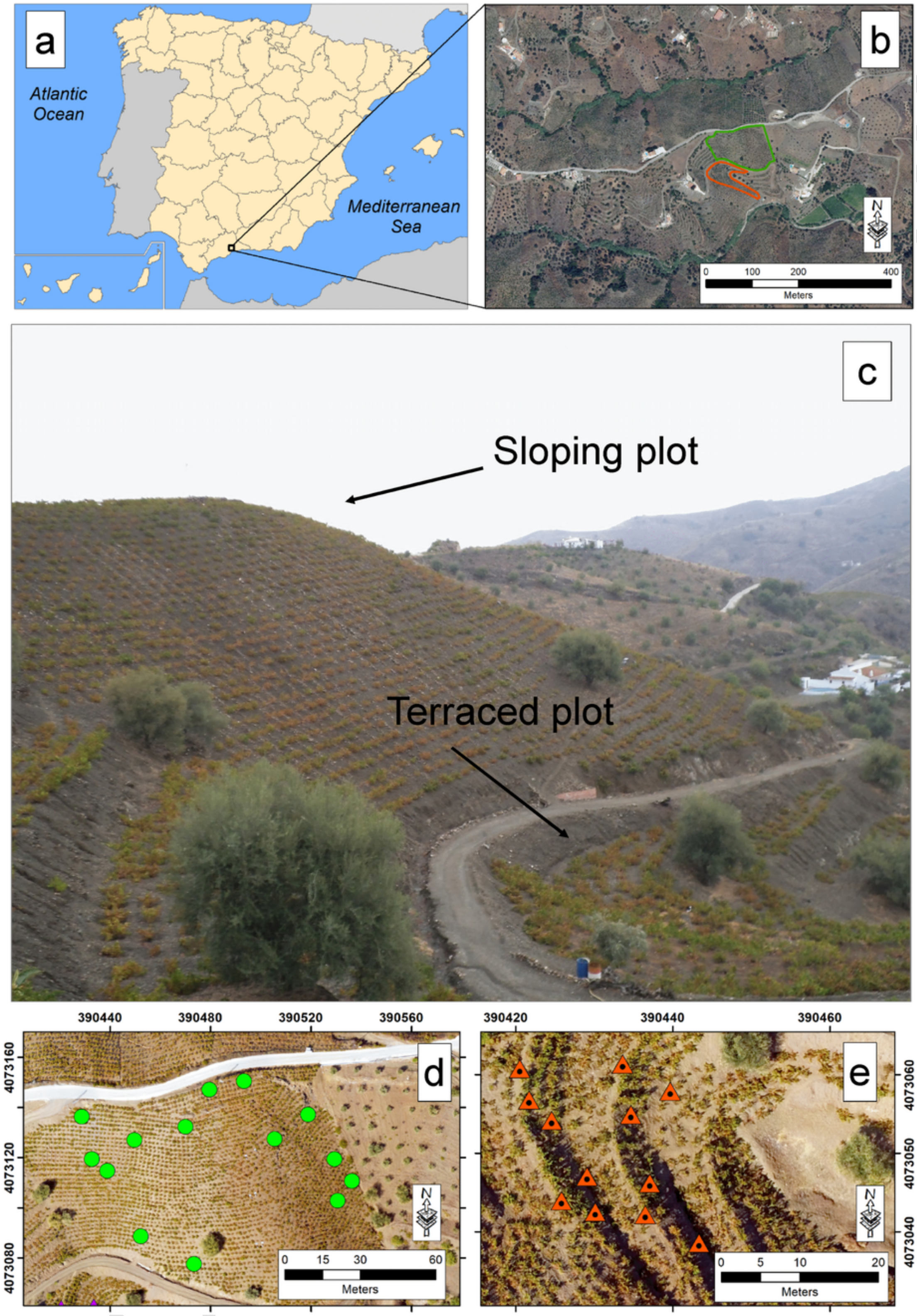

Fig. 1. Localization of the study area. a–b: Geographical situation; c: panoramic picture of the sloping and terraced vineyard; d: experiments conducted in the sloping vineyard; e: experiments conducted in the terraced vineyard.*UAV airphoto by I. Marzolff, Institute of Physical Geography, Goethe University Frankfurt am Main, Germany.*

2.2. Rainfall simulations

2.2.1. Rainfall simulator characteristics

Initial soil loss, sediment concentration, runoff, runoff coefficient and time to runoff generation were measured using a small portable rainfall simulator. The rainfall simulator is a nozzle-type device based on the one designed by Cerdà (1997). Simulated rainfall was calibrated by Ries et al. (2009) and Iserloh et al. (2013) as well as standardized by the design improvements of Iserloh et al. (2012). The round test plot has an area of $0.28\,m^2$ and a diameter of 60 cm. Selected rainfall intensity was $40\,mm\,h^{-1}$ because this is considered to be a typical rainfall storm intensity in the area (Rodrigo-Comino et al., 2016, 2017b, 2017c).

2.2.2. Experiment procedures

A total of 26 rainfall simulations were conducted in September 2017 in two paired plots (Fig. 1c). Rainfall simulations were performed during one field campaign under dry soil conditions in order to avoid any variability induced by changes in soil moisture conditions (<1% soil moisture during the field campaign). Fourteen experiments were performed at different slope positions in a sloping vineyard (Fig. 1d). Twelve further simulations were conducted in a poorly maintained terraced vineyard close to the embankment (Fig. 1e) in order to assess the initial soil erosion processes in the nickpoint, where we hypothesize that the highest soil and water losses are occurring. Each experiment had a duration of 30 min, divided into six measuring intervals (5 minute duration). Prior to the beginning of each simulation, the following plot characteristics and SSC, usually used for these kinds of experiments (Iserloh et al., 2013), were measured: i) the slope inclination (°), using a digital inclinometer; ii) vegetation and stone cover (%), comparing visual values made by two experts (Ries et al., 2013); and iii) roughness ($mm\,mm^{-1}$), following the chain method (Saleh, 1993).

Time to runoff generation (Tr) measured in seconds is the time from the beginning of the experiment to the moment when the first drops reached the outlet of the ring plot. After that, during the simulation, runoff with eroded material was collected in plastic bottles. At the beginning of a new interval, the bottles were changed and the total runoff (l and $l\,m^{-2}$) amount was gravimetrically estimated for each bottle. The collected runoff with sediments in each bottle was filtrated, dried and weighed thereafter to determine soil loss (g and $g\,m^{-2}$). Furthermore, sediment concentration ($g\,l^{-1}$) was calculated by dividing soil loss and total runoff amount. Finally, runoff coefficient (%) was calculated using the total simulated rainfall applied on the plot and the collected runoff.

2.3. Statistical analysis

Firstly, averages, standard deviation, maximum and minimum values were calculated for the plot characteristics and the initial soil erosion rates of each experiment. Then, soil loss, runoff, runoff coefficient, sediment concentration and time to runoff generation were depicted in box plots using SigmaPlot version 13 (Systat Inc.). In the box plots, the mean (dash lines) and median values, and the results between 5th and 95th percentiles were presented.

Differences between the sloping and the terraced vineyards in hydrological response and soil erosion results were compared. The normal distribution of data was checked using the Shapiro-Wilk test. After confirming that results followed a normal distribution, a Tukey test was conducted to assess the significant differences between vineyards. Finally, a Spearman's rank correlation coefficient (S_{rc}) was computed to evaluate the possible influence of environmental plot variables on initial soil erosion processes.

3. Results

3.1. Differences in plot characteristics

In Table 1, some clear differences in plot characteristics could be found among vineyards. The sloping vineyard registered average inclination values of 31.1 ± 8.5°, with a maximum of 42° and minimum of 15°. Since the rainfall simulations were conducted close to the embankment of the terraces, average steep slopes were also recorded (23.6 ± 8.4°) on the terraced plots. In both plots, vegetation cover was minimum (<4%), showing how the farmers leave the soil bare. To correctly interpret our results, it is important to remark that the average stone cover content on the sloping vineyard (87.7 ± 9.4%) was

Table 1
Plot characteristics in the sloping and terraced vineyards.

n[a]	Inclination (°)		Vegetation cover (%)		Stone cover (%)		Roughness ($mm\,mm^{-1}$)	
	Sloping	Terraced	Sloping	Terraced	Sloping	Terraced	Sloping	Terraced
1	26	15	5	5	95	75	1.05	1.03
2	38	18	0	5	93	55	1.03	1.03
3	15	26	3	0	85	50	1.05	1.05
4	39	30	3	0	95	60	1.08	1.00
5	34	29	10	0	80	60	1.05	1.04
6	41	9	2.5	5	60	60	1.03	1.04
7	36	30	2	0	95	50	1.04	1.11
8	42	21	3	0	95	50	1.05	1.10
9	30	23	3	0	85	40	1.10	1.03
10	29	28	7	0	85	65	1.06	1.06
11	25	39	5	0	90	75	1.05	1.08
12	35	15	2	0	90	75	1.06	1.07
13	16	–	3	–	95	–	1.03	–
14	30	–	3	–	85	–	1.05	–
Average	31.1	23.6	3.7	1.3	87.7	59.6	1.05	1.05
SD	8.5	8.4	2.4	2.3	9.4	11.4	0.02	0.03
Max	42	39	10	5	95	75	1.10	1.11
Min	15	9	0	0	60	40	1.03	1.00
Diff.	$p = 0.032$		$p = 0.015$		$p \leq 0.001$		$p = 0.871$	

[a] n: number of experiment; SD: standard deviation; Max: maximum absolute values; Min: minimum absolute values; Diff.: statistically significant difference using Tukey test.

higher than on the terraced one (59.6±11.4%). Finally, the roughness showed similar values in both areas (1.05 mm mm^{-1}), although the variations, maximum and minimum values were higher in the terraced plot.

3.2. *Differences in initial soil losses and water mobilization between the terraced and the sloping vineyard at the pedon scale*

3.2.1. *Total soil loss and hydrological responses*

Soil losses and hydrological responses are presented in Fig. 2. Moreover, in Table 2, the statistically significant differences among soil erosion results in the sloping and the terraced vineyards are summarized. The runoff initiation was measured after 232 s in the terraced and 679 s in the sloping vineyard. These numbers demonstrated that the time to runoff generation was shorter in the terraced vineyard than in the sloping one.

Runoff summarized 4.9 l m^{-2} (1.4 l) in the terraced plot and 1.6 l m^{-2} (0.44 l) in the sloping one. In the terraced plot, the maximum runoff discharge amounted to 11.6 l m^{-2} while the sloping vineyard registered maximum values of 4.5 m^{-2}. These results corresponded to an average runoff coefficient of 29.5% and 9.2% respectively for terraced and sloping plots. The variability of the runoff was also different, reaching maximum runoff coefficients up to 64% in the terraced vineyard and to 33.5% in the sloping plot. The differences between terraced and sloping plots were statistically significant for all the hydrological parameters (Table 2).

The total soil loss from the 0.28 m^2 plots amounted to 42.2 g m^{-2} (11.8 g) and 9.4 g m^{-2} (2.6 g) for the terraced and sloping plots, respectively. The maximum soil particle yield was 147.3 g m^{-2} on the terraces, and 33.3 g m^{-2} on the sloping plot. Statistically significant differences were also confirmed for soil loss ($p < 0.004$). Finally, average sediment concentration values were 11.8 g l^{-1} for the terraced and 6 g l^{-1} for the sloping vineyard. The highest sediment concentration value registered in the rainfall simulations conducted in the terraces amounted to 28.2 g l^{-1}. Meanwhile, 34.4 g l^{-1} was the maximum sediment concentration registered in the sloping vineyard. In Table 2, the Tukey test did not show statistically significant differences among plots.

3.2.2. *Initial soil erosion processes during the rainfall simulation experiment*

Fig. 3 is divided into two sub-figures. From Fig. 3a to c, the box plots represent the variation of the soil erosion results per interval (the median, indicated by solid lines; the averages, indicated by dotted lines; and 5th and 95th percentile values). From Fig. 3d to f, the box plots were substituted by lines that join the mean values of each box plot per interval in order to decipher the erosional and hydrological dynamic during the rainfall simulation in both plots. Paying attention to the runoff discharge and soil loss results, for the poorly maintained terraced vineyard, higher values in all the intervals can be noted than in the sloping one. Soils become saturated more quickly and with a greater intensity in the terraced vineyard than in the sloping one. Between the second and third intervals, runoff and soil

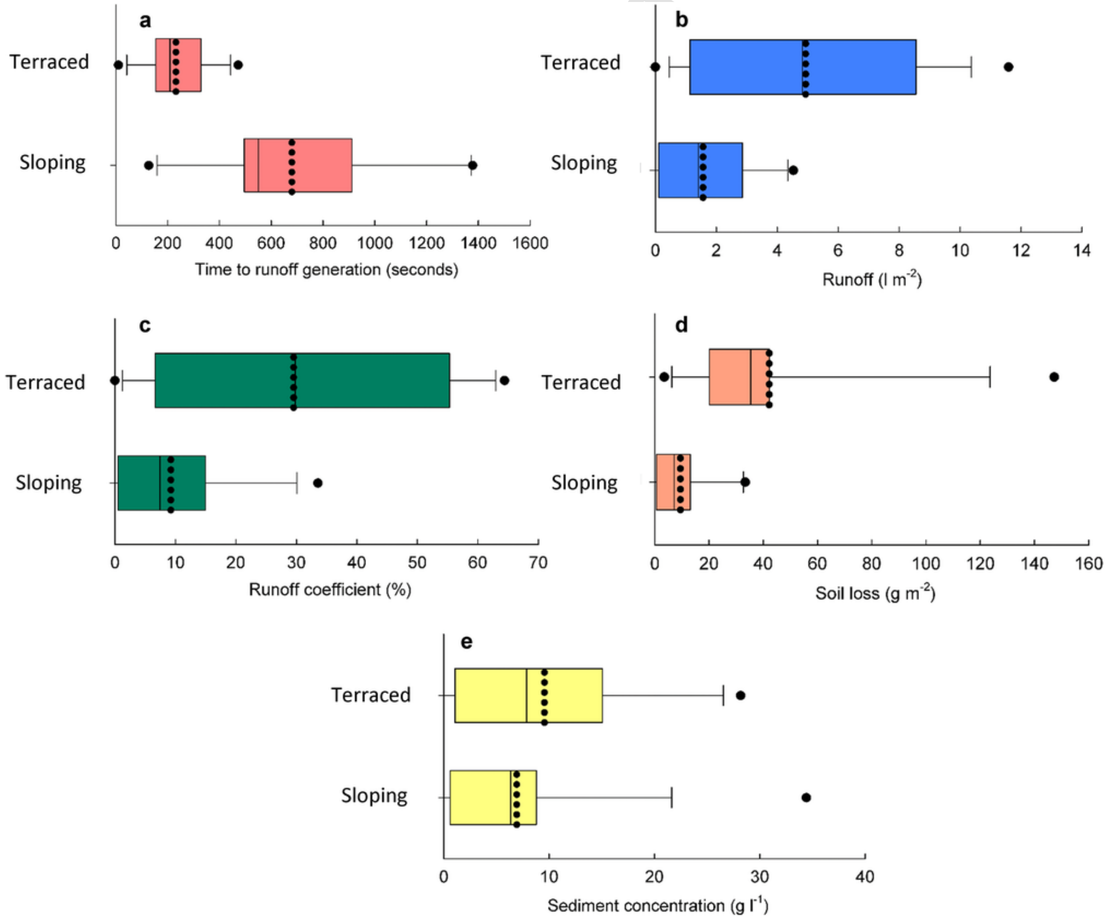

Fig. 2. Box plots of soil erosion results. a: Time to runoff generation; b: total runoff discharge; c: runoff coefficient; d: soil loss; e: sediment concentration.

Table 2
Statically significant differences among soil erosion results in sloping and terraced vineyards.

Variable[a]	Runoff	Soil loss	Sediment concentration	Runoff coefficient	Time to runoff generation
Diff.	p=0.008	p=0.004	p=0.456	p=0.007	p=0.001

[a] Tukey test was performed.

losses increase in both plots. In the terraces, the soil erosion results remain constant after the fourth interval. However, in the sloping vineyard, water and soil losses continue to increase slightly. Sediment concentration for the terraced vineyard, however, experiences a strong increase until the second interval, and then drastically decreases from the third to the fifth intervals, after which it again increases. In the sloping vineyard, sediment concentration is very low at the beginning, and after the third interval starts to increase, showing similar values during the fourth and fifth intervals to the values on the terraced plot.

3.3. Key factors in understanding the initial soil erosion process differences between a terraced and a sloping vineyard

In Tables 3 and 4, Spearman's rank coefficients for both the poorly managed terraced and the sloping vineyard are shown. Since the soil erosion results did not show a normal distribution, this test was preferred instead of others that work using linear trends such as Pearson correlation.

In the mismanaged terraced grapevine plantation, the highest positive correlations were found for runoff with soil loss ($S_{rc}=0.90$); sediment concentration ($S_{rc}=-0.56$); time to runoff generation ($S_{rc}=-0.54$); and roughness ($S_{rc}=0.68$). Soil loss had a negative correlation with time to runoff ($S_{rc}=-0.69$), and positive with roughness ($S_{rc}=0.56$). Sediment concentration registered a positive correlation with the slope ($S_{rc}=0.63$). Also, the slope recorded a negative correlation with vegetation cover ($S_{rc}=-0.70$).

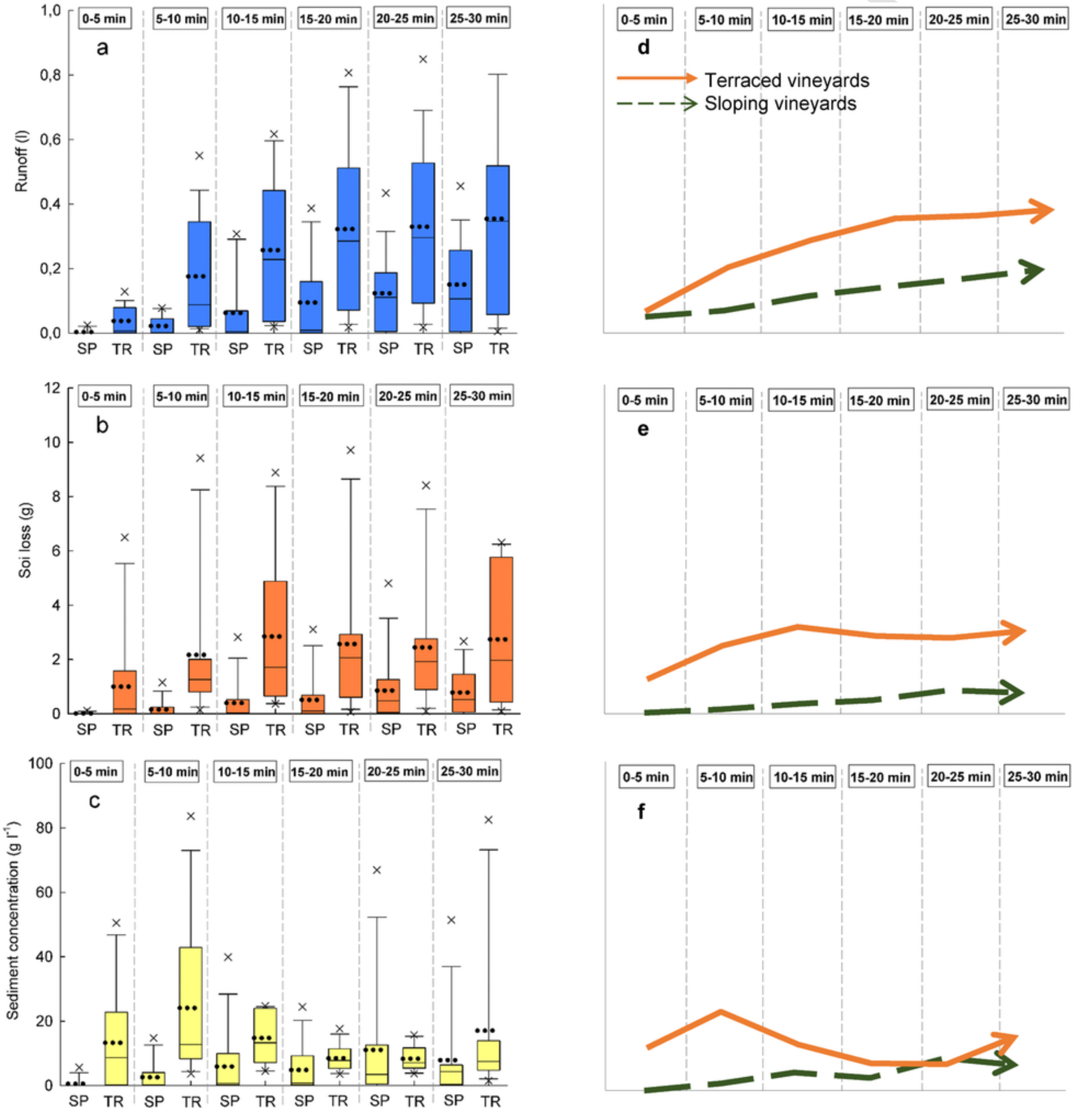

Fig. 3. Box plots of the soil erosion results per intervals during the rainfall simulations and trend lines through the mean values in each box plot.

Table 3
Spearman's rank coefficient of soil erosion results and plot characteristics in terraced vineyards.

	Runoff	Soil loss	Sediment concentration	Tr[a]	Slope	Vegetation cover	Stone cover	Roughness
Runoff		**0.90**	**−0.56**	**−0.54**	−0.25	−0.17	−0.21	**0.68**
Soil loss			−0.35	**−0.69**	−0.25	−0.28	−0.29	**0.56**
Sediment concentration				0.01	**0.63**	−0.42	−0.12	−0.32
Tr[a]					0.00	0.25	0.32	−0.34
Slope						**−0.70**	−0.09	0.27
Vegetation cover							0.20	−0.42
Stone cover								−0.05
Roughness								

[a] Time to runoff generation.

Table 4
Spearman's rank coefficient of soil erosion results and plot characteristics in sloping vineyards.

	Runoff	Soil loss	Sediment concentration	Tr[a]	Slope	Vegetation cover	Stone cover	Roughness
Runoff		**0.81**	**0.81**	−0.25	0.00	−0.15	−0.06	0.08
Soil loss			**1.00**	0.10	−0.07	−0.04	−0.05	−0.16
Sediment concentration				0.10	−0.07	−0.04	−0.05	−0.16
Tr[a]					−0.06	0.19	0.34	0.18
Slope						−0.48	0.09	−0.05
Vegetation cover							−0.21	0.36
Stone cover								0.07
Roughness								

[a] Time to runoff generation.

The number of plot characteristics identified with high correlation for the sloping vineyard was considerably lower, showing only a positive correlation between soil loss, runoff and sediment concentration ($S_{rc} = 0.81$), and between soil loss and sediment concentration ($S_{rc} = 1.00$).

4. Discussion

4.1. Consequences of correctly and poorly managed terraces

It is well-known that terraces reduce slope inclination and modify soil processes by dividing the hillslopes into short gentle sections (Dijk and Bruijnzeel, 2004; Li et al., 2014). These human structures, if correctly designed, conserved and managed, are able to positively modify soil hydrology, vegetation development and biogeochemical cycles (Krahtopoulou and Frederick, 2008; Stanchi et al., 2012). As Wei et al. (2016) demonstrated using a δ index, the most relevant role of agricultural terraces was related to the improvements in soil erosion control, water retention capacity, biomass accumulation, water recharge, and nutrient enrichment. Therefore, *a priori*, no negative consequences should appear after transforming sloping fields into terraced ones. However, it was also highlighted that this positive dynamic could be significantly changed by poorly-designed or poorly-managed terraces and the SSC (Arnáez et al., 2015; Ruiz-Sinoga et al., 2010). Sometimes, the lack of a strict and specific legislation about how a terrace system must be designed and managed can presuppose negative consequences. One of them is the increase in soil erosion and, subsequently, land desertification. As Mann et al. (2018) stated according to the Sustainable Development Goals, it is vital for the implementation of integrated landscape management to have strong collaboration by actors, sectors, and scales. In order to achieve a successful implementation in these kinds of Mediterranean vineyards, further work is needed to change the perceptions of farmers and policymakers regarding markets and extremely difficult environmental conditions (Marqués et al., 2015; Martínez-Casasnovas et al., 2010).

4.2. A key question: are poorly managed terraces necessary?

The case of the sloping vineyards of the Montes de Málaga (Southern Spain), where land degradation processes are dramatic, is a clear example which confirms that poorly managed terraces must be avoided. Our results clearly demonstrate that the incorporation of poorly managed terraced areas drastically changes the morphological and micro-topographical characteristics of the vineyards.

Fig. 4 shows a representation of the hydrological and geomorphological transformations which occurred in the study area. The recent terraces are characterized by two kinds of spaces: a flat area where the vines are planted, and embankments which are transition zones between terraces . The trafficability along the terraces is drastically increased, and the work can be carried out more comfortably (Kosmowski, 2018). At the same time, there is a clear reduction in the number of plants cultivated in the terraced sections as compared to sloping ones (Fig. 1c), which generates a reduction in the agricultural intensification and less intense soil depletion (Tarolli et al., 2014). Besides plant density, the growth stage of plants during the intense rainy season could also play a role (Belmonte and Romero-Diaz, 1998; Leuning et al., 1994). Also, in the flat areas of the terraces, water retention capacity will increase because of a significant reduction of the slope inclination (Cammeraat et al., 2005; Chaplot and Le Bissonnais, 2000).

However, after extreme rainfall events and tillage practices, the soil is mobilized, and runoff discharge is activated. Soils are saturated, and the water which accumulates in ponds on the flat areas overpasses the terraces and descends down the embankments, generating rills and ephemeral gullies . This situation was also confirmed by Rodrigo-Comino et al. (2018) in the Valencia vineyards (Eastern Spain) using the improved stock unearthing method (ISUM). They observed that the connectivity processes were activated on the embankments between terraces. Our results confirmed that the embankments still conserve a high inclination (>20°), and are totally bare, which several authors confirmed as a key factor for soil erosion activation (Biddoccu et al., 2017; Chaplot and Le Bissonnais, 2003). This

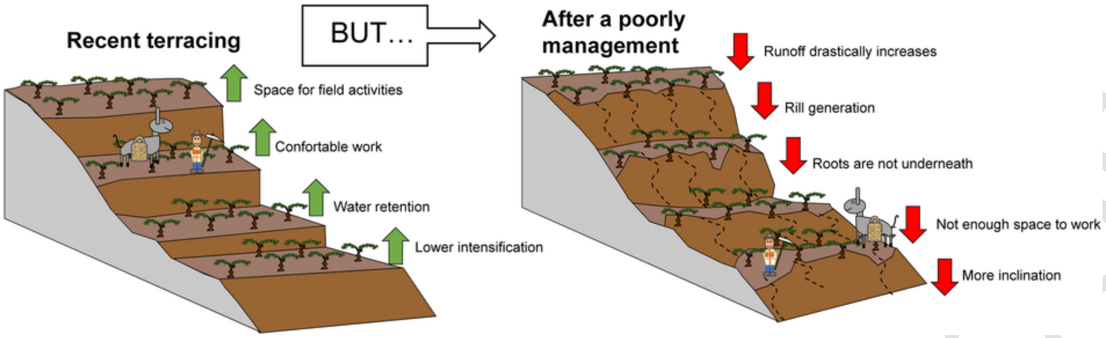

Fig. 4. Evolution and morphological changes with immediate impact on the initial soil erosion results before and after terracing.

is indeed the main reason, and so we can confirm that terraces are not ideal when they are not correctly managed and designed. Further research must be done in order to check if the addition of dry-stone walls or cover plants can improve soil stability.

4.3. The role of SSC on hydrological processes in sloping and poorly managed terracing vineyards

Other factors to be considered are the SSC. It is important to notice the main differences in plot characteristics because, in vineyards, the soil surface components (Follain et al., 2012; Quiquerez et al., 2014) and morphological changes (Ben-Salem et al., 2018) can determine the activation of soil erosion processes.

The terraces and embankments, like the sloping vineyards, have no vegetation cover, which means that no protection against rainfall events (Novara et al., 2011) and tillage practices (Quiquerez et al., 2014) can be activated. In vineyards that follows a vine training system in non-sloping areas, which are similar to the terraces, processes of connectivity between rows and inter-rows have also been confirmed, showing different flow paths and a high variability of hydrological processes (Ben-Salem et al., 2018). Another key element to be considered was the decrease of stone cover content, which in some human ecosystems can be considered a danger sign (Xia et al., 2018; Zhang et al., 2016). In vineyards, Rodrigo-Comino et al. (2017d) confirmed the elimination of the rock fragments in the soils as a mistake, because these fragments enhance the infiltration, delaying the runoff and retaining the soil. The presence of rills also generated an increase in the roughness, which represents another key factor that enhances the activation of soil erosion processes as other authors demonstrated in abandoned and agricultural areas (Nearing et al., 2017; Römkens et al., 2002). The S_{rc} confirmed that a higher roughness allows an increase in soil and water losses. This result could also confirm that higher micro-topographical changes establish connected channels that enhance the connectivity (Turnbull et al., 2018).

In both vineyard management systems, the soil loss is activated when runoff starts. However, in the poorly conserved terraced plot, this dynamic is clearer and reflected in the high negative correlation obtained between runoff and soil loss with the time to runoff generation. This hydrological dynamic is often repeated in the Mediterranean areas such as abandoned or natural lands (López-Vicente et al., 2015; Ruiz-Sinoga et al., 2010), or agricultural fields such as olive orchards (Taguas et al., 2015, 2017) or vineyards (Biddoccu et al., 2017; Ramos et al., 2007) due to the high intra-variability of the SSC.

4.4. From these results, new challenges and further questions to be resolved

The main concern of this work is that poorly managed terrace systems are not an ideal practice for sloping vineyards and other environments. Indeed, the results of the experiment conducted in the framework of this study show that erosion in a sloping (and more vegetated) vineyard was lower than in a poorly practised terraced vineyard. The quick conclusion from this study is that poorly managed terraces are activating and enhancing erosion.

As we mentioned above, terracing is a centuries-old practice designed as an effective tool in conserving farming plots in sloping environments and controlling erosion, if done properly. There are many terrace systems around the world with substantial differences among each other (typically determined by the site-specific topography and morphology). For instance, terrace systems that are supported by dry-stone walls could be more effective in controlling erosion, provided that walls are well constructed and maintained (Camera et al., 2018). Although possibly more expensive, this could be one of the potential solutions to the bare embankment issue that we identified. Terraces that are well-designed and properly maintained can indeed serve their purpose: retain the soil even under extreme rainfall events, and provide the means for cultivation in sloping conditions. In the future, more research must be conducted in order to test both correctly and poorly managed terraces. To date, it is very difficult to achieve this goal because of the absence of terraced vineyards, but it will be easier in the new mango and avocado plantations.

The use of rainfall simulations has allowed us to detect vital processes at the pedon scale. However, we consider that further research carried out under laboratory conditions such as plot size and drop impacts (Kiani-Harchegani et al., 2018; Sadeghi et al., 2017) should also be also tested under field conditions. We hypothesize that understanding the splash effect on the soil aggregates in these different soil management practices, we could design the best soil control measures (Marzen et al., 2015), considering the SDG (Caiado et al., 2018; Chopin et al., 2017). Moreover, it is possible that by performing more experiments in other hillslopes, thanks to the connectivity processes and the degradation of the poorly managed terraces, we could quantify even some higher magnitudes of soil loss which are easily mobilized to the rivers, as other authors confirmed in mountainous areas (Minea et al., 2016; Minea and Moroşanu, 2016). Therefore, one of the most important solutions could be the use of vegetation cover above the embankments in order to reinforce their stability, always considering the selection of plants that do not need significant amounts of water (Bienes et al., 2012; Lieskovský and Kenderessy, 2014).

5. Conclusions

The erosion process that has been monitored in this research, and also by other researchers elsewhere, is primarily due to substandard practices. This is the main message that this manuscript hopes to stress: sustainable management practices in sloping environments imply well designed/maintained terraces.

This research confirms that the transformation from the sloping vineyard into a terraced one cannot be considered in the Montes de Málaga if it is followed up by poor management. This could be the best solution to reduce soil erosion and enhance water conservation if vegetation cover above the embankments and wall stones were included. The main reason is that higher soil losses and runoff were detected in the poorly managed terraced vineyard than in the sloping one. Moreover, the time to runoff generation was lower in the terraces. The key factors detected in this study were the steep slopes with bare soils in the embankment, the reduction of stone cover content, and the increase of roughness. We want to state that this study can represent the first step in showing farmers and policymakers that the imminent transformation from sloping vineyards into terraced fields could lead to several land degradation processes if no control measure is applied, which is totally contrary to the Sustainable Development Goal 15.

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