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Article

Soil and Water Conservation in Rainfed Vineyards with Different Plant Covers: Common Sainfoin and Spontaneous Vegetation under Different Physiographic Conditions

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Abstract: Soil erosion seriously affects vineyards. In this study, the influence of two plant covers on soil moisture and the effect of different physiographic conditions on runoff and sediment yields were evaluated in a rainfed vineyard formed by four fields (NE Spain) during 15 months. One field had spontaneous vegetation as plant cover and three fields had a cover crop of common sainfoin. The vineyards' rows were dry and stable, whereas the inter-row areas were wet although very variable, and the corridors were wet and very stable. Soil moisture in the inter-row areas with Common sainfoin was much higher than in the rows (62% - 70%) whereas this difference was lower with spontaneous vegetation (40%). Two runoff and sediment traps (STs) were installed in two ephemeral gullies, and 26 time-integrated surveys (TIS) done. The mean and maximum runoff yields were 9.8 and 30.7 l TIS^{-1} in ST2 and 13.5 and 30.2 l TIS^{-1} in ST3. The mean turbidity was 333 and 19 g l^{-1}, and the maximum sediment yields were 41,260 and 2,778 g TIS^{-1} in ST2 and ST3. Changes in the canopy covers (grapevines and plant covers) and rainfall parameters explained the runoff and sediment dynamics.

Keywords: cover crop; spontaneous vegetation; vineyard; topsoil water content; soil erosion; runoff coefficient; sediment trap; temporal stability; Mediterranean region.

HIGHLIGHTS:

- Soil moisture conditions in vineyards' rows were dry and stable.
- Soil moisture conditions in vineyards' inter-rows were wet although variable.
- Common sainfoin preserved soil moisture much better than spontaneous vegetation.
- Runoff yield in the two sediment traps were mainly explained by rainfall depth.
- Sediment yield dynamic was explained by rainfall intensity and canopy cover changes.

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1. Introduction

Vineyards are part of the most exposed agricultural systems deteriorated by soil erosion processes [1], which generate higher runoff rates and sediment losses in Europe, especially in the landscapes of the Mediterranean Basin [2–3]. Recently, Rodrigo-Comino [4] concluded in a review study that soil erosion rates in vineyards are higher than those in other land uses and represents a serious threat to landscape sustainability. Analysis of data collected from runoff plots across Europe and the Mediterranean illustrated that runoff coefficients in vineyards (ca. 8%) were similar as those observed in the cereal and fallow fields (8.0% and 7.3%) although soil loss was much higher in the vineyards (10.8 Mg ha–1 yr–1) than in the cropland and fallow (6.5 and 5.8 Mg ha–1 yr–1) [5]. However, observed average soil loss rates (SL) clearly differ between runoff plots from the Mediterranean zone (SL of 8.62 Mg ha–1 yr–1) and the rest of Europe (23.64 Mg ha–1 yr–1) [1].

Erosion rates in Mediterranean vineyards are extensively variable but achieve up to 16 Mg ha–1 yr–1 in Sicily, southern Italy [6], and between 2.7 – 4.7 Mg ha–1 yr–1 in NW Italy [7]. In Barcelona province, NE Spain, Ramos and Martínez-Casasnovas [8] estimated an average rate of 11.5 Mg ha–1 yr–1, whereas Bienes et al. [9] measured average rates between 2 and 28 Mg ha–1 yr–1 in Central Spain (Madrid and Cuenca) under bare soil conditions and between 0.03 and 2.5 Mg ha–1 yr–1 with cover crops. In southern France, Gómez et al. [10] observed in three experimental sites over three years average SL between 4 and 57 Mg ha–1 yr–1 under conventional tillage and between 1 and 43 Mg ha–1 yr–1 with cover crops. In Israel, Pipan and Kokalj [11] observed increased soil erosion owing to the conversion of terraced vineyards into recent plantations in slopes without terraces. Such rates are superior to soil erosion under natural, non-cropped conditions, even for steep slopes (1.6 Mg ha–1 yr–1 in 63% slopes) [12], and over the tolerable or admissible soil losses that insure land sustainability (ca. 1 Mg ha–1 yr–1) [13].

The principal reasons for the elevated erosion rates in Mediterranean vineyards hold: (i) some typical topographic features of the vineyard system, such as those, traditionally, located on hillslopes and disponed of rows plantations along the slope, that make runoff and erosion more intensive [14]; (ii) climatic conditions, that is the occurrence of intense rainfall events in spring and autumn especially which provoke high runoff peaks [15]; and (iii) high soil erodibility, as vineyards are mostly planted on steep-slopes with shallow soils [3], hence structural stability and aggregation of the soil decreases [16]. Such degradation of soil quality may lead to severe problem for wine production as soil figures as a key component of the concept of “terroir” [17]. Therefore, protection of soils is an important issue in viticulture and necessary to promote sustainable agricultural systems.

Vineyards are amongst the most important fruit crops in the world, covering 7.5 million ha and producing 75.8 million of tons of grapes and 267 million hl of wine [18]. The European Union reaches 39% of the world grape production, with Spain being its third largest wine producer, including 975,000 ha of vineyards [19], which is the largest vineyard extension in the European Union and the world. In spite of its economical pertinence, vineyard sustainability may be threatened due to land degradation and/or mismanagement, linked with runoff and sediment losses, which obstruct the development of plants and agricultural yield potential [6,20].

Most winegrowers regulate weed and ground vegetation through tilling or herbicide applications owing to the observed competition between unplanted vegetation and grapevines for water and nutrients [21]. Nevertheless, not all studies indicate the expected regression in grape yields [22,23], but such or even higher yields in vineyards with vegetation cover in the inter-rows [24,25]. In addition, some techniques usually adopted in vineyards' installation and management (e.g. intense tractor traffic throughout fixed paths) are deteriorating soil structure and producing its compaction [26]. In the literature, the benefits of plant covers in vineyards, fruit-tree orchards and reclaimed soils has been widely evaluated in a variety of soil and climate conditions through the world [10,27,28,29].

In vineyards under Mediterranean climate, several studies have demonstrated the positive effects of cover crops on soil, nutrient and water conservation such as in Italy [7,26,30], Spain [9,22,31,32,33] and France [10,34,35]. Cover crops reduce the total volume of runoff yield offering an adequate protection against erosion in comparison with bare soil management [22,31]. Moreover, soil structure and functional soil properties improved through better aggregate stability, pore

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connectivity and infiltration rates. Both labile and stable fractions improve their soil organic carbon content with the use of groundcovers, particularly the labile fraction [33]. Another attractive aspect of cover vegetation, with respect to tillage, is that cover plants are able to reduce the formation of plough pan, by virtue of a decrease in mechanized work associated with tillage and improvement of the soil structure [30].

In the same agriculture context, the antecedent moisture conditions or topsoil water content (TSWC) is a major factor to predict runoff generation over low and medium intensity storms [36,37] aside from accounting for the soil detachment rates at the first phases of an erosive event [38]. The study of Ramos and Martínez-Casasnovas [39] confirms the relationship between the volumetric soil moisture content of the soil profile with the vegetative development of the vineyard and its yield. On the other hand, annual runoff and soil losses in woody crops are strongly conditioned by few precipitation events of high rainfall intensity and/or depth [40,41]. Under low frequency–high magnitude rainfall events, straw residues and cover crops can reduce soil erosion and runoff rates in fruit-tree orchards [42].

A better comprehension of the terrain response to rainfall events, taking into consideration the variability of the annual soil surface and plant conditions, could be helpful to promote soil management decisions in vineyards, in order to reduce runoff and erosion. We hypothesises that the effectiveness of a cover crop to reduce soil loss and runoff yield in a vineyard is influenced by the physiographic conditions of the upslope contributing area. Hence, the main objective of this study is to evaluate the influence of the topographic and ground cover conditions on the runoff and sediment yields in a rainfed vineyard with a plantation of common sainfoin (Onobrychis viciifolia). We achieve this goal by means of: (i) measuring the TSWC in 48 control points in the three vineyards' compartments (rows, inter-row areas and corridors) during a 15-month test period; ii) collecting runoff and sediment samples from two runoff collectors (sediment traps; ST) installed in two ephemeral gullies with contrasted physiographic conditions between their upslope contributing areas; and iii) analyzing the spatial and temporal dynamics of TSWC, runoff and sediment yield over the test period taking into account the changes in the rainfall parameters (depth, intensity and erosivity) and ground cover (surface and canopy) conditions. Results of this study will be of interest for planning sustainable management practices in vineyards and other woody crops.

2. Materials and methods

2.1. Study area

The study area is a rainfed vineyard located in the Ebro River Basin (NE Spain; 42° 02′ 04″ N; 0° 04′ 13″ E) (Figure 1a). This vineyard includes four fields that are located in the lower part of "Los Oncenos" sub-catchment, within the Vero River catchment, near Barbastro town (Huesca province) (Figure 1b). The four fields are located on a rolling landscape with a mean slope steepness of 9.8% and elevation ranges from 447 to 468 m a.s.l. The four commercial vineyards (Fábregas Cellar, a winery with Certificate of Origin: Somontano) are cultivated with the Spanish variety Grenache (*Vitis vinifera* L. cv. Grenache); three fields with red grapes (planted in 2008; named VY1, VY2 and VY3) and one field with white grapes (planted in 2007; VY4), without any irrigation. The vineyard plantation is composed of 15,039 grapevines arranged in 147 straight lines (espalier system). Soil in the grapevine lines (row hereafter) remain between 8 and 23 cm, 13 cm on average, raised related to the soil in the inter-row area, due to the tillage practices carried out by the farmer.

The inter-row areas of the vineyards are managed with a mixture of plant species as cover crop (CC): i) spontaneous vegetation in VY4, and ii) plantation of common sainfoin (*Onobrychis viciifolia*) with spontaneous vegetation in VY1, VY2 and VY3. Spontaneous vegetation also protect the soil in the corridors between the four vineyards. The maintenance of the inter-rows and corridors includes one mowing pass in spring, usually in May, to avoid water and nutrient competition between the CC and the grapevines. However, most pruning remains stay on the same place after this practice, thus the soil cover factor (percentage of the soil surface covered with vegetation) keeps high all over the year. The farmer only used herbicides to control weeds in the rows. During this study, grape harvest

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were done in September (more details about land uses and tillage practices in "Los Oncenos" sub-catchment in [32]).

Soils are Haplic Regosols (calcaric; RGca) in the upper part of VY4 and Luvic Calcisols (CLl) in the lower part of VY4 and in VY1, VY2 and VY3 [43]. In a recent study, López-Vicente and Álvarez [32] collected 144 soil samples in 48 sampling points in the four vineyards and estimated the bulk density (BD), rock content (RF; fragments with a minimum diameter higher than 2 mm) and texture of the soil. The average (± standard deviation) BD and RF in the four vineyards, in the rows, inter-row areas and corridors were 1.482 (± 0.205), 1.343, 1.582 and 1.582 gr cm^{-3} and 15.8% (± 7.7%), 16.7%, 14.7% and 18.0%, respectively. The effective volume of the soil to store water (associated to the fine fraction of the soil) was 90.7% (± 4.7%), 90.9%, 90.8% and 88.6% in the four vineyards, in the rows, inter-row areas and corridors, respectively. Soil texture was sandy loam, loam, silt loam and loamy sand in 38%, 29%, 28% and 4% of the soil samples, with some differences between the rows (40% sandy loam, 32% silt loam and 28% loam), the inter-row areas (37% sandy loam, 31% loam, 24% silt loam and 8% loamy sand) and the corridors (44% silt loam, 33% sandy loam and 22% loam). Considering the four vineyards, sandy loam and loamy sand texture was predominant (83%) in VY1, loam and silt loam (89%) in VY2, silt loam and loam (70%) in VY3, and sandy loam and loam (74%) in VY4.

The climate is continental Mediterranean, with an average annual precipitation, R, of 446 (± 14%) mm yr^{-1} during the period Sep'2009 – Aug'2017, mainly concentrated in two rainy seasons, in spring and autumn (source data: '*Oficina del Regante*' of the Regional Government of Aragon, and CHEbro - Ebro River Basin water authorities). The summer is dry with occasional thunderstorms and snowfall events are scarce in winter. The mean annual temperature was 14.1°C and potential evapotranspiration, ET_0, was 1225 mm $year^{-1}$. The mean annual rainfall intensity was 3.1 (± 22%) mm h^{-1}. The average number of annual rainfall events during this period was 98 with 6 and 11 events per year of medium ($8 < R < 12$ mm) and high ($R > 12$ mm) rainfall erosivity. This landscape is characterized by rainfall events of low rainfall intensity (I_{30}) between November and March, and short and high intensity events between June and October [44]. The highest peaks of I_{30} are usually recorded in September and October. Consequently, different hydrological response of the soils and runoff depth is expected over the year. Saturation-excess runoff areas (occurred when the soil becomes saturated) were not observed, and thus infiltration excess runoff (generated when the rainfall intensity is higher than the infiltration rate) is the predominant overland flow generation process.

Various ephemeral gullies affect the soils in three vineyards, two cereal fields and the olive orchard in "Los Oncenos" sub-catchment [45]. Sediment delivery processes are intense, bringing to the formation of four depositional areas (alluvial fans) at the foot of the vineyards VY1 and VY4, one cereal field and of the commercial olive grove (Figure 1b). These processes has launched the development of continuous flow path lines, breaking the topographic sills of the rows in some sections (Figure 1c). The largest fan (1,480 m^2) is close to the outlet within the northern vineyard.

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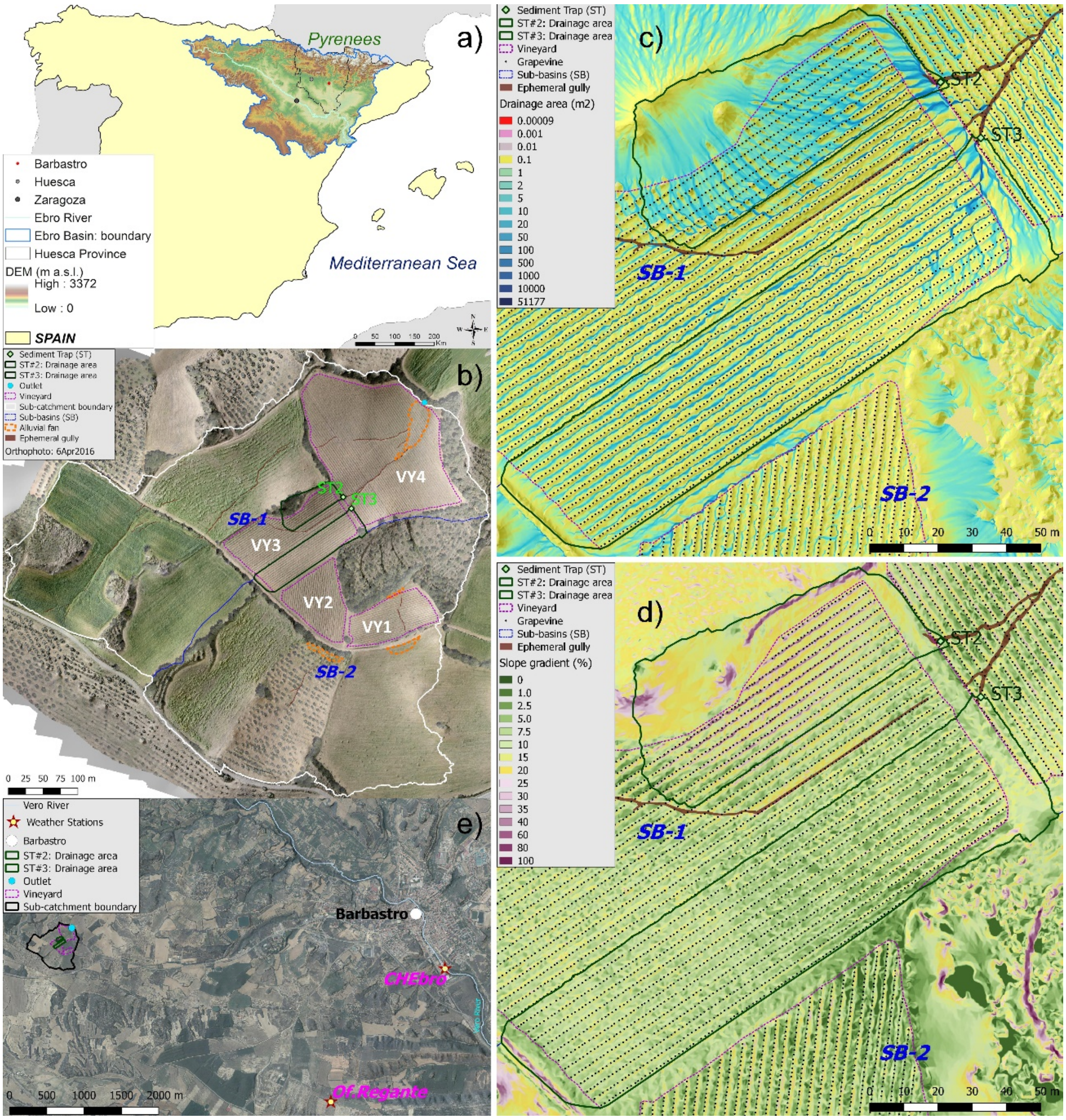

Figure 1. Location of the study area in Huesca Province, NE Spain (a); orthophoto and boundary of "Los Oncenos" sub-catchment and location of the two sediment traps (b); drainage area (c) and slope gradient (d) of the two sediment traps; location of the two weather stations used in this study (e).

2.2. Rainfall data and topsoil water content

Rainfall data was obtained from two weather stations (WSs) located 4.2 and 5.2 km eastern from the study site (Figure 1e). The "CHEbro" WS is managed by the Ebro River Basin water authorities and records precipitation values every 15 minutes. The "Of.Regante" WS is managed by the Irrigation Agency of the Regional Government of Aragon and precipitation is recorded everything 30 minutes. In order to use representative values a synthetic weather station (Syn-WS) was created by using the data of both WSs. We used the guide of the RUSLE model that establishes a period of six hours with a rainfall volume lower than 1.27 mm to distinguish between two different rainfall events. Rainfall depth (R; mm), maximum intensity in 30 minutes (I_{30}; mm h^{-1}) and rainfall erosivity (EI_{30}; MJ mm ha^{-1} h^{-1} month^{-1}) were calculated at event, monthly and average scales.

The topsoil water content (TSWC – θ_0; % vol.) was measured in the field in 48 points of undisturbed soils and three measurements of θ_0 were effectuated at each point (144 measurements per survey; Figure 2a). One survey was done every 30 days during the 15-month test period (February 2017–April 2018). Each survey was carried out in the same days of the month, between the days 15 and 19. The frequency-domain probe *Delta-T SM150T* (accuracy ± 3%) was used (Figure 2b). This

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gadget has two rods, which are initiated in the soil up to 51 mm depth. Measurements are stable regarding salinity.

A portable device was selected to assess soil moisture rather than installing permanent devices (sensors, data loggers and batteries) due to the elevated number of measurement points and therefore the high economic cost of the second option. The distance between each measurement point within each vineyard was 40m including the three compartments: rows, inter-row areas and corridors. Each survey was carried out in less than 6 hours in order to decrease any temporal change of the soil water content conditions during the survey. There was not recorded any rainfall event during each survey and also during the four previous days. Thus, measured values are representative of the monthly edaphoclimatic conditions.

2.3. Runoff and sediment traps and surface cover changes

Two sediment traps (ST2 and ST3) were established in the first inter-row of the VY4 downwards the corridor that separates the VY3 and VY4 (Figure 1c). Each ST was located in the course of an ephemeral gully and before reaching the sediment fan located at the foot of the VY4. The two STs played the role of collectors of runoff and sediment generated during the different rainfall-runoff events. Each trap had two boxes: one box was buried and permanently remained in the field; the other one was located inside the first box. A metal grid with square holes of 4 mm length was located on the top of the smaller box to avoid the entrance of undesirable animals, insects and rocks. Finally, a metal cap with big square holes (7 cm length), which allowed the entrance of runoff, was used to close the external section of the trap with screws and nuts (Figure 2c). Each trap was designed to hold a maximum volume of 32.2 litres (460 mm length x 200 mm width x 350 mm depth). The STs were installed below the soil surface to avoid any disturbance with the tillage practices and tractor traffic. Both STs were installed in December 2016 and tested in January 2017. From February 1st, 2017 on both STs were ready to collect samples. During the 15-month test period and after each heavy rainfall event of after several low or medium intensity rainfall events the runoff and sediment samples were collected in a time-integrated field survey (TIS). After each TIS the internal boxes were replaced by clean boxes. Then, the total runoff with sediments of each trap was weighted and sediment was separated by decantation. The wet sediment was dried in an oven at 60 °C and the dry sediment was weighted. Finally, the total runoff (Q; l TIS^{-1}) and sediment yield (SY; g TIS^{-1}) were calculated for each ST and TIS.

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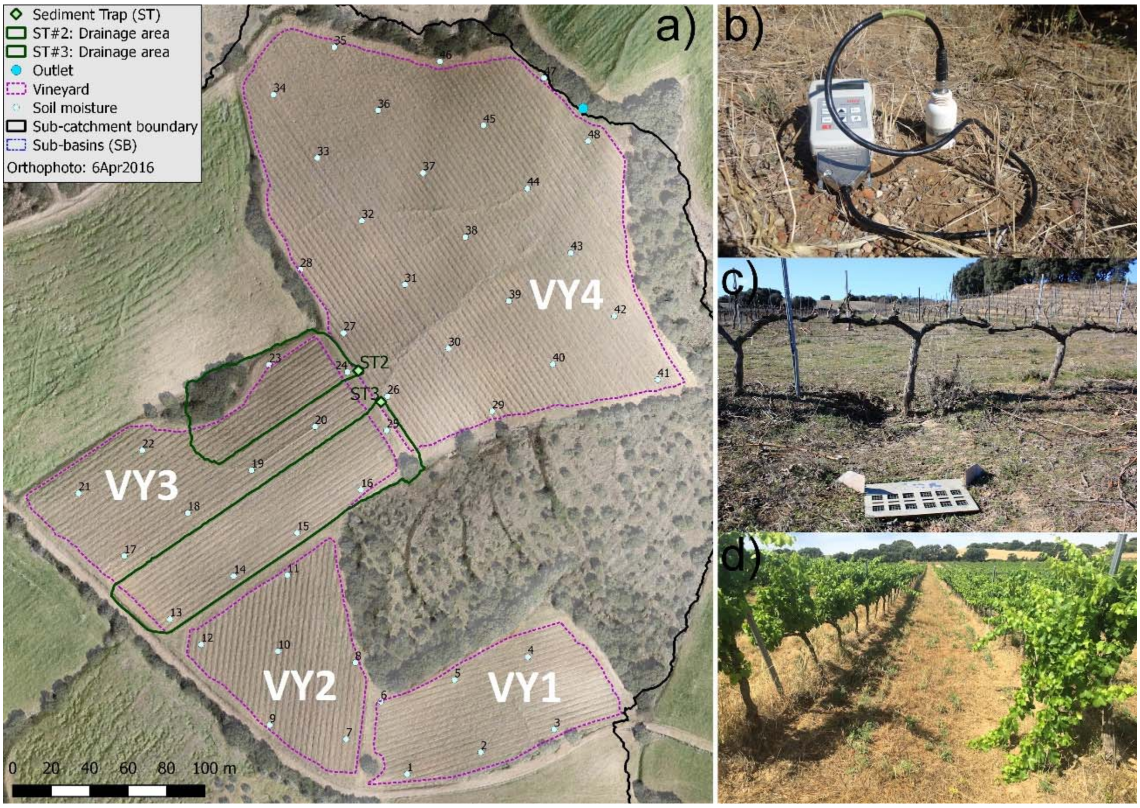

Figure 2. Location of the topsoil water content (TSWC) measurement points in the four vineyards of "Los Oncenos" sub-catchment (a). Photos of the device to measure TSWC (b), of the sediment trap #2 with the upslope contributing area (c; taken on February 12th, 2018), and of the cover crop in the contributing area of the sediment trap #3 after the mowing pass in late May 2017 (d; taken on June 27th, 2017).

The contributing areas (CAs) of the ST2 and ST3 were 3,286 and 6,214 m^2, respectively (Figure 1c) (Table 1) (more details about the overland flow patterns in "Los Oncenos" sub-catchment in [45]). The mean slope of the two CAs were 17.0% and 9.2% for the ST2 and ST3, respectively (Figure 1d). Concerning the vegetation cover, the soil surface of the CA of the ST2 had less vegetation with an average percentage of bare soil of 18.4%, whereas the CA of the ST3 only had 10.6% of the soil surface without vegetation (Figure 2c,d). Significant changes in the surface cover were observed over the twelve months of the year due to the phenology of the grapevines, the cover crop, the spontaneous vegetation and the tillage practices (e.g. grape harvest and mowing pass) (Figure 3). In a recent study, López-Vicente and Álvarez [45] calculated the soil roughness (SR), the convergence index (CI) and the index of runoff and sediment connectivity (IC) in "Los Oncenos" sub-catchment (Table 1). Clear differences appeared in these parameters between the CAs of the two STs. The mean SR and the mean and maximum hydrological connectivity were higher in CA-ST2 than in CA-ST3 indicating active processes of sediment delivery. Moreover, the CI in CA-ST2 was closer to a concave topography whereas CA-ST3 indicated a general convex surface. All the topographic information used in this study was derived from a digital elevation model (DEM) at 0.2 m of cell size generated by using aerial orthophotos taken with a professional drone and the structure-from-motion (SfM) technique [45].

Table 1. Physiographic characteristics of the upslope contributing area of the two sediment traps.

Sediment trap number	A m^2	S (mean ± sd) %	Average bare soil %	SR* mm	CI* %	IC* mean (max)
ST2	3,286	17.0% ± 9.5%	18.4%	21.5	-0.143%	-6.394 (-4.695)
ST3	6,214	9.2% ± 5.0%	10.6%	11.6	-0.668%	-6.821 (-4.818)

A: total area; S: slope gradient; SR: soil roughness; CI: convergence index; IC: index of runoff and sediment connectivity; * values from [45].

Figure 3. Temporal changes in the canopy cover of the grapevines and the cover crop of common sainfoin over the twelve months of the year.

2.4. Statistical analysis and metrics

The spatial pattern of TSWC was calculated for each survey by means of the relative difference, δ_{im}, between the average value of TSWC at each measurement point '*i*', θ_{0im}, and the mean value of TSWC in the four vineyards study area at each month '*m*', $\overline{\theta_{0m}}$:

$$\delta_{im} = \frac{\theta_{0im} - \overline{\theta_{0m}}}{\overline{\theta_{0m}}} \quad (1)$$

$$MRD_{iT} = \frac{1}{N_T} \sum_{m=1}^{m=N_T} \delta_{im} \quad (2)$$

where MRD_{iT} is the mean relative difference for the location '*i*' and N_T is the number of observation times (15 months). The temporal stability analysis of these differences was done calculating the standard deviation of the set $\delta_{i,m=1}$, $\delta_{i,m=2}$, …, $\delta_{i,m=T}$ of relative differences at the location '*i*' over the test period:

$$SDRD_{iT} = \sqrt{\frac{1}{N_T - 1} \sum_{m=1}^{m=N_T} \left(\delta_{im} - MRD_{iT}\right)^2} \quad (3)$$

The value of $SDRD_{iT}$ serves as one of the measures of the temporal stability [28,32,46,47] by comparing its magnitude to the spatial variability of MRD_{iT}. The sensitivity analysis was done for the vineyards' compartments (rows, inter-row areas and corridors) of each field and for the whole study area.

3. Results

3.1. Synthetic weather station and soil moisture

Small differences appeared between the rainfall data of the two WS due to the distance between them (Table 2). However, in some cases the difference was absent like the case of the minimum rainfall depth which was about 0.2 mm in the two weather stations. During the test period, the

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maximum rainfall depths were 69.0 and 56.4 mm for the "CHEbro" and "Of.Regante", respectively; and the total rainfall was 749 and 632 mm. However, the total number of rainfall events (*Re*) clearly changed between the two WS, with 50 and 135 *Re* registered by the "CHEbro" and "Of.Regante" WSs, respectively. The dominance of very low erosivity events ($R < 4$ mm event^{-1}) was observed in the two WS (64% and 70% of the total *Re*). The second dominant type of rainfall events was that of high erosivity ($R > 12$ mm event^{-1} or $R > 6$ mm in 15 minutes) adding 18% and 15% of the total *Re* in the"CHEbro" and "Of.Regante" WSs. To a lesser extent, the low ($4 < R < 8$ mm event^{-1}) and medium ($8 < R < 12$ mm event^{-1}) erosivity *Re* added the remaining 18% and 15%. The mean and maximum values of rainfall intensity (I_{30}) were similar between the two WSs and we only observed differences in the median values of I_{30}. The mean and total values of rainfall erosivity (EI_{30}) showed moderate differences between the two WS, and the corresponding differences were -18% and -38%, respectively. The highest mean, maximum and total values of EI_{30} were observed in the "Of.Regante" WS. All these differences supported the necessity of generating a synthetic weather station to study the processes of runoff and soil erosion in "Los Oncenos" sub-catchment.

Table 2. Rainfall data and erosivity in the two weather stations during the 15-month test period.

Parameter	Type / Value	Of.Regante	CHEbro	δ (%)
Rainfall events	Total	135	50	-63%
(*Re*)	Very low erosivity - *n* (%)	95 (70%)	32 (64%)	-66%
	Low erosivity - *n* (%)	9 (7%)	6 (12%)	-33%
	Medium erosivity - *n* (%)	11 (8%)	3 (6%)	-73%
	High erosivity - *n* (%)	20 (15%)	9 (18%)	-55%
Rainfall depth	Minimum	0.2	0.2	0%
(*R*)	Mean	5.5	6.2	13%
	Median	0.6	2.0	2.33%
	Maximum	69.0	56.4	-18%
	CV (%)	187%	156%	-17%
	Total	748.7	631.6	-16%
Rainfall intensity	Minimum	0.4	0.4	0%
(I_{30})	Mean	3.0	3.5	17%
	Median	0.8	1.6	100%
	Maximum	24.0	25.2	5%
	CV (%)	157%	126%	-20%
Rainfall erosivity	Minimum	0.006	0.007	17%
(EI_{30})	Mean	7.09	5.81	-18%
	Median	0.04	0.28	600%
	Maximum	187.01	117.22	-37%
	CV (%)	315%	260%	-17%
	Total	957.48	592.18	-38%

The total rainfall depth in the synthetic weather station (Syn-WS) was 690.2 mm during the 15-month test period (TP), and the total rainfall erosivity was 735.3 MJ mm ha^{-1} h^{-1} TP^{-1} (Figure 4). The highest rainfall depths were registered in April 2018 (117 mm), March 2017 (108 mm) and March 2018 (86 mm) and the lowest ($R < 12$ mm month^{-1}) in August 2017, November 2017 and July 2017. However, the highest values of rainfall erosivity (EI_{30}) were obtained in April 2018 (139 MJ mm ha^{-1} h^{-1} month^{-1}), March 2017 (112 MJ mm ha^{-1} h^{-1} month^{-1}) and October 2017 (108 MJ mm ha^{-1} h^{-1} month^{-1}). The

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highest mean values of rainfall intensity (I_{30}) appeared in November 2017 (6.4 mm h^{-1}), October 2017 (6.0 mm h^{-1}) and June 2017 (5.2 mm h^{-1}), and the lowest (I_{30} < 1.2 mm h^{-1}) in August 2017 and in the period December 2017 – February 2018. The number of monthly medium and high erosivity events (MH-Ee) ranged from 0 to 5, with none MH-Ee during 5 months, whereas four months had three or more MH-Ee. The correlation between the values of EI_{30} and those of R (R^2 = 0.6525) and I_{30} (R^2 = 0.5498) were high and with the number of MH-Ee was weak (R^2 = 0.2245). The correlation between R and I_{30} was very weak (R^2 = 0.0853) and non-correlation appeared between I_{30} and number of MH-Ee. However, a good correlation was found between R and the number of MH-Ee (R^2 = 0.5775).

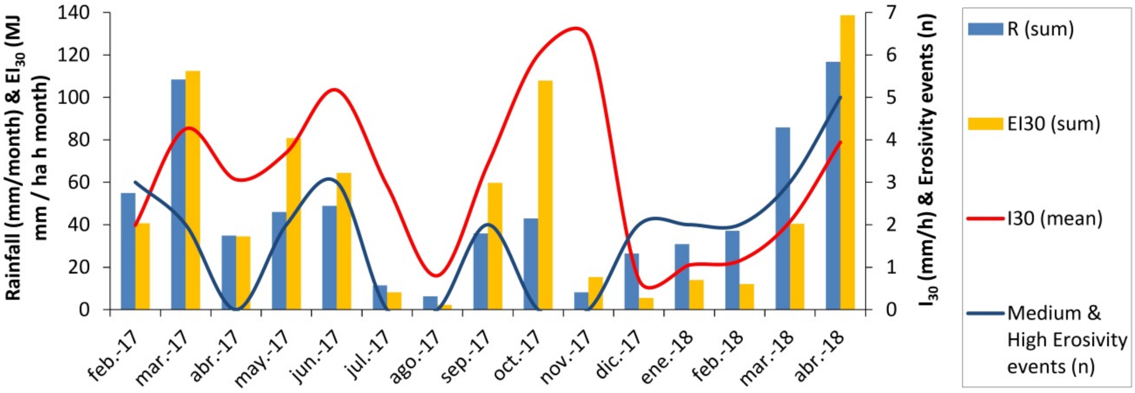

Figure 4. Monthly values of rainfall depth (R), maximum intensity (I_{30}) and erosivity (EI_{30}), and number of medium and high rainfall erosivity events (n) in the synthetic weather station (Syn-WS).

The values of TSWC clearly varied over the test period, with high average values (θ_0 > 20% vol.) in February 2017 and during the period December 2017 – April 2018. The driest average soil conditions (θ_0 < 6.5% vol.) were observed in June and July 2017 (Figure 5). This temporal pattern was identical in the three vineyards' compartments. During the 15-month test period, the average TSWC in the four fields was 15.9% vol. (Table 3). TSWC was higher in the inter-row areas (average θ_0 = 18.5% vol.) and the corridors (average θ_0 = 19.4% vol.) than in the rows (average θ_0 = 12.1% vol.). This spatial pattern was constant in the four fields regardless the type of plant covers. However, these differences were much higher in the three fields (VY1, VY2 and VY3) with common sainfoin as CC (differences between 62% and 70%) than in the VY4 with spontaneous vegetation as CC. In the latest case the difference were 40% on average during the test period. The corridors had slightly wetter conditions than the inter-row areas in 11 months although the differences between these two compartments were not significant. As expected, a moderate positive correlation was found between the monthly values of TSWC and those of rainfall depth (Pearson's r = 0.439). However, we found a similar but negative correlation between TSWC and I_{30} (Pearson's r = -0.458).

Concerning the relative differences of TSWC at each measurement point (δ_{it}), the minimum differences reached the lowest values during the wettest months and the highest values during the driest months (R^2 = 0.7716). In the same way, the maximum relative differences appeared reached the lowest values during the wettest months and the highest values during the driest months (R^2 = 0. 8222) (Supplementary Figure 1). Thus, the spatial variability of TSWC increased during the dry months and conditions that were more homogeneous appeared during the wet months.

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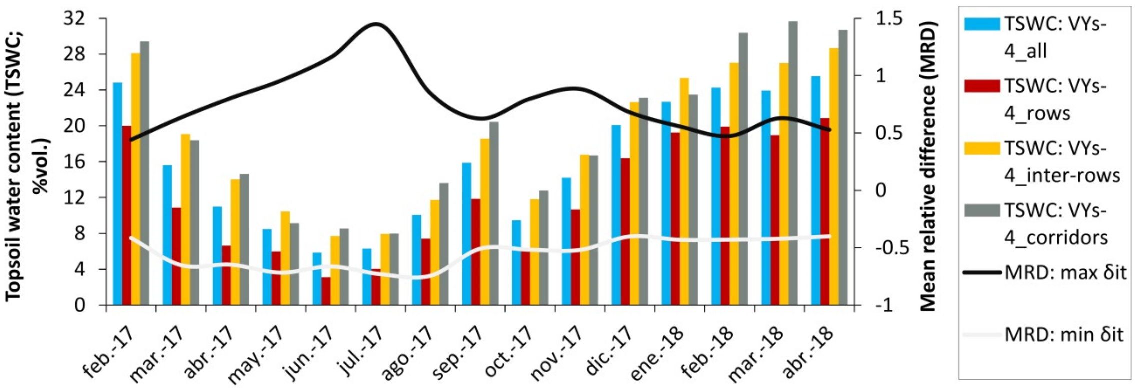

Figure 5. Evolution in the values of TSWC in the three vineyards' compartments.

Table 3. Topsoil water content (TSWC) in the different vineyards and compartments over the test period. The mean relative difference (MRD), standard deviation of the MRD (SDRD) and the coefficients of variation (cv) are included.

Vineyard compartment	PC	TSWC (% vol.) mean	TSWC (% vol.) cv	MRD	SDRD	cv	Conditions
The 4 vineyards (VYs)	----	15.9	33%	0	0.212	----	----
VYs – rows	BS	12.1	25%	-0.271	0.188	69%	Dry and stable
VYs – inter-row areas	CC&SP	18.5	23%	0.186	0.239	129%	Wet and very variable
VYs – corridors	SP	19.4	18%	0.239	0.149	62%	Wet and very stable
VY1 – rows	BS	12.1	22%	-0.258	0.228	89%	Dry and variable
VY1 – inter-row areas	CC	20.7	25%	0.343	0.271	79%	Very wet and stable
VY2 – rows	BS	12.9	18%	-0.197	0.193	98%	Dry and variable
VY2 – inter-row areas	CC	21.6	11%	0.381	0.245	64%	Very wet and very stable
VY3 – rows	BS	11.7	18%	-0.305	0.179	59%	Very dry and very stable
VY3 – inter-row areas	CC	18.9	18%	0.194	0.194	100%	Wet and variable
VY4 – rows	BS	12.1	23%	-0.284	0.179	63%	Very dry and very stable
VY4 – inter-row areas	SP	16.9	21%	0.093	0.257	276%	Slightly wet and very variable

PC: plant cover; SP: spontaneous vegetation; BS: bare soil; CC: cover crop of common sainfoin.

The temporal stability of the spatial patterns was analyzed in the three vineyards' compartments and at field scale too (Table 3). The most stable conditions appeared in the corridors and vineyards' rows, whereas higher temporal variability was observed in the inter-row areas. This temporal dynamic was not constant in the four fields. VY1 and VY2 presented similar conditions between them although VY3 had very dry and very stable conditions in the rows. On average, the vineyards' rows had dry and stable conditions in the three fields with common sainfoin as cover crop, and very dry and very stable conditions in the field with spontaneous vegetation. The soil moisture conditions in the inter-row areas in the three field with common sainfoin were wet and very wet and stable, whereas in VY4 were slightly wet and very variable. Thus, the different plant covers affect the spatial and temporal dynamics of TSWC in the vineyards' compartments.

3.2. Runoff and sediment yield

From the total of 26 time-integrated surveys (TIS) we collected runoff and sediment samples in 21 TIS (Table 4). During the five TIS without runoff generation the accumulated rainfall depth, $\sum R$, was lower than 12 mm and the accumulated rainfall erosivity, $\sum EI_{30}$, was lower than 5.2 MJ mm ha^{-1} h^{-1} TIS^{-1}. There were only two TIS with runoff generation (Q) with $\sum R < 12$ mm and one TIS with Q > 0 litres with $\sum EI_{30} < 5.2$ MJ mm ha^{-1} h^{-1} TIS^{-1}; during these events the maximum rainfall intensity (I_{30})

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was higher than 3 mm h^{-1} in the first case and $\sum R$ was ca. 14 mm in the second case. The $\sum R$ threshold to reach Q > 20 l TIS^{-1} was ca. 18 mm, and Q > 30 l TIS^{-1} was only found with $\sum R$ > 45 mm. A positive correlation was found between $\sum R$ and Q in ST2 (Pearson's r = 0.546) and ST3 (Pearson's r = 0.595) (Table 5). A weak correlation was found between Q and $\sum EI_{30}$ and none correlation between Q and I_{30}. Between the TISs number 4 and 26 the mean Q was 9.8 and 12.9 l TIS^{-1} in ST2 and ST3, and the total Q was 224.7 and 297.3 l TIS^{-1} in ST2 and ST3. The three first TIS were excluded in this comparison owing to the malfunctioning of ST2 during this period. Correlation between Q values from the two STs was high (Pearson's r = 0.700), although we observed runoff generation in ST2 in the TIS#6 without runoff yield in ST3 and conversely we collected runoff in ST3 in the TIS#7 and #10 without runoff yield in ST2. During the TIS#6 and #7 Q < 1 l TIS^{-1} while Q > 20 l TIS^{-1} in ST3 in the TIS#10.

Table 4. Accumulated rainfall depth ($\sum R$) and erosivity ($\sum EI_{30}$), number of rainfall events (*Re*), mean rainfall intensity ($\overline{I_{30}}$), runoff (*Q*) and sediment (*SY*) yields observed in the two sediment traps (ST) at each time-integrated survey (TIS) during the 15-month test period.

TIS		$\sum R$	*Re*	$\overline{I_{30}}$	$\sum EI_{30}$	ST	Q	SY
Date	#	mm	n	mm h^{-1}	MJ mm ha^{-1} h^{-1} TIS^{-1}	#	l TIS^{-1}	g TIS^{-1}
07/02/2017	1	24.3	3	4.0	10.3	ST2	MF	ND
						ST3	26.488	16.1
16/02/2017	2	30.1	3	3.6	30.4	ST2	MF	ND
						ST3	23.824	39.8
08/03/2017	3	34.1	8	1.5	43.1	ST2	MF	ND
						ST3	3.678	22.6
28/03/2017	4	70.3	4	4.0	68.1	ST2*	30.195	30.9
						ST3*	30.010	124.6
17/04/2017	5	11.7	2	4.0	5.1	ST2	0	0
						ST3	0	0
04/05/2017	6	23.3	7	2.4	29.4	ST2	0.720	3.4
						ST3	0	0
17/05/2017	7	31,9	6	3.6	68.8	ST2	0	0
						ST3	0.930	2.9
06/06/2017	8	39.9	5	4.8	27.9	ST2	1.500	2.3
						ST3	4.787	7.1
16/06/2017	9	2.8	1	3.0	0.8	ST2	0	0
						ST3	0	0
27/06/2017	10	19,4	1	16.2	47.6	ST2	MF	ND
						ST3	21.128	38.9
10/07/2017	11	10.8	4	3.3	8.0	ST2	0.383	1.7
						ST3	0.462	1.4
29/08/2017	12	7.6	9	1.0	2.4	ST2	0	0
						ST3	0	0
19/09/2017	13	16.7	6	1.5	9.0	ST2	0.645	27.8
						ST3	0.206	15.2
26/09/2017	14	18.1	1	17.8	50.7	ST2**	9.942	32,825.8
						ST3	7.071	1,821.6

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17/10/2017	15	1.3	3	0.4	0.1	ST2	0	0
						ST3	0	0
25/10/2017	16	42.9	2	8.9	107.9	ST2**	8.546	41,260.2
						ST3**	26.513	2,778.4
17/11/2017	17	8.0	1	12.6	15.3	ST2	23.156	281.4
						ST3	8.252	911.6
20/12/2017	18	13.8	8	0.8	2.9	ST2	1.012	2.2
						ST3	0.276	0.4
18/01/2018	19	28.6	19	0.8	12.1	ST2	28.396	60.5
						ST3	24.612	38.1
12/02/2018	20	42.4	9	0.8	11.5	ST2	2.287	0.8
						ST3*	28.766	44.6
19/02/2018	21	9.5	4	5.8	5.0	ST2	0	0
						ST3	0	0
07/03/2018	22	45.4	5	2.0	18.1	ST2*	30.711	13.3
						ST3*	30.237	18.8
19/03/2018	23	23.3	10	2.3	16.8	ST2	28.466	84.5
						ST3	28.380	40.7
05/04/2018	24	17.7	6	1.3	5.6	ST2	0.861	4.1
						ST3*	28.900	42.0
18/04/2018	25	93.8	8	4.4	101.1	ST2*	28.834	59.2
						ST3*	29.034	30.2
30/04/2018	26	22.4	4	4.9	37.6	ST2*	29.023	94.3
						ST3*	27.702	572.7

MF: malfunctioning; *: ST completely full of runoff; **: ST completely full of sediments.

Table 5. Pearson's correlation coefficients between observed runoff (Q) and sediment (SY) yields at each sediment trap (ST) during the 26 time-integrated surveys (TIS) and the corresponding values of rainfall depth (R), maximum intensity (I_{30}) and erosivity (EI_{30}).

Sediment trap	Observed values	R	I_{30}	EI_{30}
ST2	Q	0.546	0.042	0.329
	SY	0.082	0.536	0.537
ST3	Q	0.595	0.040	0.365
	SY	0.056	0.594	0.533

The sediment yield (SY) clearly changed between ST2 and ST3. Between the TIS#4 and #26, the mean SY was 3,250 and 282 g TIS^{-1} in ST2 and ST3, the median 3.4 and 18.8 g TIS^{-1}, the maximum 41,260 and 2,778 g TIS^{-1}, and the total 74,752 and 6,489 g TIS^{-1} (Table 4). The number of TIS when SY < 50 g TIS^{-1} was 9 and 12 in ST2 and ST3, whereas SY > 100 g TIS^{-1} in 3 and 5 TISs in ST2 and ST3 (Figure 6). We only observed high (SY > 1,000 g TIS^{-1}) and very high (SY > 30,000 g TIS^{-1}) soil erosion dynamics in the TIS#14 and #16. The total SY collected during these TISs represented 99% and 70% of the total SY recorded in ST2 and ST3 during the whole test period, respectively.

A positive correlation was found between I_{30} and SY in ST2 (Pearson's r = 0.536) and ST3 (Pearson's r = 0.594), and also between $\sum EI_{30}$ and SY in both STs (Table 5). None correlation was found between $\sum R$ and SY. The observed SY in ST2 correlated very well with that of ST3 (Pearson's r = 0.946) although very low correlation was found between the values of Q and SY during the test period

(Pearson's r = 0.072). Runoff turbidity (QT) was calculated considering the total runoff volume and sediment weight observed during the test period, obtaining a QT value of 333 and 19 g l^{-1} in T2 and T3.

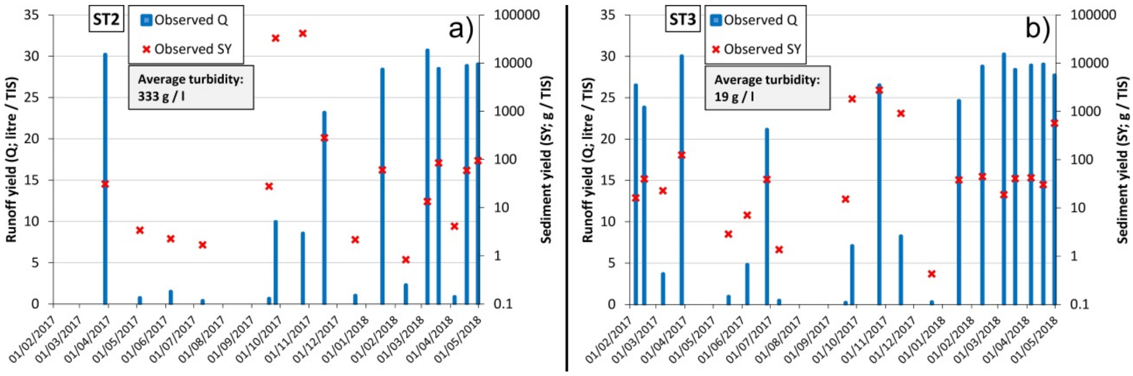

Figure 6. Evolution of the runoff coefficients and sediment yield in the two ST during the test period.

4. Discussion

4.1. Soil moisture dynamics

The contrasted climatic conditions in the study area, with two humid periods, one in spring and one in autumn, a dry and hot summer, and a soft and relatively dry winter, explained the observed temporal evolution of TSWC over the year in the four vineyards. In Mediterranean regions, changes in the rainfall inter-seasonal distribution have been observed and evaluated in vineyards, indicating potential soil moisture stress during the critical growth stages of the grapevines [48]. Thus, monitoring soil moisture in the different vineyards' compartments over the year appears as a necessary task to propose best management practices for commercial vineyards.

On average, TSWC in the vineyards' inter-row areas were 52% higher than in the rows. These results can be explained by the conservation role played by the plant covers, and agreed with the results obtained by López-Vicente and Álvarez [32] in a previous study in "Los Oncenos" sub-catchment after analysing an older database of TSWC in several land uses. The observed differences in the effectiveness of water conservation between the cover crop (CC) of common sainfoin and the plant cover of spontaneous vegetation (SP) may be explained by the differences in plant density, much higher in the CC than in the SP. In olive orchards in southern Spain, López-Vicente et al. [28] also found different runoff coefficients in runoff crops with homogeneous and heterogeneous plant covers. The wet and stable soil moisture conditions observed in the corridors may be explained by (i) the occasional tractor traffic than compact the topsoil reducing evaporation; (ii) the lack of grapevines in this compartment that clearly reduces the water consumption; and (iii) the presence of SP that favoured water infiltration. Also high values of soil moisture were found in the unpaved trails in "Los Oncenos" sub-catchment in the previously cited study [32]. In the same context, Biddoccu et al. [7] found an increase in the TSWC in vineyards due to the soil compaction by tractor traffic that seals the topsoil surface.

The elevated temporal variability of TSWC observed in the vineyards' inter-row areas can be explained by the significant changes in the surface cover factor over the year (Figure 3). Very low soil protection took place during the summer and at the beginning of autumn owing to the tillage practices done by the farmer at the end of May and the adverse climatic conditions during the summer for the growth of the plant covers. At the end of autumn the percentage of the soil surface cover started increasing and reached the maximum values in April and in the first part of May (almost 100%). The adopted soil management for the plant covers has strong impacts on the spatio-temporal variations of the soil surface characteristics (soil cover, topsoil structure and soil crusting) and on the soil hydrological properties and processes, which handle the partition of rainfall between runoff and

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infiltration at the field-scale [49]. Thus, different tillage practices of the plant covers may be considered in further research studies in vineyards and other woody crops.

4.2. Hydrological response of the soil

The accumulated rainfall threshold observed in this study (ca. 12 mm) was higher than the rainfall threshold (between 4.6 and 8.5 mm) observed by Rodrigo-Comino et al. [50] in sloping vineyards in southeastern Spain. This difference was explained by the soil surface conditions of both study sites: the cover crop of common sainfoin in our study area and totally bare soil conditions in the inter-row areas of Rodrigo-Comino's et al. [50] study site. The higher mean and total runoff yields, 32% higher, observed in ST3 in comparison with ST2 were explained by the larger upslope contributing area (CA) of ST3 that is 89% larger than the CA of ST2. The lack of correlation between the observed values of Q and SY at each ST during the test period was explained by the non-linearity relationship between runoff, soil erosion and sediment delivery. Smets et al. [51] also found considerable differences between the runoff and sediment yields during laboratory experiments with simulated rainfall (60 minutes) on a silt loam cultivated topsoil.

During the five TISs with the highest values of rainfall erosivity (EI_{30} > 50 MJ mm ha^{-1} h^{-1} TIS^{-1}) we observed two contrasted hydrological and erosive response of the soil. During the TIS#4 (March 2017), and #25 (April 2018) runoff yields were very high but SY was low, and during the TIS#7 (May 2017) both Q and SY were low. During these three events the soil surface cover was very high owing to the growth of the cover crop (see Figure 3). However, during the TIS#14 (September 2017) and #16 (October 2017) the highest values of SY were observed. During these two months the soil surface cover was minimum owing to the phenology of the cover crop, the dry and hot summer and the mowing pass done in late May 2017 on the cover crop. The presence of the plant debris (from the mowing pass) was only visible from June to August, and their soil conservation role was negligible in September and October. Thus, the evolution in the canopy cover of the grapevines and plant covers played an important role in the soil erosion dynamic of the two contributing areas. Biddoccu et al. [52] also found in Italian vineyards high temporal variability of hydraulic conductivity and soil water content influenced by the soil surface conditions in relation to vineyard management, such as tilled inter-rows and grass cover.

5. Conclusions

Topsoil water content (TSWC) varied during the test period, showing a good agreement with the evolution in the values of total rainfall depth that presented contrasted conditions over the year. Dry conditions favored higher relative differences of TSWC along the vineyards while more homogeneous spatial patterns appeared during the wet surveys. Concerning the different vineyards' compartments, the moistest conditions appeared in the inter-rows and corridors, with presence of plant covers, whereas drier conditions appeared in the rows that had bare soil conditions. In addition, TSWC in the inter-row areas with common sainfoin was much higher than the inter-row areas with spontaneous vegetation. Regarding the temporal stability, the soil moisture conditions in the rows and corridors were stable. The inter-rows presented higher temporal variability owing to the tillage practices that affected the plant covers and the climatic conditions.

The joint analysis of the rainfall parameters and those of runoff and sediment yields in the two sediment traps and during the time-integrated field surveys allowed identifying the threshold values of accumulated rainfall depth and/or rainfall erosivity that were necessary to generate runoff and thus net soil loss. Besides, the rainfall depth and erosivity thresholds to trigger high values of runoff and sediment yield in a vineyard with a cover crop of common sainfoin were identified. Satisfactory correlations were observed between the runoff yield and rainfall depth and between the sediment yield and rainfall intensity and erosivity.

Despite the different magnitudes of the mean and total runoff and sediment yields observed in the two sediment traps, correlations between the runoff yields and between the sediment yields of the two sediment traps were high and very high, respectively. These results suggested that both contributing areas were activated during the same rainfall-runoff events and the differences in Q and

SY over the test period were explained by: (i) the differences in the physiographic characteristics, such as the total area, the slope gradient, and the percentage of soil surface cover, of the upslope contributing areas of the two STs; and (ii) the changes in the total surface cover over the twelve months of the year that were associated to the plants' phenology and the tillage practices. The results of this study are of interest to improve the management and conservation of soil and water in rainfed Mediterranean vineyards, appearing the common sainfoin as an efficient cover crop.

Author Contributions: M.L.-V. conceived and designed the research; N.B.-S., S.A. and M.L.-V. performed the field and laboratory work and processed the data; N.B.-S. and M.L.-V. analysed the data and wrote the paper; M.L.-V. supervised the work and reviewed the final manuscript.

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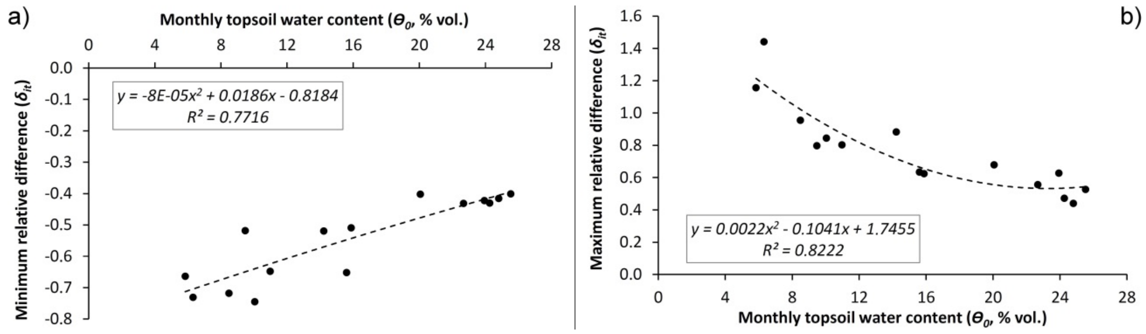
Conflicts of Interest: The authors declare no conflict of interest.

Supplementary figure 1. Correlation between the minimum (a) and maximum (b) relative differences (δ_{it}) of TSWC during the 15-month test period, and the average value of monthly TSWC (θ_0, % vol.) in the four vineyards.



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