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The Effect of Shallow Tillage on Soil Erosion in a Semi-Arid Vineyard

Agata Novara [1,*], Giovanni Stallone [1], Artemio Cerdà [2] and Luciano Gristina [1]

[1] Dipartimento di Scienze Agrarie Forestali e Ambientali, University of Palermo, viale delle Scienze 4, 90100 Palermo, Italy; giovannistallone96@libero.it (G.S.); luciano.gristina@unipa.it (L.G.)
[2] Soil Erosion and Degradation Research Group, Department of Geography, University of Valencia, 46010 Valencia, Spain; artemio.cerda@uv.es
* Correspondence: agata.novara@unipa.it; Tel.: +39-091-23862214

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Abstract: Soil erosion has been considered a threat for semi-arid lands due to the removal of solid materials by water and wind. Although water erosion is currently considered the most important process of soil degradation, a growing interest has been drawn to the impact of soil tillage. Although numerous studies on tillage erosion have been carried out on arable land using a moldboard plow, a chisel, and a tandem disc for different crops, there are no studies on the effect of shallow tillage on soil redistribution in vineyards. The aim of this work was to evaluate the soil tillage erosion rate in a vineyard using a ^{13}C natural abundance tracer. A strip of soil (C_3-C soil) was removed, mixed with C_4-C tracer, and replaced. After the installation of the strip, tillage (upslope in one inter-row and downslope in the other inter-row) was performed with a cultivator and soil was collected along the slope with an interval of 0.2 m from the C_4-C strip. Soil organic carbon and δ^{13}C were measured and the total mass of translocated soil (T) soil was calculated. The net effect of tillage after two consecutive operations (downslope and upslope tillage) was a T of 49.3 ± 4.2 kg m^{-1}. The estimated annual erosion rate due to tillage in the studied vineyard was 9.5 ± 1.2 Mg ha^{-1}year^{-1}. The contribution of the soil tillage erosion rate was compared with that of water erosion in the same vineyard, and we conclude that tillage is a threat to soil degradation.

Keywords: tillage erosion; vineyards; soil translocation; ^{13}C natural abundance

1. Introduction

Agriculture is the land use that contributes to the highest soil losses in all continents and climatic conditions [1–5]. Within the biogeographical zones of the planet, the Mediterranean suffers from high erosion rates due to the low soil protection of the vegetation cover and the high rainfall intensity [6–8]. The vineyard is one of the land uses, in semi-arid environments, with higher erosion rates [9,10]. The steep slope on which the vineyard usually lies, the low soil fertility, climatic characteristics, and intensive agricultural practices are the main factors contributing to the high erosion rate [11]. Water flow and wind have been considered the main drivers of sediment and nutrient translocation, whereas little relevance has been attributed to soil erosion as a consequence of tillage. Unlike rill and sheet erosion, whose effects are remarkably visible and sometimes dramatic in relation to rainfall intensity, tillage erosion is continuous with an evident effect only after several years. However, the magnitude of tillage erosion is comparable to water erosion, especially under intensive conventional agriculture [12,13]. Tillage erosion represents the downslope reallocation of soil sediment through tillage practices and could be an important factor in soil and field evolution in the agricultural landscape [14,15]. It is expressed as the translocated soil amount per meter width and is calculated as net soil distribution between downslope and upslope tillage.

The range of soil tillage erosion rates per operation, reported in the literature, is quite wide, being the translocation influenced by factors relating both to environmental conditions and tillage practice. It is affected by slope gradient, morphological aspects (concavity and convexity), and soil characteristics (water content, texture) [16,17]. The type of equipment, the shape of the tool, tillage frequency, tillage depth, tillage direction, speed, and the skill of the operator also affect tillage erosivity, producing high variability on tillage erosion rates [18].

The first studies on tillage erosion were carried out by Mech and Free [19], which showed the strong effect of slope gradient on soil tillage erosion rates; they found values for the tillage transport coefficient per operation of 24 kg m^{-1} in downslope direction with shallow moldboard tillage and of 13 kg m^{-1} with chisel tillage. Results of more recent studies have shown a higher tillage transport coefficient, with values reaching up to 770 kg m^{-1} for an operation as recorded by da Silva et al. [20] during moldboard tillage at 0.4 m depth. Although the transport coefficient provides helpful information to compare the erosivity of different tillage operations, the erosion rate values (Mg ha year^{-1}) indicate the severity of soil tillage on soil loss for a specific cropping system. Thapa et al. [21] estimated values of tillage erosion rates for a 25% slope of 456 Mg ha^{-1} year^{-1} for five moldboard plowing operations up- and downslope used for one corn crop season. Other authors found lower values in a wheat-based system [22] and in a pasture [23].

Therefore, considering the wide tillage erosion rate range found in the literature, the few available field measurements, and the high variability of study areas, further research studies should be performed to quantify and compare the risk of tillage erosion with water erosion.

Another major uncertainty that must be analyzed in soil erosion studies concerns tillage erosion measurements. Fiener et al. [24] compared different measuring techniques (tracers and topographical methods) in a field plot experiment, finding a relatively wide range of soil translocation rates in the same slope positions. In the literature, the most widely used measuring techniques are based on chemical tracers (^{137}Caesium, radionuclide, ^{239}Pu, sodium chloride solution) or physical tracers (numbered metal cubes, flat steel washers, colored rocks and gravel, magnetic tracers) [25–31]. Alternative methods that have been used are based on topographical variation using photogrammetry, high-resolution digital elevation models, or terrestrial laser scanners [24,32].

Most of the translocation and tillage erosion studies have focused on primary tillage, such as the chisel and moldboard plow [14], but very few studies have investigated the effect of secondary tillage and seeding implements [18] because it was assumed to be negligible. These assumptions must be validated.

Considering the actual uncertainty and the lack of knowledge in soil tillage erosion studies, the aim of the study was (i) to quantify the effect of soil tillage erosion in a semi-arid vineyard due to shallow tillage using a carbon isotopic natural abundance approach to estimate the translocation coefficient and (ii) to evaluate the relative contribution of tillage erosion in comparison to water erosion.

2. Material and Methods

2.1. Experimental Design

The field experiment was carried out in a semi-arid vineyard located in Santa Margherita del Belice (37°41′ N; 13°02′ E), in Sicily. The climate in the area is Mediterranean with a mean annual temperature of 18 °C and an annual rainfall of 516 mm. The soil is Calcic Gleyic Vertisol according to Word Reference Base (WRB) [33], (clay 43%, silt 23%, and sand 34%; bulk density before tillage 1.2 Mg m^{-3}). The selected vineyard (cultivar Syrah) lies on a 15% slope. It was planted in 2007 with a distance of 2.50 m (intra-row) and 1 m (inter-row). Vineyards in the area are managed mainly with conventional tillage with frequent shallow tillage (from four to six per year) to control weeds and reduce soil evaporation in the summer. In the selected vineyard soil was tilled six times from September 2017 to August 2018.

The translocated soil was measured using the difference in ^{13}C natural abundance between the vineyard soil (C_3-C soil) and the labelled strip. Previous erosion studies have used the differences in ^{13}C natural abundance to trace soil sediment or carbon distribution [34–36]. In the vineyard, two adjacent inter-rows were selected. In each inter-row, a strip of soil (1 m length × 0.2 m wide, 0.15 m depth) was removed, carefully weighed and mixed with ground biomass of *Posidonia oceanica* L. (C_4 plant; δ^{13}C = −17‰) (Figure 1). This kind of tracer, with respect to other C_4 biomass, is easily available in the Mediterranean environment and is free. The soil mixed with *P. oceanica* was replaced in the strip.

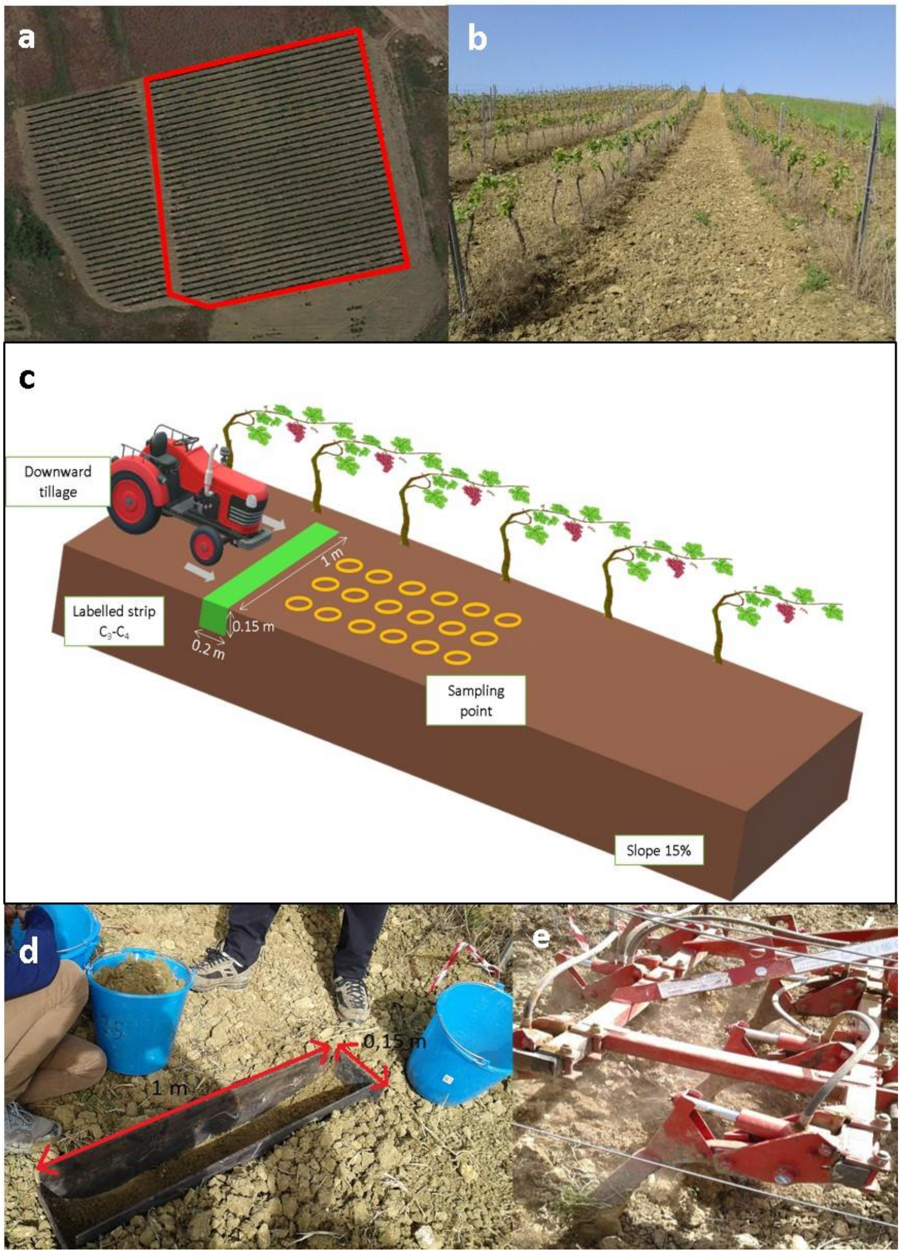

Figure 1. Representation of field experiment: (**a**) study area (Google Earth image); (**b**) inter-row of the selected vineyard; (**c**) schematic representation of field experiment and sampling points; (**d**) installation of the labelled isotopic strip; (**e**) cultivator used for tillage operation.

After the installation of the strips, tillage (upslope in one inter-row and downslope in the other inter-row) was performed with a cultivator (tractor speed of 4 km h^{-1}). After tillage, the soil was collected with a cylinder PVC tube and bulk density was measured [37]. Soil water content was measured before tillage (14.1%). Three soil subsamples of each plot were collected along the slope with an interval of 0.2 m from the C_4-C strip. Soil samples were sieved and carbonate was removed, before soil organic carbon and δ^{13}C analysis by acid fumigation following the method used by Harris et al. [38]. Furthermore, three soil subsamples for each plot were taken in the labelled strip with C_4-C and in the vineyard soil before the experiment ($\delta^{13}C = -26.5‰$) (Figure 1).

2.2. Calculation

Organic C in soil was measured using an elemental analyzer (NA1500 Carlo Erba, Milan, Italy). For δ^{13}C analysis of the soil, an elemental analyzer isotope ratio mass spectrometry (EA-IRMS) was used. Details about the reference material used for analysis are described in Novara et al. [36]. The results of the isotope analysis are expressed as a δ value (‰) relative to the international Pee Dee Belemnite standard as follows:

$$\delta^{13}C‰ = \frac{R_s - R_{st}}{R_{st}} \times 1000, \tag{1}$$

where $\delta = \delta^{13}C$, $R = {}^{13}C/{}^{12}C$, R_s is the sample, and R_{st} is the standard.

Differences in δ^{13}C were used to determine the fraction of C_4-C (%), derived from the labelled strip's soil, in the sampled soil (each interval of 0.2 m from the strip), after the tillage operation:

$$fraction\ of\ C_4\text{-}C\ (\%) = \left(1 - \frac{\left(\delta^{13}C_{sample} - \delta^{13}C_{strip}\right)}{\left(\delta^{13}C_{vineyard} - \delta^{13}C_{strip}\right)}\right), \tag{2}$$

where $\delta^{13}C_{sample}$ is the isotopic composition of soil sampled after tillage; $\delta^{13}C_{strip}$ is the C isotopic composition of soil in the strip after adding the *Posidonia*, and $\delta^{13}C_{vineyard}$ is the C isotopic composition of the vineyard soil. The fraction of C_4-C (%) in soil samples after each interval of 20 cm from the labelled strip was converted in the translocated soil (Equation (3)) using the soil organic carbon (SOC) content (g kg^{-1}) of the soil sampled after tillage (SOC_{sample}), the SOC content of the soil in the labelled strip (SOC_{strip}), and the mass (kg) of soil in the strip (SM_{strip}). The labelled strip's translocated soil for each tillage operation was estimated by measuring the spatial distribution of C_4-C (%). The decrease of C_4-C (%) is directly related to the mass of soil translocated per width unit (kg m^{-1}). For a specific sampling point at x distance from the labelled strip, the translocated soil is calculated as follows:

$$Translocated\ soil\ (x) = fraction\ of\ C_4\text{-}C(x) \times \mathrm{SOC}(x) \times \frac{SM_{strip}}{SOC_{strip}}. \tag{3}$$

The total translocated soil (T) per unit slope width (kg m^{-1}) was calculated according to Equation (4):

$$T = \frac{1}{w}\int_0^d Traslocated\ soil\ (x)dx, \tag{4}$$

where x is the distance of the tracer displacement from the labelled strip, d is the maximum distance of the tracer displacement, and w is the strip width that was labelled (Figure 2). This approach assumes that the tracer of a hypothetical adjacent labelled strip is distributed after tillage along the slope with the same trend of the labelled strip [39,40].

Net downslope translocation was calculated by the difference between soil translocation upslope and soil translocation downslope. The value of T was converted into the erosion rate (Mg ha^{-1}) using the real width of the tilled field portion. In our case study, the vineyard had 34 intra-rows and the cultivator width was 2 m; therefore, the considered field width was 64 m. Moreover, the annual tillage erosion was calculated considering the number of tillage operations downslope and upslope during one year of vine cultivation.

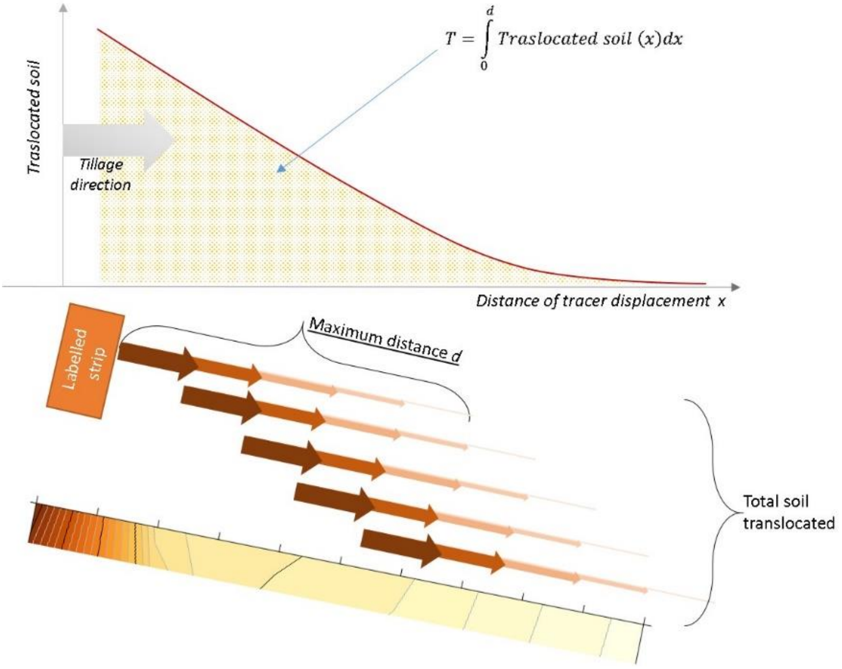

Figure 2. Graphical representation of the estimation method of the total translocated soil.

2.3. Soil Erosion Assessment

The total soil erosion rate, that includes both water and tillage erosion, was estimated using the pole method developed by Novara et al. [41]. That method is based on the difference of pole heights between planting and the current time. According to this approach, the measured erosion rate includes water, wind, and tillage erosion. The pole height (pole distance equals 7 m) was measured on three inter-rows and calculated according to Novara et al. [41]. The pole height was measured at five points in the intra-row transect between two poles [41].

2.4. Statistical Analysis

Upslope and downslope datasets were analyzed separately. Normality of the data and homogeneity of variance were checked prior to statistical analysis. Post-hoc comparisons among the distances from the strip were compared using the least significant difference (LSD) test at 0.05 significance level [42].

3. Results and Discussion

3.1. Tillage Transport Coefficient

After the downslope tillage, the δ^{13}C values increased from the labelled C_3-C_4 strip (−18.14 ± 0.05‰) up to 120 cm (Figure 3a).

After 120 cm, the δ^{13}C values were not significantly different from values of the vineyard C_3-C soil, indicating that there was no contribution of labelled substance in the soil. This result allows the calculation of the maximum distance (*d*) of soil translocation, which was 120 cm in the downslope direction in a 15% slope.

The translocated soil after 20 cm from the strip was 19.5 ± 1.8 kg m^{-1}, representing the constant value for each interval of 20 cm. However, the portion of soil coming from the strip and translocated along the slope decreased. The translocated soil after 40 cm, 60 cm, 80 cm, 100 cm, and 120 cm from the strip was 15.4 ± 1.4 kg m^{-1}, 14.4 ± 0.9 kg m^{-1}, 7.7 ± 0.15 kg m^{-1}, 3.9 ± 0.15 kg m^{-1}, and 1.2 ± 0.1 kg m^{-1}, respectively. The total translocated soil (*T*), calculated according to Equation (4), resulted in 62.1 kg m^{-1} in the downslope direction (Figure 3a).

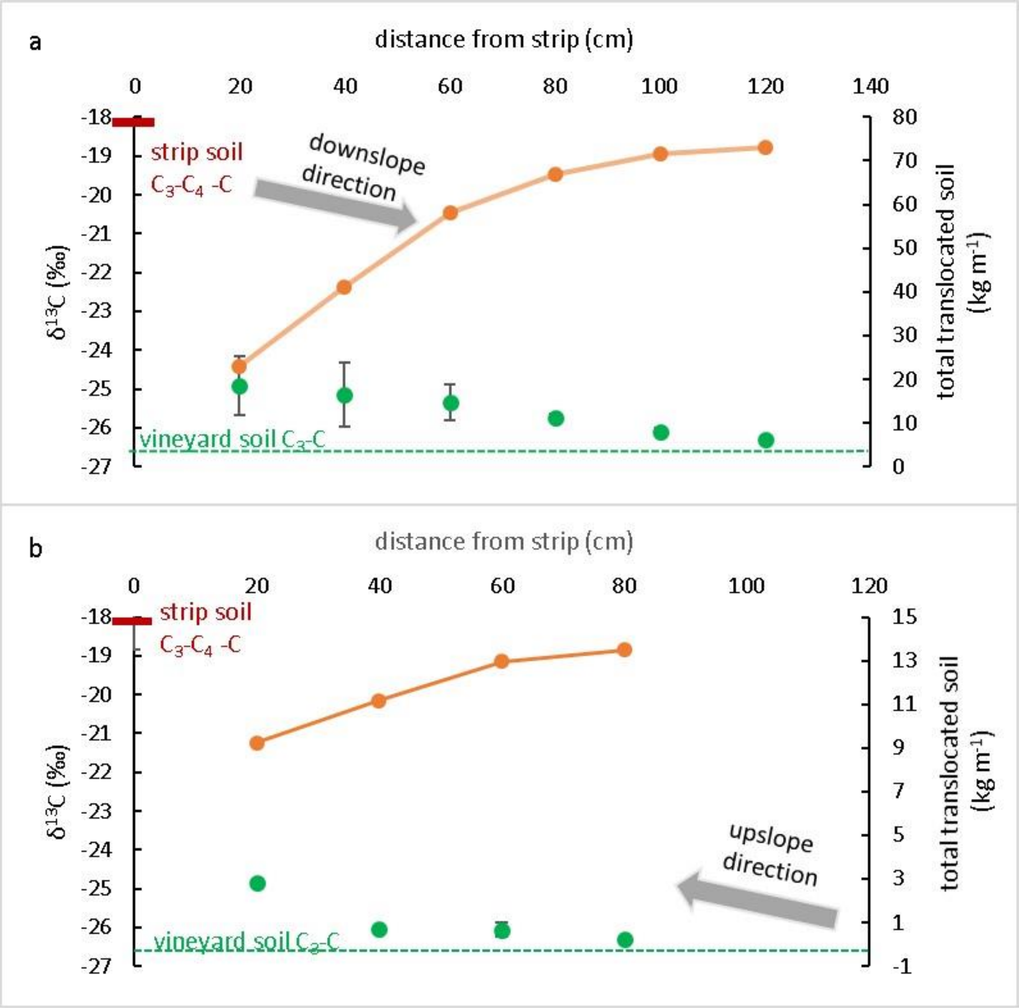

Figure 3. δ^{13}C values (‰) and total translocated soil (kg m^{-1}) in (**a**) downslope tillage and (**b**) upslope tillage.

In upslope tillage, the δ^{13}C values increased from the labelled C$_3$-C$_4$ strip (−18.14 ± 0.05‰) up to an 80 cm distance from the strip (Figure 3b). The tillage translocation distance was lower by 40 cm in upslope in comparison to downslope tillage. The translocated soil in upslope tillage was 8.6 ± 0.9 kg m^{-1} after 20 cm from the labelled strip and 0.5 ± 0.1 kg m^{-1} after 80 cm; the cumulative erosion rate amounted to 12.8 kg m^{-1} (Figure 2b). Therefore, the net effect of tillage after two consecutive operations (downslope and upslope tillage) was a net T of 49.3 ± 4.2 kg m^{-1}.

The T found in this study was lower than those recorded in research studies with moldboard tillage, a chisel and a tandem disc [20,43–45]. Our results were in the same magnitude with those obtained by Kouselou et al. [46] under reduced and minimum tillage in dryland agriculture. There are no studies on the effect of tillage erosion in an orchard system, but these first results show that greater attention should be paid to this situation.

3.2. Soil Tillage Contribution to Total Erosion

In order to understand the role played by tillage in vineyard erosion, the annual erosion rate was estimated using the T value. The vineyard in the study area was tilled on average six times during the year (three upslope and three downslope till operations in each intra-row), producing a soil loss of 9.5 ± 1.2 Mg ha^{-1}year^{-1}. Such an erosion rate can be considered a risk for degradation of the cultivated soil; the tolerable soil loss, in fact, ranges from 1 Mg ha^{-1} year^{-1} for shallow sandy soils to 5 Mg ha^{-1} year^{-1} for deeper well-developed soil, as reported in Europe's environment assessment

(European Environment Agency, 1998). High soil loss rates lead to the depletion of soil nutrients and the reduction of vine vigor, decreasing the sustainability of vineyards which require ever greater external inputs [11].

The contribution of the soil tillage erosion rate was compared with that of water erosion in the same vineyard. The pole's current height was different in comparison to that at the vines' planting; the height difference ranged from +0.02 m to −0.17 m. The estimated soil water loss (the average of 11 years since planting) was 35.5 ± 3 Mg ha^{-1}year^{-1}. Therefore, the tillage erosion/water erosion rate ratio was equal to 0.26. Van Oost et al. [13], in a review work, compared tillage and water erosion rates in mechanized agriculture, reporting values of tillage erosion/water erosion rate ratios ranging from 0.15 to 23. The ratio is noticeably affected by the water erosion rate and, therefore, by studies undertaken in different regions or cultural systems. Nonetheless, the information presented in their review can be helpful in understanding the role of tillage erosion in soil redistribution with respect to soil management for a specific agricultural site. In the present study, the vineyard was managed under conventional tillage, which is widely known to be responsible for high erosion rates. Regarding the studied vineyard, the annual water and tillage erosion rates were also estimated under hypothetical soil management with a cover crop. Previous studies carried out by Novara et al. [41] in a Sicilian vineyard with similar characteristics showed that cover crop soil management with *Vicia faba* significantly reduced the water erosion rates. Therefore, using the C-factor derived from the USLE equation (Universal Soil Loss Equation) estimated by the same authors [41], the water erosion rate in the studied vineyard could likely be reduced from 35.5 to 7.2 Mg ha^{-1}year^{-1} (Figure 4). Similarly, considering the lower number of till operations under cover crop soil management (three operations during the year), the tillage erosion rate could be reduced to 4.7 Mg ha^{-1}year^{-1}. Therefore, the tillage/water erosion ration is 0.66 under cover crop management. This estimation highlights the fact that the contribution of tillage erosion is in the same order of magnitude as that of water erosion in the overall erosion rate under cover crop management.

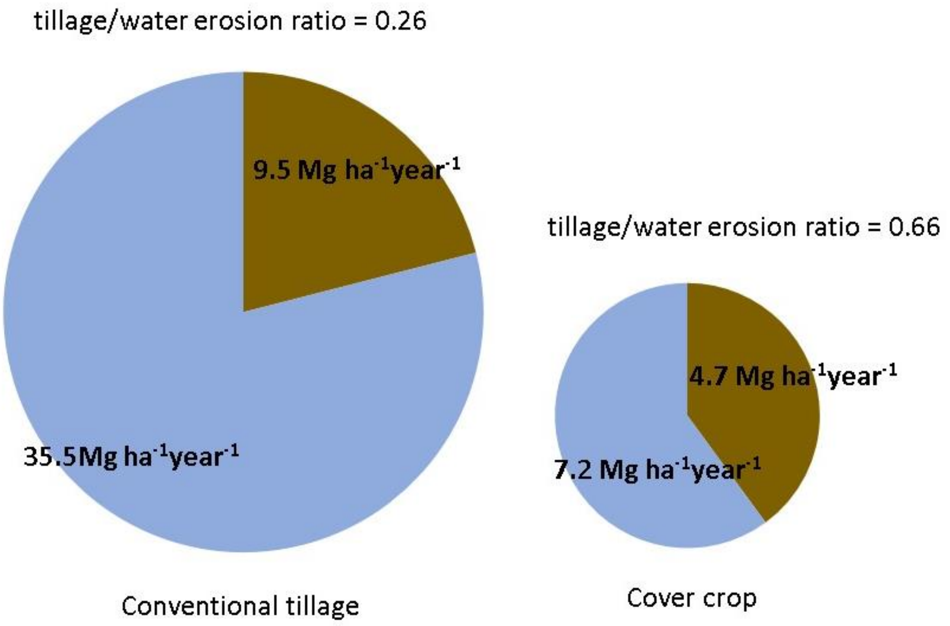

Figure 4. Comparison between (brown area) tillage erosion and (blue area) water erosion in the studied vineyard under conventional tillage soil management and a hypothetical cover crop soil management.

Our results demonstrate that tillage is one of the concerns to be considered for achieving sustainable development in Mediterranean agricultural lands. Therefore, the impact of tillage must be researched more than water erosion, as is claimed by researchers such as Rodrigo-Comino et al. (2018) [47]. This will contribute to achieving sustainable development and then respecting the United Nations

Goals for Sustainable Development and dealing with the Land Degradation Neutrality issues [48]. Our research has found that not only soil water erosion threatens the future of the soils in vineyards and that this fact should be considered in the future [49].

4. Conclusions

Soil erosion by water has been seen as the main cause of soil erosion in the Mediterranean. Although this is well proven, there are other key mechanisms that result in high erosion rates, such as tillage translocation. Tillage has been a widespread agricultural practice in the Mediterranean for the last ten millennia, and little is known about how much soil is eroded due to this activity. This paper demonstrates that tillage is relevant for understanding soil erosion processes, representing a consistent contribution to total soil removed.

Most of the research on tillage erosion has been focused on cereal crops, where tillage takes place once or twice a year using moldboard plowing at 20–30 cm soil depth. However, little is known about the impact of tillage on soil erosion in tree plantations such as citrus, fruit, or vineyards. This should be also researched to adequately survey the impact of tillage in Mediterranean agricultural lands.

According to the results of this field experiment, soil tillage erosion in orchards due to the frequent shallow tillage can be considered a hidden threat for soil degradation. This study's findings showed that the contribution of soil tillage erosion was 9 Mg ha^{-1} year^{-1} on a total of 45 Mg ha^{-1} year^{-1} of soil eroded. The tillage erosion rate was generally lower in comparison to that of water erosion (tillage/water erosion = 0.26); the use of a cover crop consistently reduces the total soil erosion but increases the relative contribution of tillage erosion.

Further studies should be carried out considering different soil management and agronomic strategies. While water erosion is mainly affected by factors which cannot be modified by farmers, except for soil vegetation cover, the soil tillage erosion can be controlled by reducing operations, regulating speed and depth, and choosing more sustainable tillage tools. Moreover, there is also a lack of knowledge on the effects of different secondary tillage tools in orchards in relation to soil conditions (water content, texture), which could help farmers to adequately decide the tillage period.

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