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Article

Soil Erosion as an Environmental Concern in Vineyards: The Case Study of Celler del Roure, Eastern Spain, by Means of Rainfall Simulation Experiments

Jesús Rodrigo-Comino [1*], Saskia Keesstra [2,3] and Artemi Cerdà [4]

[1] Department of Geography, Instituto de Geomorfología y Suelos, University of Málaga, 29071 Málaga, Spain
[2] Soil, Water and Land Use Team, Wageningen Environmental Research, Wageningen UR, 6708PB Wageningen, The Netherlands; saskia.keesstra@wur.nl
[3] Civil, Surveying and Environmental Engineering, The University of Newcastle, Callaghan 2308, Australia
[4] Soil Erosion and Degradation Research Group, Department of Geography, University of Valencia, 46010 Valencia, Spain; artemio.cerda@uv.es
* Correspondence: rodrigo-comino@uma.es

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Abstract: Soil erosion in vineyards is considered as an environmental concern as it depletes soil fertility and causes damage in the fields and downstream. High soil and water losses decrease soil quality, and subsequently, this can reduce the quality of the grapes and wine. However, in specialized journals of viticulture and enology, soil erosion studies are not present. This paper surveys the soil erosion losses in the vineyards of Celler del Roure, Eastern Spain, as an example of Mediterranean vineyards. We applied rainfall simulation experiments (10 plots) using a small portable rainfall simulator and 55 mm h^{-1} in one hour to characterize soil erodibility, runoff discharge, and soil erosion rates under low-frequency–high-magnitude rainfall events at different positions along the vine inter-row areas. We found that 30% of the rainfall was transformed into superficial runoff, the sediment concentration was 23 g L^{-1}, and the soil erosion rates reached 4.1 Mg ha^{-1} h^{-1}; these erosion rates are among the highest found in the existing literature. We suggest that the vineyard management should be improved to reduce land degradation, and also should be shifted to sustainable agricultural production, which could improve grape and wine quality.

Keywords: soil loss; terroir; simulated rainfall; sustainability; Mediterranean viticulture

1. Introduction

Soil quality is one of the most important parameters that affects the production of resources in agricultural fields [1,2], being especially important in vineyards and their final products such as grapes, wine or raisins [3,4]. Vineyards are commonly identified as terroir because they are also conditioned by climate and human variables as well [5,6]. However, vineyards' soils are altered by intensive ploughing, the use of herbicides to keep the soil bare, and unsuitable land management strategies that favour soil contamination and nutrient impoverishment [7–9]. During the last two decades, the scientific community was aware of the driving factors that enhance soil degradation in vineyards, and soil erosion is a key factor in desertification processes in vineyards [10].

In vineyards, the most common driving factors for soil erosion are high slope angles [11], a lack of vegetation cover [12,13], the use of heavy machinery [14], the trampling effect [15], spatial variability of soil properties [16], the age of the plantation [17,18], and extreme rainfall events [19,20].

However, although soil erosion in vineyards has been confirmed to be a concern for grape and wine quality and cost [21], in the scientific literature, soil erosion studies in viticultural and enological journals are scarce or non-existent [10]. Soil erosion affects plant vigor [22] and causes nutrient losses such as loss of nitrogen [23], which is assimilated by plants in the forms of ammonic nitrogen and nitric nitrogen [24]. According to some studies, nitrogen has a great influence on the growth of shoots and roots, inducing the growth of clusters due to larger numbers of flowers that form in its presence and reaching high concentrations in the leaves [25,26]. Also, the soil pH is modified following high peaks of surface flow [27], trending towards more acidic levels. These dynamics can also affect the composition of the grapes and the taste of the wine. Changes in soil pH influence plants' growth, as the pH of the soil determines the pH of the soil water that plants use [28,29]. Soil erosion also affects grape quality and water availability to the plants, because it reduces soil depth and infiltration capacity [30,31]. In addition, highly eroded soil horizons will have a direct impact on the organic matter content and micro-organism activities [32,33]. Therefore, table grapes, raisins, or wine quality are affected by the consequences of soil erosion. Hence, special attention is needed to avoid soil erosion in vineyards. However, as for other crop cultivations, such as olive or citrus orchards, the perception of several farmers and companies is that soil erosion is not an important concern at short–medium terms [34,35]. A great amount of vine growers and wine producers are reticent to include soil erosion control measures such as vegetation cover, because they prefer to have tidy plantations and, therefore, they prefer to keep the soil bare [23,36]. The lack of interest of farmers and land owners in the damage soil erosion causes is the reason why this problem is still unsolved today worldwide [37].

Farmers, managers, and landowners need firm and easy-to-understand information to solve the environmental problems that soil erosion causes in vineyards. This is why the use of rainfall simulation experiments under low-frequency–high-magnitude rainfall events [38,39] can show the farmers that when soil is lost, there is also an economical loss due to the fact that soil is a nonrenewable resource that endangers the United Nations Sustainability Goals [40]. Therefore, the main aim of this research is to measure soil erosion along a vineyard to show the stakeholders the high water and soil losses that soil erosion causes.

2. Materials and Methods

2.1. Study Area

The Celler del Roure winery and vineyards are located in Eastern Spain and produce *Monastrell, Mandó,* and other local grape varieties in the Moixent municipality, in the region of Valencia, Spain (Figure 1).

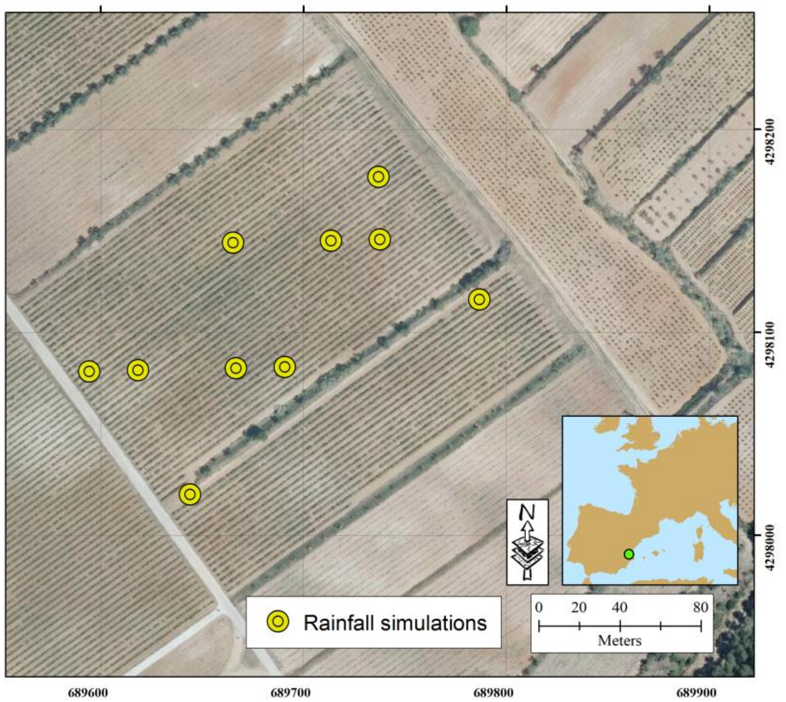

Figure 1. Study area (Celler del Roure, Valencia, Spain). Yellow symbols represent the location of each rainfall simulation experiment.

The mean annual rainfall is 450 mm and the average mean temperature is 15 °C. The climate is defined by three to five drought months in summer (June–September), with a total mean yearly rainfall of about 350 mm year^{-1} and mean temperatures of 13.8 °C. From September to November, extreme rainfall events with intensities higher than 200 mm day^{-1} can be amounted and summer thunderstorms yearly can reach 30 mm in half an hour. The vineyards are located on Cretaceous limestones (hills) and Eocene marls (valley bottom), as well as on colluvium at the base of hillslopes. Soil can be classified as Terric Anthrosol with colluvic material, with an organic matter content of 1.5 to 2% [41]. The soil texture is sandy loam. The vine plantation framework consists of 3.0 × 1.4 m. Prior to planting, soils were leveled and the plants were situated on an unsloping surface (terraces). In the soil profiles, we can distinguish a homogeneous horizon with some signals of compaction from a 40 to 60 cm depth due to the intensive traffic caused after the tillage that occurs four times per year with a tractor. The upper part of the hills is covered with a pine forest (*Pinus halepensis*) and shrubs (*Quercus coccifera* and *Juniperus oxycedrus*), which are used as rangelands.

2.2. Rainfall Simulations

We used rainfall simulation experiments on small plots to measure soil detachment, and the whole slope that was planted with vines was surveyed. The total number of plots was 10 and they were located at different topographical positions.

Ten rainfall simulation experiments were carried out at 55 mm h^{-1} rainfall intensity for one hour on circular paired plots (Figure 2A,B; 0.55 m in diameter, 0.25 m^2) because it corresponds to the typical intensity of a thunderstorm in the region. The plant cover, the rock fragment cover, and the roughness coefficient were measured prior to rainfall experiments. The plant and the rock fragment cover were determined by measuring the presence (1) or the absence (0) in 100 points regularly distributed at each 0.25 m^2 plot, and the total amount of 1-values was considered to be representative of each plot (Figure 2C) [42]. The roughness of the soil surface was determined in four 55 cm long adjacent transects located at the north, the south, the east, and the west of each plot using a 1 m long chain [43]. The chain was carefully placed on the irregular soil surface and the roughness coefficient (m m^{-1}) was calculated as the total length of the chain that was distributed over a horizontal distance of 55 cm. Soil samples (0–20 mm) were collected in points a few centimeters downslope from each study plot, and the soil water content (%) was measured on a weight basis after drying the samples (105 °C, 24 h). The soil organic matter was determined by the Walkley–Black method (Walkley and Black, 1934). The bulk density was measured by the ring method for the 0–60 mm soil layer. For more information, we refer to [44,45].

All the experiments were carried out during the summer drought, when the soil moisture was constant and low. At each plot, the runoff flow was collected at 1 min intervals using plastic bottles, and the water volume was measured. The runoff coefficient was calculated as the percentage of rainfall water running out of the circular plot. Runoff samples were desiccated (105 °C, 24 h) and the sediment yield was calculated on a weight basis in order to calculate the soil loss per area and time (Mg ha^{-1} h^{-1}). The sediment concentration in the runoff was measured every five min and was determined by desiccation. During rainfall simulation experiments, the time to ponding (the time required for 50% of the surface to be ponded; Tp, s), the time to runoff initiation (Tr, s), and the time required by the runoff to reach the outlet (Tro, s) were recorded. The Tp was determined when the ponds were found, and the Tr was determined when those ponds were communicated by the runoff.

Environmental plot characteristics were depicted in box plots using SigmaPlot 13.0 (Systact Software Inc., London, UK). The descriptive statistics of soil erosion results such as averages, standard deviation, coefficient of variation, maximum and minimum values, skewness, and kurtosis were also calculated using SigmaPlot 13.0 (Systact Software Inc.). All the locations of the experiments were registered with a GPS in the UTM coordinate system with ETRS 1989 datum. Maps with proportionated symbols for soil erosion, runoff coefficient, and sediment concentration were performed with ArcMap 10.5 (ESRI, Redlands, CA, USA).

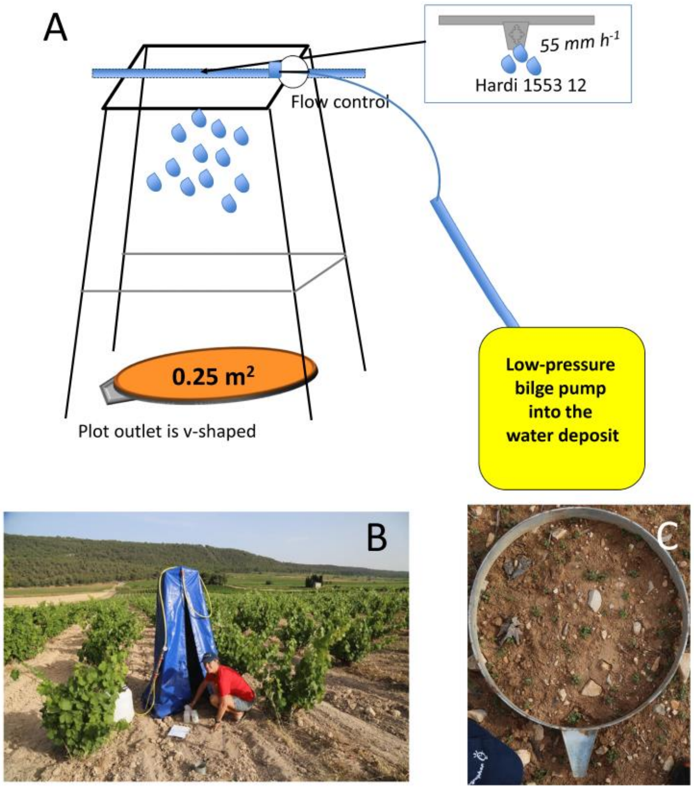

Figure 2. Rainfall simulator (**A**, **B**) and ring plot (**C**).

3. Results and Discussion

3.1. Plot Characteristics

In Figure 3, the environmental plot characteristics were depicted in box plots to show the averages, median values, maximum and minimum values, and 5th and 95th percentiles. Mean slopes are 10.1° and showed maximum values of 10° and minimum values of 1°. The vineyards are cultivated in low-inclined terraces, which should enhance the water retention capacity and delay or disrupt the overland flow; however, against heavy storms, the rapid peaks can be bigger than in sloping vineyards [30,46]. The rock fragment cover has an average value of 17%, and 25% and 12% as the maximum and minimum values, respectively. The percentage of rock fragments in the soil has to be considered when we observe soil erosion results, because other researchers have confirmed [42,47,48] that they can reduce soil loss, splash erosion, and runoff, and can enhance infiltration. In some viticulture areas such as the Mosel Valley (Germany) or the Montes de Málaga (Spain), rock fragments are also known to preserve soil temperatures, which, as farmers acknowledge, directly influence grape maturity, intensifying grapes' and wine's taste [49,50]. Low vegetation cover was registered in the studied vineyards on an average of only 1%. Therefore, we can consider the soil bare. The observed environmental plot characteristics show that the studied vineyards are cultivated on bare soils, which enhance soil erosion processes as other authors have confirmed in the past for other areas [12,51]. The maximum values of vegetation cover only reach 9%. The roughness is 1.11 mm mm^{-1} and showed maximum values of up to 1.15 mm mm^{-1}. These values are typical for vineyards that are tilled by machinery, where the microtopographical changes play an important role in the connectivity processes at the pedon scale [52]. Mean bulk density values are 1.24 g cm^{-3}, with maximum and minimum values of 1.26 and 1.19 g cm^{-3}, respectively. Finally, the experiments confirm very low stable mean values of antecedent soil moisture of less than 7% because the experiments were conducted during the dry period in summer.

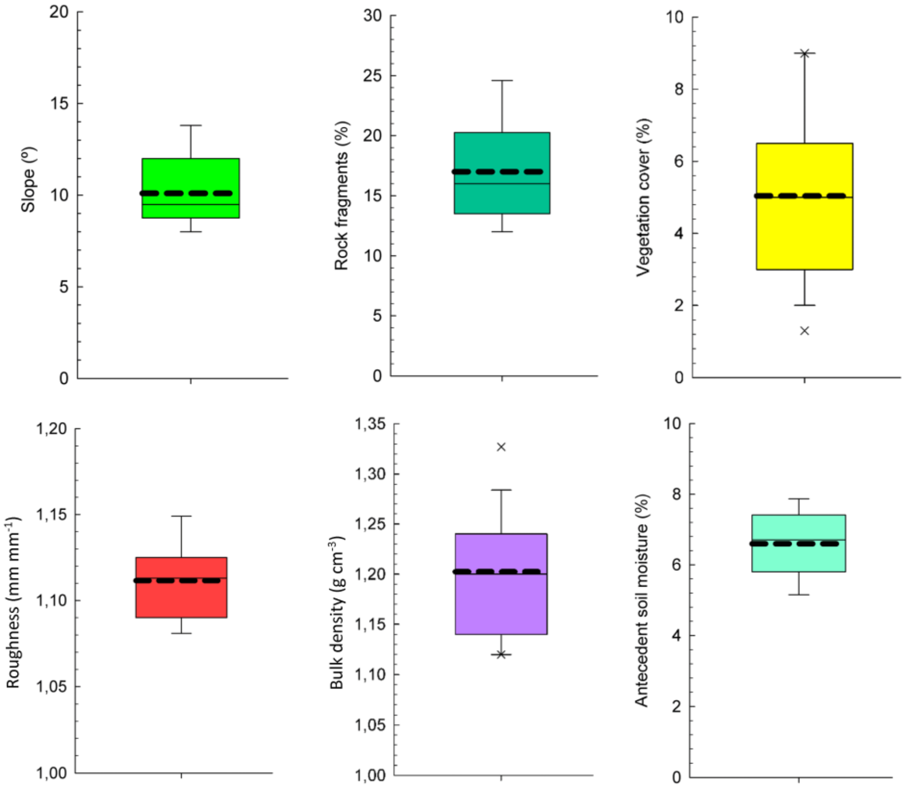

Figure 3. Environmental plot characteristics depicted in box plots.

3.2. Hydrological Soil Response

After starting each rainfall simulation experiment, the time to ponding (Tp), the time to runoff generation (Tr), and the time to runoff in outlet (Tro) were registered to assess the hydrological soil response (Table 1). These hydrological parameters show the soil's ability to conserve water for the plants, which is highly recommended in areas characterized by poor and shallow soils. As above-mentioned, a sufficient soil water content is one of the most important parameters to ensure a good productivity and quality of grapes and wines [53,54].

The mean Tp in the plots was found to be 251.5 ± 28 s, with a maximum value of 298 s and a minimum value of only 215 s. For Tr, values of 434.2 ± 27.1 s were registered, reaching 467 and 401 s as maximum and minimum values, respectively. Finally, Tro was 774.3 ± 32.1 s. The time needed to pond the surface, to allow for runoff generation, and to reach the outlet of the plot can be considered as fast in comparison to other land uses such as persimmons [55], apricots [45], almonds [56], or olive orchards [57].

Table 1. Time to ponding (Tp), time to runoff generation (Tr) and time to runoff in outlet (Tro).

Results	**Tp (s)**	**Tr (s)**	**Tro (s)**
Average	251.5	434.2	774.3
Standard deviation	28.0	27.1	32.1
Maximum	298	467	824
Minimum	215	401	726

3.3. Soil Erosion Results

In Table 2, soil erosion results are presented showing the main descriptive statistics and units. Moreover, in Figures 4–6, the spatial distribution was mapped.

Table 2. Soil erosion results. R: Runoff; RC: Runoff coefficient; SC: Sediment concentration; Sy: Sediment yield; Se1: Soil erosion in g m^{-2} h^{-1}; Se2: Soil erosion in Mg ha^{-1} h^{-1}.

Results	**R**	**RC**	**SC**	**Sy**	**Se1**	**Se2**
Units	L	%	g L^{-1}	g	g m^{-2} h^{-1}	Mg ha^{-1} h^{-1}
Average	4.45	32.4	22.9	102.4	409.4	4.1
Standard deviation	0.4	3.0	3.0	19.9	79.8	0.8
Maximum	5.2	38.1	28.1	138.2	552.7	5.5
Minimum	3.9	28.5	19.5	78.6	314.5	3.1

The total mean runoff (R) was 4.45 ± 0.4 L, reaching maximum values of 5.2 L and minimum values of 3.9 L. These results showed a mean runoff coefficient of 32.4 ± 3%, with maximum values of 38.1% and minimum values of 28.5%. The sediment concentration (SC) registered values of 22.9 ± 3 g L^{-1}, with maximum values of 28.1 and minimum values of 19.5 g L^{-1}. Soil erosion (Se2) registered in the studied area was 4.1 ± 0.8 Mg ha^{-1} h^{-1}. The maximum and minimum values were 5.5 Mg ha^{-1} h^{-1} and 3.1 Mg ha^{-1} h^{-1}, respectively.

To compare these values in Table 3, the values of other soil erosion studies using the same rainfall simulator are summarized. We have to remark that soil erosion results were not related to the type of species. The main differences were the age of plantation and the land management. We observed that the studied vineyards registered the second highest soil erosion rate after the young plantations of vineyards (12.1 Mg ha^{-1} h^{-1}, the highest), and very similar values were registered with the citrus orchards (3.8 Mg ha^{-1} h^{-1}). Therefore, we can confirm that bare soils and the age of plantations are the most important driving factors that enhance soil erosion, as was mentioned above. Moreover, we can affirm that soil erosion in vineyards are high and intolerable. Soil erosion rates higher than 1 Mg ha^{-1} $year^{-1}$ were not sustainable [58], and in the vineyards, soil erosion rates were >4.0 Mg ha^{-1} h^{-1}. Therefore, all the above-mentioned problems related to soil erosion, such as soil nutrient losses, pH changes, decrease in plant vigor, and water scarcity could be reduced if we performed specific studies on soil conservation.

Related to the runoff coefficient, although high in comparison with other study areas and land uses such as olive orchards, this study showed the lowest runoff coefficient.

Table 3. Comparison of runoff coefficients (RC) and soil erosion rates (Se) with other studied land uses in the Valencia region using the same rainfall simulator.

Results	**RC**	**Se**
Land use	%	Mg ha^{-1} h^{-1}
Persimmons (herbicides) [45]	40.4	0.91
Citrus [60]	60.1	3.8
Vineyards with straw mulch [44]	39.3	0.63
Young vineyards [17]	72	12.6
This research	32.4	4.1

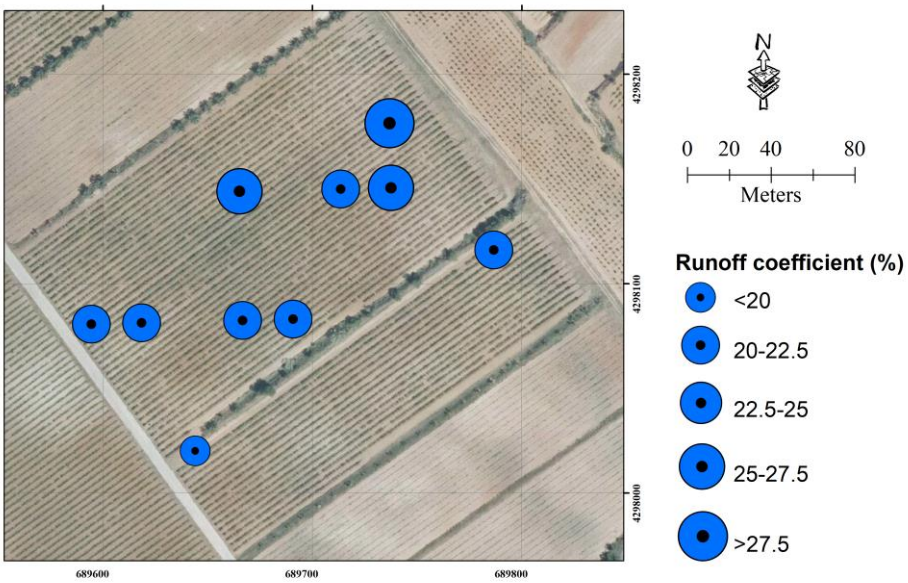

Figure 4. Spatial distribution of runoff coefficient.

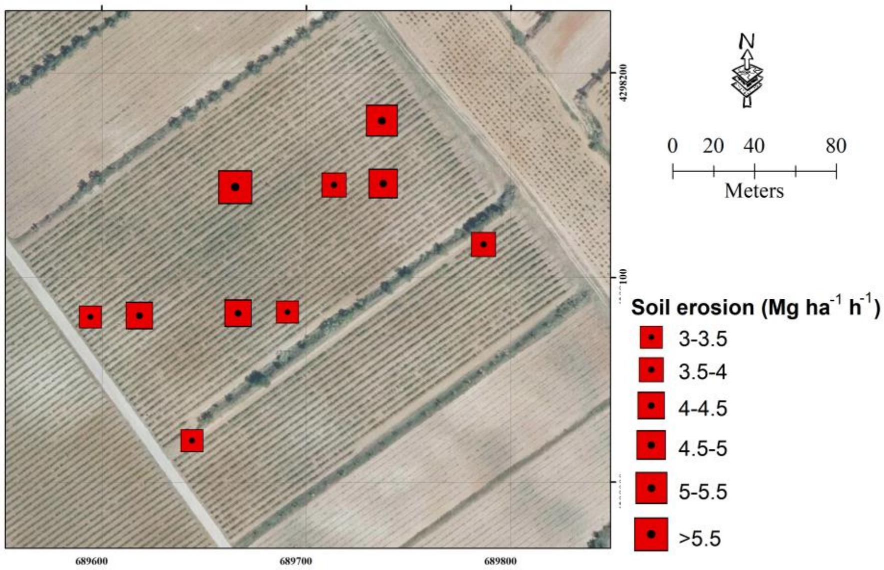

Figure 5. Spatial distribution of sediment concentration.

Figure 6. Spatial distribution of soil erosion rates.

These high rates are also observed by other authors in French [61,62], Spanish [7,63], German [64,65], Hungarian [66], and Italian [8,12] vineyards, where subsequent problems related to grapes and wine quality and productivity occur. The use of tractors enhances the micro-topographical changes [67,68] and the flow path and subsequent connectivity processes are affected by this [69] and soil erosion features such as rills or sinks [70,71]. Therefore, the use of soil erosion control measures that protect uncovered soils and conserve grape and wine quality can be considered a priority [51,72]. However, sometimes water competition in semiarid environments such as the Mediterranean areas [73] or the farmers perception [36] can make its application difficult. Thus, other nature-based solutions [74] must be developed such as the use of rock fragment covers [42] or the use of agri-spillways to canalize water and sediments [50]. Finally, we want to claim the importance of soil erosion within the viticulture knowledge, because soils are one of the most important part of the grape and wine production [5,31] and it should not be obviated by enologists, vine and wine growers.

4. Conclusions

Soil erosion rates in vineyards' bare soils are not sustainable. In our study area, soil erosion rates of up to 4.1 Mg ha^{-1} h^{-1} were quantified using rainfall simulation experiments. Moreover, high water losses were also detected, reaching values of higher than 30%. Using proportional symbol maps, we observed high soil erosion rates at different slope positions and under distinct environmental plot characteristics. We conclude that bare soils are one of the most important driving factors that enhance soil erosion rates. After observing the high soil and water losses in the study, it must be stressed that special attention must be paid to the development of soil erosion control measures by vine and wine growers.

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Author Contributions: Artemi Cerdà and Saskia Keesstra conceived, designed, and performed the experiments; Jesús Rodrigo-Comino analyzed the data and contributed reagents/materials/analysis tools. All the authors wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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