https://doi.org/10.5194/egusphere-2025-3542
Preprint. Discussion started: 18 August 2025

Soil erosion in Mediterranean olive groves: a review

Andrés Peñuela[1], Filippo Milazzo[2], Emilio J. González-Sánchez[1,3]

[1]ETSIAM, Universidad de Córdoba, Campus Rabanales, Edif. Da Vinci, 14071, Córdoba, Spain

[2]Agricolus, Via Settevalli 320, 06129, Perugia, Italy

[3]European Conservation Agriculture Federation (ECAF). Rond Point Schuman, 6, box 5 B-1040 · Brussels · Belgium

Correspondence to: Andrés Peñuela, email: apenuela@uco.es

Abstract. Olive groves are a defining feature of the Mediterranean landscape, economy, and culture. However, this keystone agroecosystem is under severe threat from soil erosion, a problem exacerbated by the region's unique topographic, climatic conditions and agricultural practices. Although soil erosion in olive groves has been extensively studied, significant uncertainties remain due to the high variability of scales and measurement methods. Knowledge gaps persist regarding the average soil loss rates and runoff coefficients as well as the effects of different management approaches and the influence of triggering factors on soil erosion rates. So far, an effort to quantify this effect on Mediterranean olive cultivation has not been made comprehensively. Therefore, the aim of this literature review is to discern clearer patterns and trends that are often obscured by the overall heterogeneity of the available data. By systematically analysing the data according to measurement methodology, this review provides clear answers to these knowledge gaps and reveals a consistent narrative about the primary drivers of soil loss. While natural factors like topography, rainfall intensity and soil properties establish a baseline risk, this review shows that agricultural management, particularly the presence of groundcovers, is the pivotal factor controlling soil degradation. The long-standing debate on erosion severity is largely reconciled by the finding that reported rates are highly dependent on the measurement methodology, and hence on the spatial and temporal scale. Conservation practices consistently reduce soil loss by more than half, an effect far more pronounced for sediment control than for runoff reduction. Ultimately, the path to sustainability requires a shift away from conventional tillage and bare-soil management towards the widespread adoption of vegetation/groundcover, driven by effective policies and a commitment to multi-scale and multi-proxy research to improve predictive models.

1. Introduction

Soil erosion is widely recognized as one of the most significant forms of soil degradation worldwide. The Mediterranean region is particularly vulnerable due to a confluence of natural and anthropogenic factors. Natural drivers such as sparse vegetation cover, low soil structural stability, steep slopes, and intense rainstorms are compounded by human activities including land cover change, forest fires, intensive grazing, and soil tillage practices, all of which exacerbate erosion risks.

Among Mediterranean agricultural systems, olive groves (*Olea europaea*) stand out both economically and culturally, with more than 95% of global olive production concentrated in the Mediterranean basin. However, these groves are frequently situated on marginal, low-fertility, and steeply sloping land, where soil erosion constitutes a major threat to their long-term sustainability (Gómez et al., 2009b; Vanwalleghem et al., 2010). It is essential to recognize that the primary driver of this degradation is not the olive tree itself or the local conditions, but the conventional soil management practices associated with its cultivation. Both traditional and modern olive farming has been characterized by the systematic removal of competing vegetation through frequent mechanical tillage (Figure 1), which degrades soil structure and leaves the ground surface bare and vulnerable (Álvarez et al., 2007; Gómez et al., 2004). This practice is deeply rooted in a cultural identity where a "clean" tilled, weed-free field is perceived as signs of diligent farming, while the presence of groundcover is seen as neglect (Rodrigo-Comino et al., 2020; Sastre et al., 2017). When this practice of maintaining bare soil is combined with the common siting of olive groves on steep, erodible slopes, the conditions for severe soil erosion are perfected.

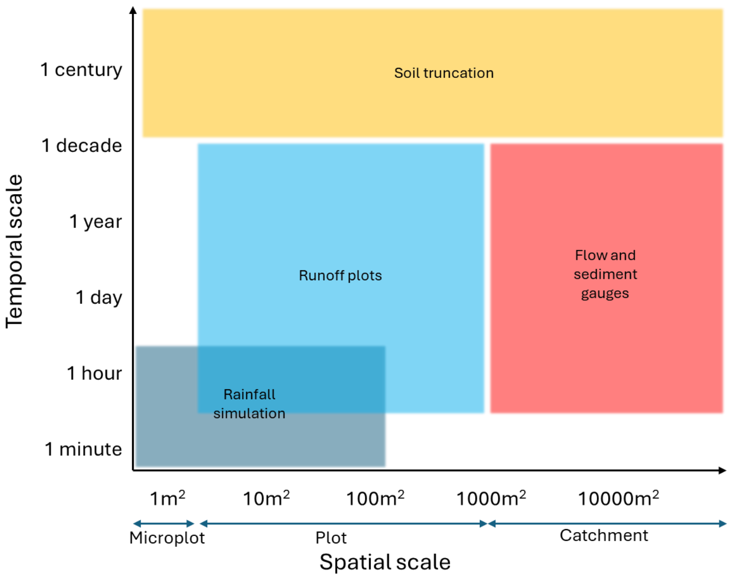
https://doi.org/10.5194/egusphere-2025-3542
Preprint. Discussion started: 18 August 2025

Figure 1 Image of an olive orchard under conventional tillage bare-soil management (systematic removal of competing vegetation through frequent mechanical tillage) on steep slopes in Montefrío (Granada). (photo by A. Peñuela)

Accurate, evidence-based knowledge of erosion rates is essential for defining effective soil conservation policies. However, the scientific literature on soil erosion in olive groves is marked by significant debate and seemingly contradictory findings. A frequently cited soil loss estimate of 80 t ha^{-1}yr^{-1} for south Spain groves is based on USLE model estimates (López-Cuervo, 1990). This very high soil loss rate estimate are supported by long-term estimates based on tree mound measurements in Jordan, 132 t ha^{-1}yr^{-1} (Kraushaar et al., 2014), and in South Spain, 184 t ha^{-1}yr^{-1} (Vanwalleghem et al., 2010) and on fallout radionuclides in Spain, 75 t ha−1 y−1 (García-Gamero et al., 2024) and runoff plot studies in Greece, 56 t ha^{-1}yr^{-1} (Koulouri and Giourga, 2007) and in Spain 60 t ha^{-1}yr^{-1} (Gómez et al., 2017). These figures paint an alarming picture of an agroecosystem in crisis. In contrast, (Fleskens and Stroosnijder, 2007) argue that average rates rarely exceed 10 t ha^{-1} yr^{-1}. In response, (Gómez et al., 2008) criticized Fleskens and Stroosnijder's (2007) incomplete interpretation and conclusions drawn from short-term plot-scale experiments. In any case, erosion rates far exceed natural soil formation rates, depleting this vital resource (Huber et al., 2008)

Understanding soil erosion in olive groves is complicated by the wide array of methods used for its quantification, each with inherent strengths, limitations, and, most critically, different spatial and temporal scales of operation (Figure 2). These methods can be broadly classified into field measurements and predictive models. Field measurements provide direct empirical data but vary significantly in what they measure. A crucial distinction must be made between methods that estimate gross soil loss, i.e. the total amount of soil detached and transported from a specific area, and those that estimate net soil loss, which accounts for both erosion and deposition within a larger landscape unit. Additionally, some methods focus on sediment yield, which quantifies the amount of eroded soil that actually exits the catchment or watershed, typically measured at the outlet. Field measurements can be divided into runoff simulations (Palese et al., 2015; Repullo-Ruibérriz De Torres et al., 2018), runoff plots (Espejo-Pérez et al., 2013), soil truncation studies using soil loss estimates derived from fallout radionuclides (FRN) (Gdiri et al., 2024; Mabit et al., 2012) and tree mound measurements (Kraushaar et al., 2014; Vanwalleghem et al., 2010), and sediment yield measurements at the catchment outlet (Gómez et al., 2014; Taguas et al., 2013). Small-scale studies, such as rainfall simulation and runoff plots, tend to miss key large-scale erosion processes such as rill and gully formation, tillage erosion, and sedimentation within fields. Long-term historical methods, such as tree mound measurements and fallout radionuclide-based estimates, can capture cumulative effects, such as the long-term effects of land use change or soil conservation practices, but are inadequate for capturing the temporal variability and episodic high-intensity events typical of Mediterranean climates. No single method provides a complete picture; rather, each offers unique insights depending on the scale and timeframe of analysis (Table 1).

https://doi.org/10.5194/egusphere-2025-3542
Preprint. Discussion started: 18 August 2025



85 *Figure 2 Spatial and temporal scale of application for different land measurements methods applied in the literature to estimate soil loss rates and runoff coefficients in olive grov*

https://doi.org/10.5194/egusphere-2025-3542
Preprint. Discussion started: 18 August 2025

Table 1 Summary of soil erosion measurement/estimation methods

Method	**Principle / Type of soil erosion measured**	**Typical Scale (Spatial & Temporal)**	**Strengths**	**Key Limitations**
Rainfall Simulations	Delimited plots under artificial rainfall; collect and measure runoff & sediment / Gross soil loss	Microplot (< 2 m²) / Seconds to Minutes	Controlled environment; useful for comparing management practices and quantify their effectiveness	Unrealistic absolute erosion rates; border effects; not representative of natural processes; does not capture deposition and rill erosion processes
Runoff Plots	Delimited plots under natural rainfall; collect & measure runoff & sediment / Gross soil loss	Microplot to Field (< 1000 m²) / Months to Years	Useful for comparing management practices and quantify their effectiveness	Limited in space and time; border effects; difficult to extrapolate the results; does not capture deposition and rill erosion processes
Soil Truncation	Measure soil profile thinning over time using fallout radionuclides activity in soil cores (FRN) or height of mounds around tree trunks (Tree mounds) / Net soil loss	Catchment (> 1000 m²) / Decades to Centuries	Provides long-term and spatially distributed net soil loss estimates; captures cumulative effect of all erosion processes; useful for model calibration and evaluation	Does not capture temporal variability of soil erosion; does not differentiate between water and tillage erosion
Flow and sediment gauge at the catchment outlet	Measure water discharge and sediment concentration at the outlet of a catchment / Sediment yield	Catchment / Event-based to years	Provides a direct measurement of sediment yield from a catchment; integrates all water erosion processes; useful for model calibration and evaluation	Does not provide information on sediment sources or spatial patterns of erosion and deposition within the catchment; can be expensive and technically demanding, limiting the length of measured data
Modelling	Mathematical simulation of erosion processes using empirical, conceptual, or physically-based models / estimates gross or net soil loss and sediment yield	Plot to global scale / Event to centuries	Integrates multiple processes and factors; supports scenario analysis; suitable for large-scale assessments and planning	Highly dependent on input data quality; simple models only represent part of the erosion processes; complex models require extensive calibration; model outputs may be highly uncertain due to limited field data for model calibration and evaluation

https://doi.org/10.5194/egusphere-2025-3542
Preprint. Discussion started: 18 August 2025

Models can provide with long-term and large-scale predictions and temporal and spatial resolutions that are beyond the reach of field experiments. However, their reliability is strongly tied to input data quality. Improper calibration and evaluation, or application beyond a model's original scope, often lead to misleading results, highlighting the "garbage in, garbage out" principle. For instance, the most widely used model for studying soil erosion is the Revised Universal Soil Loss Equation (RUSLE), however it was designed to be applied at the plot scale and hence, it only estimates gross soil loss. When its application is upscaled to larger areas the accuracy of its predictions can be significantly compromised. Model validation/evaluation is particularly challenging due to scale mismatches and the scarcity of long-term, high-quality data. Moreover, the inconsistency in field measurement results significantly limits the evaluation of models, making it difficult to ascertain if a model behaves as expected or if its outputs align with real-world observations under comparable conditions. Therefore, investing in long-term monitoring and consistent data is not just an academic pursuit but a prerequisite for developing reliable, policy-relevant modelling tools.

This review analyses existing studies on soil erosion in Mediterranean olive groves, grouping them by measurement methodology, and hence in similar spatial and temporal scales. The aim is to discern clearer patterns and trends that are often obscured by the overall heterogeneity of the available data, thereby addressing a significant challenge in the current scientific literature. This will provide general findings to evaluate model performance and assess the effectiveness of current management practices, ultimately contributing to more robust conservation strategies. This systematic approach will also address key research questions, including: What are the typical soil loss rates and runoff ratios in Mediterranean olive groves? What is the influence of factors such as topography, soil, vegetation, and climate on soil loss and runoff generation? What is the impact of soil conservation practices?

2. Methods

2.1. Data collection

A dataset of erosion rates and soil loss measurements was constructed from published literature focusing on Mediterranean olive groves. For each entry, the following variables were collected where available: erosion rate (t $ha^{-1}yr^{-1}$) or soil loss per mm of rain (t $ha^{-1}mm^{-1}$), runoff coefficient (%), spatial location (country), spatial scale (microplot, plot, catchment), measurement method, temporal scale (minutes, hours, event, years, decades), slope gradient (%), soil texture (sand, silt and clay %) and soil organic matter content (%) and soil conservation practices

To ensure comparability, data were categorized. Spatial scale was classified as: microplot (<2 m²), plot (2–1000 m²), and catchment (>1000 m²). Measurement methods were grouped into: (i) rainfall simulation (RS), (ii) runoff plot (RP), (iii) flow and sediment gauge (FG), (iv) soil truncation (ST) such as FRN-based estimates and tree mound measurements, and (v) modelling (MOD). Soil conservation practices were classified as: (i) no-soil conservation practices (No-CP), including conventional tillage and no-tillage with herbicides/bare soil and (ii) soil conservation practices (CP) including cover crops (CC), reduced tillage (RT) and mulching (M) with materials like pruning residues.

2.2. Statistical analyses

Given the large variability in the collected data, statistical analyses were applied to identify the main trends regarding the effects of slope gradient, soil texture, organic matter, rain intensity and vegetation cover on soil loss and runoff. To reduce the uncertainty of comparing data from different methodologies, analyses were applied separately to data derived from distinct measurement methods (e.g., RS vs. RP). Ordinary least square linear (OLS) regression was used to examine the contribution of individual explanatory variables on the response variable. For this purpose, we used the Python library statsmodels (www.statsmodels.org) to fit the model and examine the resulting coefficients (R^2) and their significance (p-values). A higher coefficient (when standardized) means the variable has a greater impact on soil loss. In cases where model assumptions were violated, in particular when residuals are not normally distributed, a log-transform was applied to the dependent variable (soil loss rates or runoff coefficient).

https://doi.org/10.5194/egusphere-2025-3542
Preprint. Discussion started: 18 August 2025

In cases of low R^2 values (<0.5), where variability between studies might obscure the effect or when residuals are not normally distributed a log-transform was applied to check if the R^2 increases and/or the residuals get normally distributed. Multiple linear regression (MLR) models were also used to test the combined ability of several explanatory variables to predict the response variable. The coefficients from the model will indicate the relative influence of each variable. For all analyses, a p-value < 0.05 was considered statistically significant. We also checked for multicollinearity (when independent variables are highly correlated).

3. Results and discussion

3.1. Description of dataset

The literature search revealed that the vast majority of studies are concentrated in Spain, with far fewer in Italy, Greece, Portugal, Jordan and Syria (Table 2). The most frequently employed measurement method in the compiled literature is the runoff plot (RP), and the most common experimental design compares conventional tillage (CT) against various forms of soil conservation practices (CP), particularly groundcovers. This focus in the literature underscores the scientific community's recognition of soil management as a critical variable. The most used model is RUSLE (Renard, 1997), followed by AnnANGPS (Bingner and Theurer, 2001), WaTEM/SEDEM (Van Oost et al., 2000) and SEDD (Ferro and Minacapilli, 1995).

For comparison reasons, soil loss rates in rainfall simulations (RS) are expressed per mm of simulated rainfall. It must be also noted that some runoff plot (RP) studies report soil loss rates at the event scale instead of yearly rates. For this reason, these rainfall simulation and event scale values are only used for relative comparisons, such as assessing soil loss and runoff reduction between No-CP and CP practices and should not be interpreted as representative of average annual soil loss.

https://doi.org/10.5194/egusphere-2025-3542
Preprint. Discussion started: 18 August 2025

Table 2 Average single values or ranges (min-max) reported in the studies of the variables collected from published literature, if available. CT = Conventional tillage, NT = No tillage (with some vegetation cover), NTH = No tillage + Herbicides (no vegetation cover), CC = Cover crops, SV = Spontaneous vegetation, LA = Land abandonment, M = Mulching, O = Organic. No-CP = No-soil conservation (practices with no or very low ground/vegetation cover including CT and NTH); CP = Soil conservation practices (practices with some ground/vegetation cover including CC, NT, SV, M, LA). Empty cells (-) = Not applicable or Not reported. Some studies are included in two Methods because they report results for both categories. Please note that rainfall simulations erosion rates are in t/ha per mm of simulated rain and for Runoff plots in t/ha per year with the exception of event scale results which are in t ha^{-1}. *Sediment yield at the catchment outlet

Method	Reference	Country	Spatial Scale	Temporal Scale	Soil Texture	Slope (%)	No-CP	CP	Erosion Rate (t/ha/mm) [No-CP]	Erosion Rate (t/ha/mm) [CP]	Runoff coefficient (%) [No-CP]	Runoff coefficient (%) [CP]
Rainfall Simulation	*Castro et al. (2006)*	Spain	Plot	Minutes	Sandy clay loam	7	CT	CC	0.001-0.008	0-0.002	0-18	0-18
	Fleskens & Stroosnijder (2007)	Portugal, Italy	Microplot	Minutes	Clay loam	5-39	CT	NT	0.03-0.3	0.03-0.11	32-54	23-49
	Giraldez et al. (2006)	Spain	Microplot, Plot	Minutes	Clay loam	20	NTH, CT	NT	0.06-0.28	0.02-0.04	-	-
	Palèse et al. (2015)	Italy	Microplot	Minutes	Sandy loam	10	CT	SV	-	-	24	8
	Repullo-Ruibérriz et al. (2018)	Spain	Plot	Hours	Loam	20	CT	CC, SV	0.002-0.016	0-0.001	0.04-0.13	0-0.06
	Rodrigo-Comino et al. (2020)	Spain	Microplot	Minutes	Silt loam	3	NTH	M	0.019	0.002	50	38

Method	Reference	Country	Spatial Scale	Temporal Scale	Soil Texture	Slope (%)	No-CP	CP	Erosion Rate (t/ha/y) [No-CP]	Erosion Rate (t/ha/y) [CP]	Runoff coefficient (%) [No-CP]	Runoff coefficient (%) [CP]
Runoff Plots	*Bombino et al. (2021)*	Italy	Plot	Event	Clay loam	20	CT	M	0.05	0.01	62	42
	Bruggeman et al. (2005)	Syria	Plot	Event	Clay loam	35	CT	CC	41.5	5	-	-
	Espejo-Pérez et al. (2013)	Spain	Microplot	Years	Loam	6-22	CT	CC	1.7-9.9	0.3-3.3	5-17	3-12
	Francia Martínez et al. (2006)	Spain	Plot	Years	Sandy loam	30	NTH, CT	NT	5.7-25.6	2.1	3-11	5
	Gómez et al. (2004)	Spain	Plot	Years	Silty clay	13	NTH, CT	CC	4-8.5	1.2	7-22	3
	Gómez et al. (2009a)	Spain	Plot	Years	Sandy loam	11	CT	CC	19.4	0.4	16	6
	Gómez et al. (2009b)	Spain	Plot	Years	Silty clay	13	NTH, CT	CC	2.9-6.9	0.8	3-12	1
	Gómez et al. (2011)	Spain	Plot	Years	Loam	4-11	CT	CC	1.3-19.4	0.09-0.4	11-16	2-6
	Gómez et al. (2017)	Spain	Plot	Years	Loam	11-30	CT	CC	0.9-60	0.7-46.7	0.1-0.4	0.1-0.4
	Kairis et al. (2013)	Greece	Plot	Years	Clay loam	17	NTH, CT	NT	0.11-0.26	0.03	2-5	0.8
	Kormas et al. (1997)	Greece	Plot	Years	Sandy loam	20	NTH	NTH	-	0-0.03	-	0-0.02
	Koulourl & Giourga (2007)	Greece	Plot	Years	Clay	25-40	-	LA	-	12-56	-	-
	López-Vicente et al. (2021)	Spain	Plot	Event	Loam	14	CT	CC	1.72	0.77	-	0.01
	Marquez-Garcia et al. (2024)	Spain	Microplot	Years	Loam, Clay	16-43	CT	CC	1.3-8.2	0.2-1.4	4-16	3-8
	Ordóñez-Fernández et al. (2007)	Spain	Microplot	Years	Loam	-	CT	CC	0.8-1.8	0.2-0.4	-	-
	Raglione et al. (1999)	Italy	Plot	Event	Clay loam	-	CT	CC	41	0.36	-	-
	Sastre et al. (2017)	Spain	Microplot	Years	Sandy loam	11	CT	CC	6.8	1.4-4	-	-
	Zuazo et al. (2009)	Spain	Plot	Years	Sandy loam	30	NTH	NTH	17.3	6.05	0.37	0.02
	Zuazo et al. (2020)	Spain	Plot	Years	Loam	20	CT, O, NT	NTH	3.25	0.7-2.1	6	2-4

https://doi.org/10.5194/egusphere-2025-3542
Preprint. Discussion started: 18 August 2025

Method	Sub-method	Reference	Country	Spatial Scale	Temporal Scale	Soil Texture	Slope (%)	No-CP	CP	Erosion Rate (t/ha/y) [No-CP]	Erosion Rate (t/ha/y) [CP]	Runoff coefficient (%) [No-CP]	Runoff coefficient (%) [CP]
Soil truncation	FRN	*Cuesta & Delgado (1997)*	Spain	Points	Decades	-	15	NTH, CT	CC	13-21	12	-	-
		Garcia-Gamero et al. (2024)	Spain	Catchment	Decades	Clay	10	CT	-	43-85	-	-	-
		Gdiri et al. (2024)	Tunisia	Plot	Decades	Clay loam	20	-	-	7	-	-	-
		Mabit et al. (2012)	Spain	Plot	Decades	Clay loam	13	CT	-	12	-	-	-
	Tree mound measurements	*Kraushaar et al. (2014)*	Jordan	Plot	Decades	Clay	6-16	CT	-	72-132	-	-	-
		Lima et al. (2023)	Spain	Plot	Decades	Loam	2-24	CT	-	128	-	-	-
		Vanwalleghem et al. (2010)	Spain	Plot	Decades	Loamy sand, Loam	10-33	CT	-	61-184	-	-	-
		Vanwalleghem et al. (2011)	Spain	Plot	Decades	Clay, Loam	15-38	CT	-	29-47	-	-	-
Flow and Sediment Gauge		*Di Stefano et al. (2016)*	Spain	Microcatchment	Years	Sandy loam	15	-	NT	-	2*	-	9
		Gómez et al. (2014)	Spain	Microcatchment	Years	Clay	9	-	RT	-	16*	-	15
		Taguas et al. (2009)	Spain	Microcatchment	Years	Loamy sand	10	NTH	-	1*	-	2	-
		Taguas et al. (2010)	Spain	Microcatchment	Years	Sandy loam	15	-	NT	-	1*	-	3
		Taguas et al. (2013)	Spain	Microcatchment	Years	Sandy loam	15	-	NT	-	2*	-	5
Modelling	RUSLE	*Álvarez et al. (2007)*	Spain	Plot	Years	Sandy loam	44-46	CT	-	33-38	-	-	-
		Gómez et al. (2003)	Spain	Plot	Years	Sandy loam	3-20	NTH, CT	CC	11-83	2-48	-	-
		Parras-Alcantara et al. 2016	Spain	Plot	Years	Silty clay	5	CT	M	7	1	-	-
		Rodríguez Sousa et al. (2023)	Portugal	Plot	Years	Sandy loam	12-23	NTH, CT	O, NT, LA	109-139	24-36	-	-
		Vanwalleghem et al. (2011)	Spain	Plot	Decades	Clay, Clay loam	15-38	CT	-	8-124	-	-	-
	AnnAGNPS	*Taguas et al. (2009)*	Spain	Microcatchment	Years	Sandy loam	10	NTH	-	1*	-	3	-
		Taguas et al. (2012)	Spain	Microcatchment	Years	Sandy loam	15	CT	SV	2-4*	3-4*	10	3
	WaTEM/SEDEM	*Garcia-Gamero et al. (2024)*	Spain	Microcatchment	Years	Clay	10	-	RT	-	19	-	-
	SEDD	*Taguas et al. (2011)*	Spain	Microcatchment	Years	Sandy loam	15	NTH	-	32; 1*	-	-	-

https://doi.org/10.5194/egusphere-2025-3542
Preprint. Discussion started: 18 August 2025

3.2. Average soil loss rates and runoff coefficients

In Table 3 average erosion rates and runoff coefficients are grouped by method and type of soil loss measured. This table highlights the wide range of values obtained by different approaches, reflecting differences in measurement scale, time period, and the distinction between gross, net soil loss and sediment yield.

The average annual soil loss rates vary by more than an order of magnitude, from as low as 1.8 t $ha^{-1}yr^{-1}$ to as high as 72.3 t $ha^{-1}yr^{-1}$. This is not a contradiction but a reflection of what each method measures. RP measure gross erosion (soil detachment and transport) from a small, defined area. It primarily captures interrill and some rill erosion. The average rate of 5.51 t $ha^{-1}yr^{-1}$ is in line with Fleskens and Stroosnijder's (2007) who argue that soil loss in olive groves is generally below 10 t $ha^{-1}yr^{-1}$. However, the large standard deviation (±11.1) highlights the extreme variability based on site-specific conditions like slope, soil type, and rainfall patterns. Notably, average soil loss without conservation practices (No-CP) is 7.51 t $ha^{-1}yr^{-1}$, but this value is reduced by about half when CP are implemented. In any case, these values are unsustainable and well above the tolerable soil loss rate, 0.3-1.4 t $ha^{-1}yr^{-1}$, in Europe (Verheijen et al., 2009).

In ST studies, the exceptionally high value of 72.3 t $ha^{-1}yr^{-1}$ represents the long-term net soil loss at a specific point on a hillslope, accumulated over decades or even centuries. This figure captures the cumulative impact of all major erosion processes, including both water erosion (interrill and rill) and, critically, tillage erosion, the progressive downslope movement of soil caused by repeated plowing. Such a high rate reflects the total historical degradation of the soil profile at that location, which explains why "alarming" values can appear in the literature. Importantly, this underscores the need to distinguish between gross and net soil loss, as well as to account for the substantial role of tillage erosion—often underestimated or overlooked in soil erosion research—even though it can surpass the effects of water erosion in many cultivated landscapes (Van Oost et al., 2006).

In FG, the relatively low value, 3.2 t $ha^{-1}yr^{-1}$, measures sediment yield, the actual amount of eroded soil that exits an entire catchment. The vast difference between the average soil truncation rate (72 t $ha^{-1}yr^{-1}$ of net soil loss) and the sediment yield (3.2 t $ha^{-1}yr^{-1}$) indicates that while a massive amount of soil is being moved around within the olive grove landscape, much of it is redeposited at the bottom of slopes or in other landscape depressions and never reaches the stream network. This phenomenon is particularly pronounced in Mediterranean catchments due to the prevalence of ephemeral stream networks that consist primarily of gullies and dry channels, which only become hydrologically connected during high-intensity rainfall events (Gómez et al., 2014; McLeod et al., 2024; Taguas et al., 2009).

In MOD studies, gross soil loss (RUSLE) estimates of nearly 35 t $ha^{-1}yr^{-1}$ (47.7 t $ha^{-1}yr^{-1}$ with No-CP and 21.1 t $ha^{-1}yr^{-1}$ with CP) align more closely with the high rates of landscape degradation suggested by soil truncation methods (e.g. (Vanwalleghem et al., 2011) rather than rates reported by runoff plots. The higher RUSLE value often stems from the model's application at broader scales with input parameters that may not perfectly reflect the conditions of a specific plot. For instance, topographic factors derived from digital elevation models can overestimate slope length and steepness, and the model's management factors (C and P) are notoriously difficult to calibrate accurately without site-specific data, often leading to an overestimation of erosion potential (Gómez et al., 2003). Indeed, some studies have explicitly found that theoretical models like USLE overestimate erosion rates when compared to direct empirical measurements in olive groves(Rodríguez Sousa et al., 2023). This gap between modelled potential and measured reality underscores a critical need for robust model calibration and validation using high-quality, long-term field data to improve predictive accuracy.

It is crucial to interpret the average values presented in Table 3 with caution, especially for those derived from ST, FG, and MOD studies. The body of literature reporting quantitative erosion and runoff rates using these specific methods in Mediterranean olive groves is still quite limited. Consequently, the averages are calculated from a small number of studies and data points. This scarcity means the mean values can be heavily skewed by single, site-specific results and may not fully represent the broader reality. Therefore, these figures should be seen as a preliminary snapshot, highlighting the need for more research to establish more robust and representative average rates.

https://doi.org/10.5194/egusphere-2025-3542
Preprint. Discussion started: 18 August 2025

Table 3 Average erosion rates and runoff coefficients for Mediterranean olive groves, as reported in the literature. Values are grouped by method and type of soil loss measured. Standard deviations are shown in parentheses. Empty cells (-) = Not Applicable or Not Reported.

Method	**Type of soil loss measured**	**Erosion Rate** (t ha^{-1}yr^{-1})	**Runoff coefficient (%)**
Runoff Plots (RP)	Gross soil loss	5.51 (± 11.1)	5.91 (± 4.8)
Soil truncation (ST)	Net soil loss	72.3 (± 45.7)	-
Flow and sediment gauge (FG)	Sediment yield	3.2 (± 0.9)	6.4 (± 3.1)
Modelling (MOD)	Gross soil loss	34.92 (± 33.8)	-
	Net soil loss	25.7 (± 9.5)	-
	Sediment yield	1.79 (± 1.1)	5.3 (± 4.0)

The considerable variation in average soil loss rates reported across the different measurement methods reflects not only the diversity of processes captured but also the methodological limitations inherent to each approach. RP artificial setup, bounded plots with restricted flow interactions, can lead to underestimation of actual runoff, since the contributing upslope or lateral flows are excluded. Moreover, the relatively short monitoring durations of many RP studies may miss rare but significant erosive events or overemphasize the conditions during a limited period. Despite these limitations, the wide use of RP in the literature provides a relatively robust, though still partial, representation of gross soil loss under plot-scale conditions.

ST estimates are associated with high uncertainty due to several critical assumptions. FRN reliable application depends on identifying a truly undisturbed reference site, often a challenge in Mediterranean landscapes (García-Gamero et al., 2024). Similarly, for tree mound methods, estimating the original soil surface (e.g., the germination point) and tree age involves potentially uncertain assumptions. Moreover, a reduction in soil depth by soil compaction can misinterpreted as erosion. FG offer no insight into the specific sources of sediment: the measured material may originate from olive groves, but also from unrelated sources such as gully erosion, bank collapse, or landslides. Additionally, the small number and limited duration of FG studies heighten uncertainty, especially in Mediterranean landscapes with highly variable rainfall regimes.

MOD results are contingent on the quality and resolution of input data and the rigor of calibration/validation procedures. Given the limited availability of empirical data specific to olive systems, many models rely on generalized or regionally interpolated parameters that may not adequately reflect site-specific conditions. Moreover, the use of average weather data can obscure the impact of extreme events, which play a crucial role in Mediterranean erosion dynamics. As such, model results should be interpreted as approximate, order-of-magnitude estimates rather than precise measurements.

Runoff coefficients are fairly similar (~5–6%) across the various methods. This suggests that the fraction of rainfall becoming surface runoff is moderately low in Mediterranean olive groves, consistent with soil infiltration capacity and episodic storms. It also implies that differences in erosion rates are not due to differences in runoff volume, but rather in how much soil is detached per unit runoff (influenced by cover, tillage, slope, etc.). In practice, extreme storm events can drive much higher instantaneous runoff and erosion than these average coefficients indicate.

This data also highlights the profound effectiveness of conservation practices (CP). In terms of how effective CP are in reducing soil loss and runoff generation, RS show the highest reduction rates, 89% for soil loss and 66% for runoff. These controlled, small-scale experiments are able to isolate the direct protective effect of a ground cover against raindrop impact (splash erosion), which is the first stage of erosion. The nearly 90% reduction in soil loss underscores the immense potential of CP to shield the soil surface. RP, which measure erosion under natural rainfall over longer periods, show a still massive, but slightly lower, reduction: 68% for soil loss and 34% for runoff. This reflects real-world conditions where factors like variable rainfall and larger-scale water flow come into play. A key insight is that CP is

https://doi.org/10.5194/egusphere-2025-3542
Preprint. Discussion started: 18 August 2025

significantly more effective at reducing soil loss than it is at reducing runoff volume. This indicates that the primary benefit of ground cover is preventing soil particles from being detached and carried away. While it also improves infiltration (reducing runoff), its main role is to protect the soil and slow the water flow, drastically reducing the water's capacity to transport sediment. The vegetation shields the soil and slows the water, drastically diminishing its capacity to transport sediment.

3.3. Statistical analysis of erosion drivers

The analysis of factors influencing soil loss and runoff generation was restricted to the RS and RP treatments. For the other treatments (ST, FG, and MOD), the available data was insufficient to perform a robust statistical analysis. This limitation arises from both the small number of published studies and the low total number of observations, even accounting for the fact that a single study can report multiple observations from different locations or experiments.

Table 4 Summary of Ordinary Least Squares (OLS) and Multiple OLS regression results showing the influence of different factors on soil loss rate and runoff coefficient. The table presents the coefficient of determination (R^2) for models based on data from Rainfall Simulation (RS) and Runoff Plot (RP) studies. 'ns' denotes a non-significant result. The number of observations (obs) is given in parentheses. An asterisk (*) indicates a that log-transformation was applied to the dependent variables (soil loss rate or runoff coefficient) to ensure normally distributed residuals. Empty cells (-) = Not Applicable or Not Reported.

	Rainfall simulation (RS)		**Runoff plots (RP)**	
OLS regression	**Soil loss rate**	**Runoff coefficient**	**Soil loss rate**	**Runoff coefficient**
Slope	0,17* (36 obs)	ns	ns	ns
Vegetation cover	0,42* (29 obs)	ns	0,73* (30 obs)	0,55 (20 obs)
Rain intensity	0,5* (36 obs)	0,52 (33 obs)	-	-
Multiple OLS regression				
Slope + Veg. cover	0,65* (29 obs)	0,41 (32 obs)	ns	ns
Rain intensity + Veg. cover	0,75* (29 obs)	0,62 (33 obs)	-	-
Clay + OC	0.54* (22 obs)	0.81* (25 obs)	ns	ns

3.3.1. Slope

The only statistically significant correlation (p-value<0.05) was observed in RS and only with the soil loss rate (per mm of rain). The OLS regression analysis confirmed a low positive relationship between erosion rate and slope gradient. The model took into account for 30% of the total variance (R^2=0.30 with 36 observations). However, several diagnostic tests (Omnibus, Jarque-Bera, Skew) indicated that the assumptions of the OLS model have been violated, specifically the assumption of normally distributed errors. Therefore, a log-transform of the soil loss variable (dependent variable) was applied. The log transformation successfully addressed the violation of the normality assumption. However, the model's explanatory power decreased, explaining only 16.7% of the variance in the log of soil loss. Despite this, the relationship between slope and soil loss remained statistically significant.

Olive groves are often on steep slopes, which inherently increases the risk and rate of erosion. On very steep slopes, the gradient can be the dominant factor, overriding management effects. However, these findings do not indicate this strong influence, at least by considering the slope alone. By combining slope with vegetation cover, the model's predictive power dramatically improved. The new MLR model explained 75.3% for RS of the variation in soil loss. After a log-transform to address non-normal residuals, the model explained 65% (RS) of the variance in the log of soil loss. Both slope and vegetation cover were highly significant predictors.

This strong influence of the combined effect of slope and vegetation cover highlights their synergistic control on soil loss. The initial model, which only considered slope, was statistically weak because it omitted the crucial protective role of vegetation. Vegetation intercepts rainfall, reducing its erosive energy, and increases infiltration, which reduces the volume of runoff. By increasing surface roughness, it also reduces the velocity and shear stress of the runoff that does occur. The result is that for the same slope and storm, the erosive force is drastically lower on a vegetated plot compared to a bare one. This explains why a simple model considering only slope is insufficient; the effect of slope is contingent on the condition of the surface. While this interaction indicates a statistical synergy, the strong correlation is likely driven heavily by the influence of vegetation cover.

3.3.2. Vegetation cover

In the rainfall simulation (RS) studies, vegetation cover on its own explained 42% of the variance in the log of soil loss (R^2=0.42 after log-transform; 29 observations). This moderate negative but significant relationship highlights the immediate, local effects of vegetation. At this scale, the primary mechanism is the reduction of raindrop impact energy by the plant canopy, which minimizes the detachment of soil particles (splash erosion), a foundational step in the erosion process (Panagos et al., 2015). Interestingly, vegetation cover showed no statistically significant influence on the runoff coefficient in these experiments. This is likely due to the nature of rainfall simulators, which apply high-intensity rainfall over a small area for a short duration. These conditions can quickly saturate the topsoil, causing infiltration capacity to be exceeded regardless of cover, thus generating similar runoff volumes across different plots.

The results from runoff plot (RP) studies are even more compelling. Here, vegetation cover alone accounted for a remarkable 73% of the variance in the log of soil loss (R^2=0.73 after log-transform; 30 observations; Figure 3a). This demonstrates that over larger areas and under natural rainfall conditions, the cumulative effects of vegetation become much more pronounced. Furthermore, at this scale, vegetation cover also explained 55% of the variance in the runoff coefficient (R^2=0.55; 20 observations; Figure 3b). This contrasts sharply with the RS results and shows that vegetation cover is effective at reducing the total volume of runoff. This is because, over time, groundcover and its associated root systems improve soil structure, enhance aggregation, and increase macroporosity, all of which significantly boost the soil's overall infiltration capacity (Keesstra et al., 2018; Gómez et al., 2009). More water entering the soil profile directly translates to less water available to generate surface runoff. The need for a log-transformation for the annual soil loss model indicates a right-skewed distribution which is in line with previous studies that suggest that there is a critical threshold of vegetation cover (Liu et al., 2020; Sastre et al., 2017; Zhang et al., 2022). Below a certain percentage of cover, the soil is highly vulnerable. Above this threshold, erosion rates can decrease dramatically. The RP data indicates that this threshold is 30-40%, below which the soil loss rate is above the tolerable rate in Europe, 1.4 t $ha^{-1}yr^{-1}$ (Verheijen et al., 2009).

https://doi.org/10.5194/egusphere-2025-3542
Preprint. Discussion started: 18 August 2025

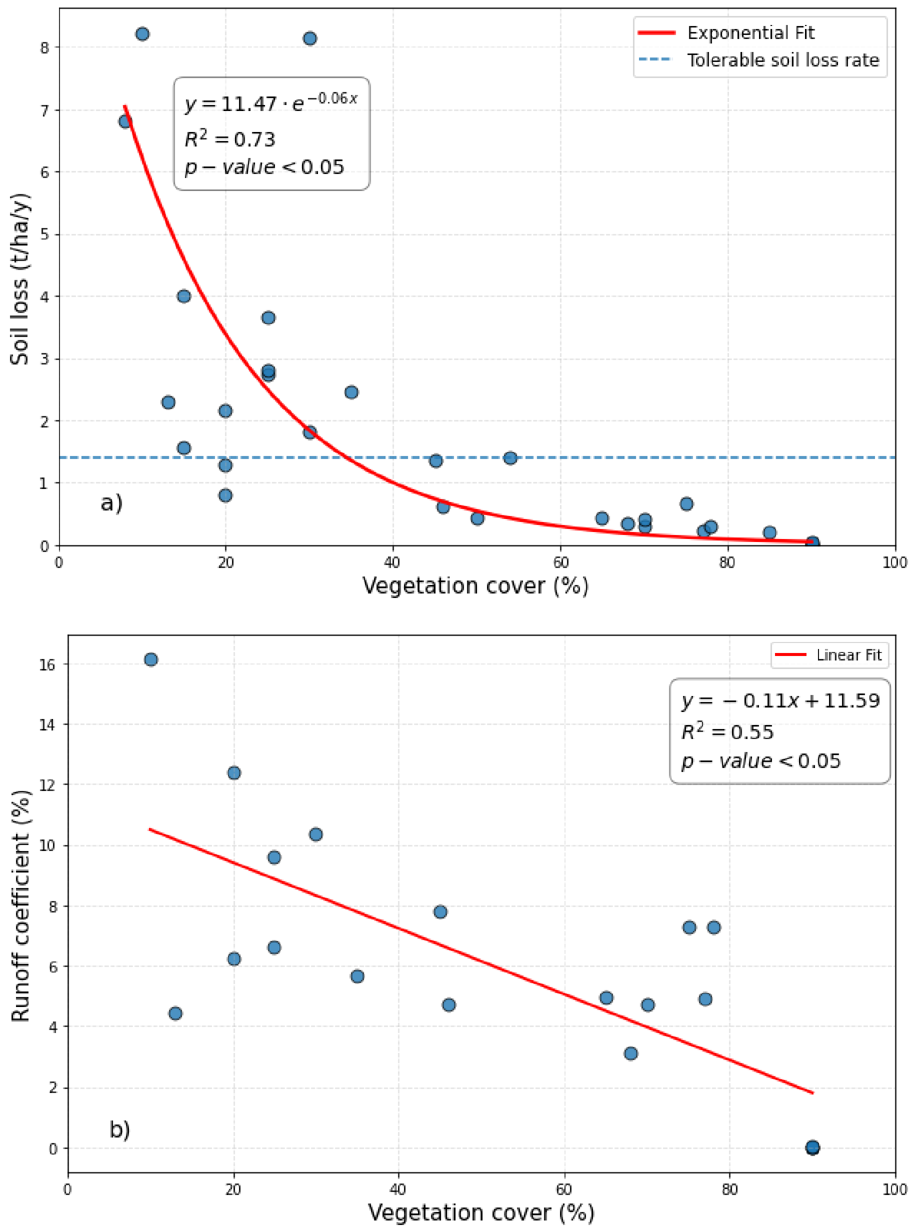


Figure 3 Runoff plot studies - Relationship between vegetation cover and: a) soil loss rate and b) runoff coefficient. Each point represents a single plot measurement. The red line represents the best fit line. The dashed line represents the tolerable soil loss rate in Europe (Verheijen et al., 2009)

Analysing vegetation cover as a standalone variable confirms its decisive role in controlling soil erosion. Combining vegetation cover with other factors improved the model's predictive power, particularly with slope gradient in RP (see section 3.3.1) and rain intensity in RS. For RS, the MLR model explained 75% of the variance in the log of soil loss per mm of rain (R^2=0.75 after log-transform; 29 observations) and 62% of the variance in the runoff coefficient (R^2=0.62; 29 observations). These results demonstrate that the published data represent the fundamental conflict between the erosive force of rainfall and the protective

https://doi.org/10.5194/egusphere-2025-3542
Preprint. Discussion started: 18 August 2025

resistance of vegetation. While high-intensity simulations can mask the influence of vegetation on runoff when viewed in isolation, combining it with the intensity variable reveals its persistent and significant role in mitigating both the volume of runoff and, most critically, the detachment and transport of soil particles. This highlights the necessity of a multi-factor approach to accurately model hydrological and erosional responses under the specific conditions of rainfall simulation. Moreover, these results also demonstrate the resilience and protective effect of vegetation cover even under extreme high-intensity conditions of RS.

Studies show that soil erosion (total sediment yield) is reduced much more effectively by plant covers than is runoff volume (Carceles Rodriguez et al., 2021). This disparity means the sediment concentration in runoff is significantly lower under conservation practices, even if runoff volume is not completely eliminated. The physical protection offered by the cover crops is a primary mechanism for reducing sediment detachment, while infiltration/runoff processes are more complex and site-dependent.

3.3.3. Rainfall intensity

The rainfall intensity is factor only considered in RS, this factor can be controlled, and it is usually kept constant during the rainfall simulations. In contrast, in RP the rainfall is natural and hence, highly variable during the period of study. The regression analysis confirmed a positive relationship (R^2=0.36 with 36 observations) between erosion rate and rain intensity of the rainfall simulations. However, the diagnostic tests indicated that the assumption of normally distributed errors is not correct. Applying a log transformation created a more accurate and statistically valid model. The conclusion remains the same, that higher rainfall intensity leads to more soil loss, but now nearly 50% of the variability in the log of soil loss per mm of rain can now be explained by rainfall intensity.

The statistical result is a direct reflection of the kinetic energy of rainfall. Higher intensity rainfall has significantly more kinetic energy, which dislodges a greater volume of soil particles, a process known as splash erosion. Moreover, more intense rain generates runoff more quickly and in greater volumes. A study by van Dijk et al. (2002) reviewed various rainfall erosivity models and confirmed that kinetic energy and rainfall intensity are the most effective predictors of splash detachment and interrill soil erosion. They highlighted that the relationship is often non-linear, which aligns with why a log transformation improved the statistical model in this analysis.

As shown above (see section 3.3.2.), by combining rain intensity with vegetation cover the model's predictive power showed the best results.

3.3.4. Soil texture and OC

For both, RS and RP the soil texture factors (sand (%), silt (%), clay (%)) and OC (%) did not show statistically significant results in the regression analysis. However, for RS when these factors were combined in a MLR model the results drastically improved. The best results were obtained when combining clay and OC. The model was then highly significant and explained 53.9% (R^2=0.54 after log-transform with 25 observations) of the variance in the log of soil loss (per mm of rain) and 80.8% (R^2=0.81 after log-transform with 25 observations) of the variance in the runoff coefficient. The results indicate that increased 'clay' content is associated with a percentage *increase* in soil loss and runoff (positive relationship), while increased 'OC' is associated with a percentage *decrease* in soil loss and runoff (negative relationship).

Soil texture influences properties like saturated hydraulic conductivity (Ksat) and compaction potential (Bombino et al., 2021). Clayey soils low in organic matter, often found in Mediterranean olive groves, can saturate quickly and have low Ksat, making them prone to runoff, especially on steep slopes. Bare soil conditions and conventional tillage can exacerbate these issues by degrading soil structure, leading to increased compaction and surface sealing, which reduces infiltration in soils regardless of texture, but particularly impacting clayey soils (Gomez et al., 2009b; Palese et al., 2015).

This shows that soil composition has a significant impact on soil loss: higher clay content increases erosion and runoff, while higher organic carbon content dramatically reduces them. Mediterranean olive soils often have low OC, so improving organic matter significantly lower erosion. Again, an increase in vegetation cover (e.g. through cover crops) can initiate a positive feedback loop by directly increasing the soil's organic

https://doi.org/10.5194/egusphere-2025-3542
Preprint. Discussion started: 18 August 2025

carbon content. Therefore, promoting vegetation cover is not just a surface-level protection strategy; it is a fundamental method for rebuilding the soil's intrinsic health and resilience from within.

3.4. Final thoughts and future challenges

Soil erosion is an inherently scale-dependent process, and no single method or metric can capture its full complexity. The ongoing debate between "alarmist" and "non-alarmist" interpretations (Fleskens and Stroosnijder, 2007; Gómez et al., 2008) of erosion severity is, at its core, a debate about the scale of truth. Different measurement methods target different parts (Figure 4) of the erosion–transport–deposition continuum, leading to seemingly conflicting figures that are, in fact, complementary. To develop a realistic and comprehensive understanding of soil erosion, particularly in agricultural landscapes, it is essential to adopt a multi-method, multi-scale approach. Each method provides a partial view, thus reveals a different "truth", emphasizing different spatial and temporal aspects of erosion dynamics:

- Runoff plots measure what's being mobilized. Runoff plot studies are ideal for capturing gross soil loss in upslope areas where contributing areas are small and deposition minimal (Francia Martínez et al., 2006; Gómez et al., 2004). These plots are valuable for comparing land management practices and assessing soil susceptibility to detachment. However, they only represent the initial phase of the erosion process and typically underestimate the cumulative effects of long-term processes like tillage erosion or gully expansion.
- Soil truncation methods measure what's lost or displaced over time. They provide spatially distributed, long-term estimates of net soil loss across entire hillslopes or catchments (Kraushaar et al., 2014; Vanwalleghem et al., 2011). These techniques capture both water and tillage erosion and are particularly suited for detecting cumulative soil displacement over decades. While they may miss short-term events like extreme gully formation, they offer a more realistic picture of landscape-scale degradation and on-site impacts.
- Sediment and flow gauges at the catchment outlet measure what's exported, the final output of the erosion system and final stage of the erosion cascade (Taguas et al., 2013). These data integrate all upstream erosion processes but often register lower values than total soil loss because much of the mobilized sediment is trapped within the landscape, stored in footslopes, depressions, gully systems, and floodplains, before it can exit the catchment. This scenario, however, changes dramatically during high-intensity rainfall events (Gómez et al., 2014), which can connect the drainage network and trigger severe gully erosion, leading to major sediment export. Sediment yield is critical for evaluating off-

https://doi.org/10.5194/egusphere-2025-3542
Preprint. Discussion started: 18 August 2025

site impacts, such as reservoir siltation or pollutant transport, but it does not reflect the full extent of on-site soil degradation.

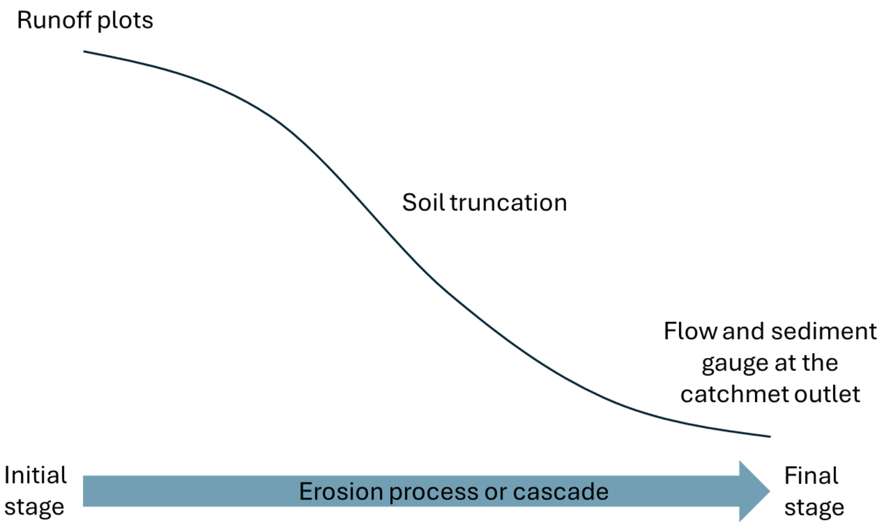


Figure 4 Conceptualization of a typical catchment hillslope and what parts and stages are characterized by the different soil erosion measurement methods.

Models, when properly calibrated, can bridge these scales and are useful for scenario analysis, but they must be interpreted with care, as they often blend assumptions from multiple processes. The apparent contradiction between moderate and high erosion figures dissolves when viewed through this lens. The "alarmist" estimates often stem from soil truncation methods that highlight the severe and unsustainable cumulative impacts of erosion, including tillage translocation and gully expansion. These high values may not apply uniformly across every square meter each year but do reflect the net outcome of persistent erosional forces acting over time.

Ultimately, embracing a multi-scale, integrated approach is not just a methodological choice, it's a necessity. It allows us to capture both the localized detachment and the landscape-level sediment delivery and is critical for the design of effective soil conservation strategies and for the calibration and validation of erosion models. For example, in areas close to the catchment limit, where deposition and the upslope contributing area are minimal, we can consider combining runoff plot estimates (representing gross soil loss due to water erosion) with soil truncation estimates (representing net soil loss due to both water and tillage erosion). The difference between the net soil loss (derived from soil truncation methods) and the gross soil loss (derived from runoff plots) in the same location could provide an inference of the tillage erosion contribution. This is because soil truncation methods inherently capture the cumulative effects of both water and tillage erosion over longer timescales, while runoff plots primarily isolate the detachment and transport by water. Therefore, the equation could be conceptually represented as:

Tillage Erosion Contribution ≈ Net Soil Loss (Soil Truncation) - Gross Soil Loss (Runoff Plots)

This would help to disentangle the significant, yet often overlooked, role of tillage in overall soil displacement within agricultural landscapes as well as to calibrate and evaluate tillage erosion models. Only by acknowledging the complexity and scale-dependency of soil erosion can we resolve inconsistencies in the literature and move toward more sustainable land management.

Yet, this scientific understanding uncovers a critical paradox in olive cultivation, a "silent crisis" where olive yields have increased (mainly driven by the mechanization of cultivation and the increase of tree density) despite alarming rates of long-term soil loss and ongoing degradation. The ability of deep soils to buffer initial losses, combined with management practices such as enhanced fertilization, pruning, and pest

https://doi.org/10.5194/egusphere-2025-3542
Preprint. Discussion started: 18 August 2025

control, has effectively masked the unsustainability of current practices (Tubeileh et al., 2014). This absence of a negative impact on yield has meant there's been no immediate or direct incentive for farmers to adopt soil management practices that prioritize conservation, allowing prolonged unsustainable practices to continue. The current system is drawing down a vital natural capital, soil, without immediate visible consequences, but with severe long-term implications for future generations. This situation urgently calls for a fundamental paradigm shift in how agricultural success is defined and measured, emphasizing long-term ecological resilience alongside productivity. Therefore, policy and farmer education must move beyond short-term yield metrics to incorporate and prioritize long-term soil health indicators such as the Soil Footprint (Garcia-Gamero et al., 2024).

The evidence overwhelmingly supports that increasing vegetation/ground cover between olive trees as the most effective strategy for erosion control in olive groves. Their multifaceted benefits, including significant erosion reduction, enhanced infiltration, increased organic matter content, and improved soil aggregation, simultaneously address several key drivers of degradation (Gómez et al., 2009a, 2009b; Márquez-García et al., 2024; Repullo-Ruibérriz De Torres et al., 2018). Despite the acknowledged challenge of water competition, the magnitude of erosion reduction achieved suggests that the benefits often outweigh the risks, especially with careful species selection and adaptive management (Gómez et al., 2009a). This implies that soil conservation practices such as cover crops are not merely "an option" but represent a fundamental requirement for achieving long-term sustainability in Mediterranean olive groves (Bombino et al., 2021). Therefore, policy incentives and research efforts should prioritize the widespread adoption and optimization of soil conservation strategies, including the development of drought-tolerant cover crops species and adaptive management strategies designed to minimize water competition during critical dry periods.

Further research integrating multi-scale or multi-proxy field monitoring with robust model calibration and validation across a wider range of environmental and management conditions is essential to accurately quantify erosion risks and develop effective and sustainable soil management strategies for Mediterranean olive groves. The path to sustainable olive cultivation lies in a paradigm shift towards evidence-based management strategies. Prioritizing soil conservation strategies, minimizing intensive tillage and maximizing vegetation/ground cover are paramount. These practices not only effectively reduce soil and nutrient loss but also enhance soil health and resilience. However, successful adoption hinges on addressing socio-economic barriers, including perceived water competition, management costs, and traditional biases (Rodrigo-Comino et al., 2020; Sastre et al., 2017).

In this context, policy support becomes a decisive factor in shifting current management paradigms toward more sustainable practices. Conservation Agriculture (CA) (Gonzalez-Sanchez et al., 2015), through its emphasis on permanent groundcovers and no tillage (FAO, 2022), offers a robust framework for mitigating erosion and restoring soil functionality in Mediterranean perennial systems such as olive groves. However, widespread adoption of soil conservation practices would remain limited without adequate training, incentives, regulatory support, and integration into agricultural subsidy frameworks. The successful implementation of CA requires not only technical knowledge but also institutional alignment and policy coherence at local and national levels. Public policies that reward farmers for maintaining soil cover, avoiding tillage, and enhancing soil organic matter, such as through eco-schemes under the Common Agricultural Policy, are essential to overcome inertia and scale up proven practices. In regions where olive cultivation is dominant, promoting CA through targeted programs can serve as a powerful lever to reduce erosion, combat desertification, and strengthen the resilience of rural landscapes.

4. Conclusions

This literature review has synthesized a diverse body of research on soil erosion in Mediterranean olive groves, leading to several key conclusions that clarify the scale of the problem and point toward a sustainable future. These are the main conclusions:

- While natural factors such as topography, rainfall and soil properties establish a baseline risk, the evidence is unequivocal that agricultural management is the pivotal factor controlling soil degradation.

https://doi.org/10.5194/egusphere-2025-3542
Preprint. Discussion started: 18 August 2025

- A central finding is that the magnitude of soil erosion is highly dependent on the measurement methodology, a reality that reconciles much of the debate in the literature.
- Plot-scale studies, which measure gross soil loss, report average rates that are often under 10 t $ha^{-1}yr^{-1}$. However, these figures stand in stark contrast to the extremely high net soil loss rates of 72.3 t $ha^{-1}yr^{-1}$ on average derived from long-term soil truncation studies. This vast difference strongly indicates that plot-scale methods fail to capture the significant contributions of processes like tillage erosion and concentrated flow in rills and ephemeral gullies. Furthermore, the limited duration of runoff plot studies may not reflect the contribution of exceptionally extreme erosion events captured by long-term soil truncation studies. Both gross and net soil loss rates are clearly unsustainable.
- Conversely, sediment yield measured at the catchment outlet is often low, suggesting that under non-extreme rainfall conditions, Mediterranean catchments have low sediment connectivity. This means that while a massive amount of soil is being redistributed within the landscape, much of it is redeposited and does not have immediate off-site impacts.
- There is a critical need for multi-scale and multi-proxy approaches studies, as no single method can capture the full complexity of erosion in agricultural catchments.
- The data consistently show that while steep slopes, intense rainfall, and soil properties (texture and organic carbon content) create the potential for erosion, the presence of vegetation cover is the decisive control. Conservation practices, such as cover crops, reduce soil loss by more than half. This effect is far more pronounced for soil loss than for runoff.
- The data indicates that there is a vegetation cover threshold of 30-40%, below which the soil loss rate is above the tolerable rate in Europe, 1.4 t $ha^{-1}yr^{-1}$ and increases exponentially.
- The average runoff coefficient remaining relatively low and consistent at 5-6% across different measurement methods. This indicates that the primary benefit of ground cover is protecting the soil surface and preventing particle detachment, rather than solely reducing water volume.
- While vegetation cover is the most important *management* factor, the inherent properties of the soil are a primary driver of how it responds to rainfall. A soil with low organic carbon and a texture prone to surface sealing (like degraded clay soils) is at a much higher baseline risk of severe erosion and runoff.
- Finally, this review highlights a significant gap between modelled potential and measured reality. Models like RUSLE simulate considerably higher soil loss rates than those measured in runoff plots. This discrepancy underscores the urgent need for better model calibration and validation using robust, long-term field data to improve the accuracy of our predictive tools.

In summary, the path to sustainability for this iconic agroecosystem is clear. It requires a shift away from conventional bare-soil management towards the widespread adoption of conservation practices that maintain permanent ground cover. The challenge is not a lack of technical solutions but one of implementation, which must be driven by effective policies, farmer incentives, and a continued commitment to integrated, multi-scale research.

Author contributions

AP and FM conducted the data curation, which included the collection, filtering, and processing of reviewed studies, and performed the subsequent statistical analysis. AP was responsible for the study's conceptualization and the primary interpretation of the results. EGS contributed to the manuscript writing and the interpretation of the findings.

Acknowledgments

This publication received funding from the European Union's Horizon Europe Research and Innovation Programme, under the HORIZON-MSCA- 2021-PF-01 grant agreement 101062258 and under the Soil Mission's MONALISA project, Grant Agreement No. 101157867. Disclaimer: Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them

https://doi.org/10.5194/egusphere-2025-3542
Preprint. Discussion started: 18 August 2025

References

Álvarez, S., Soriano, M.A., Landa, B.B., Gómez, J.A., 2007. Soil properties in organic olive groves compared with that in natural areas in a mountainous landscape in southern Spain. Soil Use Manag. 23, 404–416. https://doi.org/10.1111/j.1475-2743.2007.00104.x

Bingner, R., Theurer, F., 2001. AnnAGNPS: estimating sediment yield by particle size for sheet and rill erosion, in: Proceedings of the 7th Interagency Sedimentation Conference.

Bombino, G., Denisi, P., Gómez, J.A., Zema, D.A., 2021. Mulching as best management practice to reduce surface runoff and erosion in steep clayey olive groves. Int. Soil Water Conserv. Res. 9, 26–36. https://doi.org/10.1016/j.iswcr.2020.10.002

Espejo-Pérez, A.J., Rodríguez-Lizana, A., Ordóñez, R., Giráldez, J.V., 2013. Soil Loss and Runoff Reduction in Olive-Tree Dry-Farming with Cover Crops. Soil Sci. Soc. Am. J. 77, 2140–2148. https://doi.org/10.2136/sssaj2013.06.0250

FAO, 2022. Conservation Agriculture.

Ferro, V., Minacapilli, M., 1995. Sediment delivery processes at basin scale. Hydrol. Sci. J. 40, 703–717.

Fleskens, L., Stroosnijder, L., 2007. Is soil erosion in olive groves as bad as often claimed? Geoderma 141, 260–271. https://doi.org/10.1016/j.geoderma.2007.06.009

Francia Martínez, J.R., Durán Zuazo, V.H., Martínez Raya, A., 2006. Environmental impact from mountainous olive orchards under different soil-management systems (SE Spain). Sci. Total Environ. 358, 46–60. https://doi.org/10.1016/j.scitotenv.2005.05.036

García-Gamero, V., Mas, J.L., Peñuela, A., Hurtado, S., Peña, A., Vanwalleghem, T., 2024. Assessment of soil redistribution rates in a Mediterranean olive orchard in South Spain using two approaches: 239+240Pu and soil erosion modelling. CATENA 241, 108052. https://doi.org/10.1016/j.catena.2024.108052

Gdiri, A., Ben Cheikha, L., Oueslati, M., Saiidi, S., Reguigui, N., 2024. Investigating soil erosion using cesium-137 tracer under two different cultivated lands in El Kbir watershed, Tunisia. Euro-Mediterr. J. Environ. Integr. 9, 783–796. https://doi.org/10.1007/s41207-024-00497-0

Gómez, J.A., Battany, M., Renschler, C.S., Fereres, E., 2003. Evaluating the impact of soil management on soil loss in olive orchards. Soil Use Manag. 19, 127–134. https://doi.org/10.1111/j.1475-2743.2003.tb00292.x

Gómez, J.A., Francia, J.R., Guzmán, G., Vanwalleghem, T., Durán Zuazo, V.H., Castillo, C., Aranda, M., Cárceles, B., Moreno, A., Torrent, J., Barrón, V., 2017. Lateral Transfer of Organic Carbon and Phosphorus by Water Erosion at Hillslope Scale in Southern Spain Olive Orchards. Vadose Zone J. 16, 1–15. https://doi.org/10.2136/vzj2017.02.0047

Gómez, J.A., Giráldez, J.V., Vanwalleghem, T., 2008. Comments on “Is soil erosion in olive groves as bad as often claimed?” by L. Fleskens and L. Stroosnijder. Geoderma 147, 93–95. https://doi.org/10.1016/j.geoderma.2008.07.006

Gómez, J.A., Guzmán, M.G., Giráldez, J.V., Fereres, E., 2009a. The influence of cover crops and tillage on water and sediment yield, and on nutrient, and organic matter losses in an olive orchard on a sandy loam soil. Soil Tillage Res. 106, 137–144. https://doi.org/10.1016/j.still.2009.04.008

Gómez, J.A., Romero, P., Giráldez, J.V., Fereres, E., 2004. Experimental assessment of runoff and soil erosion in an olive grove on a Vertic soil in southern Spain as affected by soil management. Soil Use Manag. 20, 426–431. https://doi.org/10.1111/j.1475-2743.2004.tb00392.x

Gómez, J.A., Sobrinho, T., Giraldez, J., Fereres, E., 2009b. Soil management effects on runoff, erosion and soil properties in an olive grove of Southern Spain. Soil Tillage Res. 102, 5–13. https://doi.org/10.1016/j.still.2008.05.005

Gómez, J.A., Vanwalleghem, T., De Hoces, A., Taguas, E.V., 2014. Hydrological and erosive response of a small catchment under olive cultivation in a vertic soil during a five-year period: Implications for sustainability. Agric. Ecosyst. Environ. 188, 229–244. https://doi.org/10.1016/j.agee.2014.02.032

Gonzalez-Sanchez, E.J., Veroz-Gonzalez, O., Blanco-Roldan, G.L., Marquez-Garcia, F., Carbonell-Bojollo, R., 2015. A renewed view of conservation agriculture and its evolution over the last decade in Spain. Soil Tillage Res. 146, 204–212. https://doi.org/10.1016/j.still.2014.10.016

Huber, S., Prokop, G., Arrouays, D., Banko, G., Bispo, A., Jones, R.J., Kibblewhite, M., Lexer, W., Möller, A., Rickson, R.J., others, 2008. Environmental assessment of soil for monitoring: Volume I indicators & criteria. Off. Off. Publ. Eur. Communities Luxemb. 339.

Koulouri, M., Giourga, Chr., 2007. Land abandonment and slope gradient as key factors of soil erosion in Mediterranean terraced lands. CATENA 69, 274–281. https://doi.org/10.1016/j.catena.2006.07.001

Kraushaar, S., Herrmann, N., Ollesch, G., Vogel, H.-J., Siebert, C., 2014. Mound measurements — quantifying medium-term soil erosion under olive trees in Northern Jordan. Geomorphology 213, 1–12. https://doi.org/10.1016/j.geomorph.2013.12.021

Liu, Y.-F., Liu, Y., Shi, Z.-H., López-Vicente, M., Wu, G.-L., 2020. Effectiveness of re-vegetated forest and grassland on soil erosion control in the semi-arid Loess Plateau. CATENA 195, 104787. https://doi.org/10.1016/j.catena.2020.104787

López-Cuervo, S., 1990. La erosión en los suelos agrícolas y forestales de Andalucía, in: Colección Congresos y Jornadas. Junta de Andalucía Sevilla, p. 1990.

Mabit, L., Chhem-Kieth, S., Toloza, A., Vanwalleghem, T., Bernard, C., Amate, J.I., González De Molina, M., Gómez, J.A., 2012. Radioisotopic and physicochemical background indicators to assess soil degradation affecting olive orchards in southern Spain. Agric. Ecosyst. Environ. 159, 70–80. https://doi.org/10.1016/j.agee.2012.06.014

Márquez-García, F., Hayas, A., Peña, A., Ordóñez-Fernández, R., González-Sánchez, E.J., 2024. Influence of cover crops and tillage on organic carbon loss in Mediterranean olive orchards. Soil Tillage Res. 235, 105905. https://doi.org/10.1016/j.still.2023.105905

McLeod, J.S., Whittaker, A.C., Bell, R.E., Hampson, G.J., Watkins, S.E., Brooke, S.A.S., Rezwan, N., Hook, J., Zondervan, J.R., Ganti, V., Lyster, S.J., 2024. Landscapes on the edge: River intermittency in a warming world. Geology 52, 512–516. https://doi.org/10.1130/G52043.1

Palese, A.M., Ringersma, J., Baartman, J.E.M., Peters, P., Xiloyannis, C., 2015. Runoff and sediment yield of tilled and spontaneous grass-covered olive groves grown on sloping land. Soil Res. 53, 542. https://doi.org/10.1071/SR14350

https://doi.org/10.5194/egusphere-2025-3542
Preprint. Discussion started: 18 August 2025

Renard, K.G., 1997. Predicting soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). US Department of Agriculture, Agricultural Research Service.

Repullo-Ruibérriz De Torres, M.A., Ordóñez-Fernández, R., Giráldez, J.V., Márquez-García, J., Laguna, A., Carbonell-Bojollo, R., 2018. Efficiency of four different seeded plants and native vegetation as cover crops in the control of soil and carbon losses by water erosion in olive orchards. Land Degrad. Dev. 29, 2278–2290. https://doi.org/10.1002/ldr.3023

Rodrigo-Comino, J., Giménez-Morera, A., Panagos, P., Pourghasemi, H.R., Pulido, M., Cerdà, A., 2020. The potential of straw mulch as a nature-based solution for soil erosion in olive plantation treated with glyphosate: A biophysical and socioeconomic assessment. Land Degrad. Dev. 31, 1877–1889. https://doi.org/10.1002/ldr.3305

Rodríguez Sousa, A.A., Muñoz-Rojas, J., Brígido, C., Prats, S.A., 2023. Impacts of agricultural intensification on soil erosion and sustainability of olive groves in Alentejo (Portugal). Landsc. Ecol. 38, 3479–3498. https://doi.org/10.1007/s10980-023-01682-2

Sastre, B., Barbero-Sierra, C., Bienes, R., Marques, M.J., García-Díaz, A., 2017. Soil loss in an olive grove in Central Spain under cover crops and tillage treatments, and farmer perceptions. J. Soils Sediments 17, 873–888. https://doi.org/10.1007/s11368-016-1589-9

Taguas, E.V., Ayuso, J.L., Peña, A., Yuan, Y., Pérez, R., 2009. Evaluating and modelling the hydrological and erosive behaviour of an olive orchard microcatchment under no-tillage with bare soil in Spain. Earth Surf. Process. Landf. 34, 738–751. https://doi.org/10.1002/esp.1775

Taguas, E.V., Ayuso, J.L., Pérez, R., Giráldez, J.V., Gómez, J.A., 2013. Intra and inter-annual variability of runoff and sediment yield of an olive micro-catchment with soil protection by natural ground cover in Southern Spain. Geoderma 206, 49–62. https://doi.org/10.1016/j.geoderma.2013.04.011

Tubeileh, A., Turkelboom, F., Al-Ibrahem, A., Thomas, R., Sultan-Tubeileh, K., 2014. Modelling the Effects of Soil Conditions on Olive Productivity in Mediterranean Hilly Areas. Int. J. Agron. 2014, 672123. https://doi.org/10.1155/2014/672123

Van Oost, K., Govers, G., De Alba, S., Quine, T., 2006. Tillage erosion: a review of controlling factors and implications for soil quality. Prog. Phys. Geogr. 30, 443–466.

Van Oost, K., Govers, G., Desmet, P., 2000. Evaluating the effects of changes in landscape structure on soil erosion by water and tillage. Landsc. Ecol. 15, 577–589. https://doi.org/10.1023/A:1008198215674

Vanwalleghem, T., Amate, J.I., De Molina, M.G., Fernández, D.S., Gómez, J.A., 2011. Quantifying the effect of historical soil management on soil erosion rates in Mediterranean olive orchards. Agric. Ecosyst. Environ. 142, 341–351. https://doi.org/10.1016/j.agee.2011.06.003

Vanwalleghem, T., Laguna, A., Giráldez, J.V., Jiménez-Hornero, F.J., 2010. Applying a simple methodology to assess historical soil erosion in olive orchards. Geomorphology 114, 294–302. https://doi.org/10.1016/j.geomorph.2009.07.010

Verheijen, F.G.A., Jones, R.J.A., Rickson, R.J., Smith, C.J., 2009. Tolerable versus actual soil erosion rates in Europe. Earth-Sci. Rev. 94, 23–38. https://doi.org/10.1016/j.earscirev.2009.02.003

https://doi.org/10.5194/egusphere-2025-3542
Preprint. Discussion started: 18 August 2025

670 Zhang, X., Song, J., Wang, Y., Sun, H., Li, Q., 2022. Threshold effects of vegetation coverage on runoff and soil loss in the Loess Plateau of China: A meta-analysis. Geoderma 412, 115720. https://doi.org/10.1016/j.geoderma.2022.115720