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How strongly do management practices and scales influence soil erosion rates in olive orchards? Empirical evidence from Alentejo (Portugal)

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A R T I C L E I N F O

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A B S T R A C T

The use of vegetation suppression, such as herbicide application and mechanical plowing in olive orchards can exacerbate soil erosion. Maintaining understory vegetation can mitigate erosion and enhance soil fertility. Although prior research has assessed the soil management impact on erosion, knowledge gaps persist regarding dominant erosion processes across spatial scales and management effects on soil microenvironments (tree canopy, wheel ruts, vegetation strips). This study systematically evaluates how soil management (herbicides, plowing, no intervention) and spatial scales (microplots, hillslope plots) affect erosion dynamics, soil properties and their interactions with rainfall, ground cover, and orchard characteristics in Alentejo, Portugal. Over two years, seven orchards with varying management practices were monitored for erosion rates, ground cover, and soil properties. Soil management strongly influenced erosion, with herbicides inducing the highest hillslope-scale erosion (average 11.3 t ha^{-1} yr^{-1}) and plowing dominating microplot erosion, while untreated plots exhibited minimal erosion (up to 99 % lower than the herbicide treatments). Wheel rut areas increased hillslope erosion through runoff concentration and bare soil, while vegetation strips suppressed it completely. Tree canopy areas varied: plowing mobilized new sediments, whereas untreated/herbicide microplots showed no erosion due to vegetation cover or stone-lag armoring. Hillslope erosion stemmed from cumulative runoff, while microplots were influenced by soil properties like roughness or bulk density. Our findings highlight the need to consider scale effects in erosion modelling and policy. Future research should explore longer-term trends, expand underlying conditions (e.g. soil types, climatic zones or management practices), and refine soil erosion models to support sustainable soil conservation.

1. Introduction

Olive tree cultivation is particularly vulnerable to soil erosion due to intensive agricultural practices, with commercial orchards experiencing significantly higher soil degradation than traditional or semi-natural systems (Vanwalleghem et al., 2010). These practices increase soil exposure to erosive forces, leading to significant soil losses, often exceeding 20 t ha^{-1} yr^{-1} (Oliveira et al., 2024), while also promoting organic carbon depletion and water pollution through sediment transport (Márquez-García et al., 2024). The Mediterranean region, including major olive-producing areas such as Andalucía (Spain) and Alentejo (Portugal), faces severe erosion due to steep slopes, shallow soils, and high-intensity rainfall events (Rodríguez Sousa et al., 2023). Additionally, two distinct factors may amplify erosion: the sparse canopy cover of traditional groves and the intensive soil management in high-density orchards. However, the exact role of olive intensification, achieved either by reducing the distances between rows or between plants, remains understudied (Rodríguez Sousa et al., 2021).

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Olive groves are frequently cultivated on marginal lands with poor soil structure and low water retention capacity, making them particularly vulnerable to erosion (Vanwalleghem et al., 2010; Pareja-Sánchez et al., 2024). Conventional tillage and herbicide applications compact the soil, reducing infiltration and accelerating runoff (Prats et al., 2020; Cerdà et al., 2021). Furthermore, the suppression of ground cover in both traditional and intensive systems leaves soil exposed, facilitating rill and gully formation, which accounts for over 80 % of total soil loss in Mediterranean regions (Nachtergaele et al., 2001).

The Alentejo region of Portugal serves as a paradigmatic example of the challenges facing Mediterranean agriculture and related rural landscapes and territories. Situated at the forefront of climate change and socio-demographic challenges, the region is experiencing a dual and paradoxical process of desertification and rapid agricultural intensification (Rodríguez Sousa et al., 2023). The shift from traditional, low-density olive groves to highly mechanized, super-intensive orchards accounts for a representative example of land-use and landscape change occurring across many similar regions (González-Rosado et al., 2021; De la Rosa et al., 2022). Therefore, it is to be expected that these findings from the Alentejo prove to be not just of local or regional relevance, offering crucial insights into the dynamics and impacts of soil erosion and land degradation affecting other Mediterranean areas with similar climatic conditions, soil types, and land management systems.

Cover crops, which provide vegetation cover over the soil surface, are widely recognized as an effective erosion control measure, improving soil structure, organic carbon retention, and water conservation (Keesstra et al., 2018). Studies demonstrate that cover crops between olive trees can reduce erosion from > 250 t ha^{-1} yr^{-1} to < 25 t ha^{-1} yr^{-1} in olive orchards (Beniaich et al., 2023), with similar benefits observed in vineyards (Novara et al., 2011). Spontaneous or sown vegetation enhances soil organic carbon (SOC) accumulation (1.1 t ha^{-1} yr^{-1}; Vicente-Vicente et al., 2016) and reduces sediment losses by over 90 % compared to bare soil (Keesstra et al., 2016). However, farmers often restrict vegetation to non-competitive zones near tree lines, balancing erosion control with water and nutrient competition (González-Sánchez et al., 2012). In addition, the intensification of the olive plantations, ranging from extensive (100 trees/ha), to intensive (300) to super-intensive (1,000–2,000) systems, which is driven by market demands, has been associated with increased soil erosion and soil degradation (Nunes et al., 2011). However, emerging evidence is refining this understanding. For instance, in a study of Alentejo orchards that investigated this question, Rodríguez Sousa et al. (2023) found that erosion rates were more strongly influenced by soil and vegetation management than by tree density itself, with some integrated systems exhibiting high erosion due to localized herbicide use. This underscores the need for further research on the role of vegetation cover management for erosion control in olive groves.

Despite the benefits of cover crops, the prevalent management systems in intensified olive orchards are often characterized by high levels of soil disturbance through either soil tillage or chemical weed control (herbicides), both of which result in a high percentage of bare soil. While tillage temporarily increases soil roughness, promoting infiltration, this effect is often short-lived, with rapid breakdown of aggregates leading to severe post-tillage erosion (Márquez-García et al., 2024). Similarly, the long-term and widespread use of herbicides often results in surface crusting and sealing, greatly enhancing inter-rill and splash erosion (Liu et al., 2016). Techniques such as reduced tillage, minimum tillage, or mechanical weed removal are recognized conservation alternatives for mitigating soil erosion by enabling minimal soil disturbance and permanent soil cover (Carretta et al., 2021; Fishkis and Koch, 2023). Other benefits arising from the implementation of these techniques include the enhancement of soil structure stability and biological activity, the improvement of soil fertility and micro-climate, and the enhancement of water infiltration (Berger et al., 2010). These management practices resulting in bare soil conditions demonstrate the critical need for empirical studies to investigate how different methods of bare soil management affect erosion rates and processes.

In managed olive orchards, the landscape is functionally divided into distinct soil microenvironments, each with unique characteristics that govern erosion processes. The area under the tree canopy is directly influenced by management practices (e.g., herbicide or plowing), canopy cover, and litterfall. In contrast, the wheel rut, the zone of repeated machinery traffic, is characterized by soil compaction, which reduces infiltration and increases surface runoff, making it a critical area for rill initiation and sediment transport (Shaheb et al., 2021). The vegetation strip between tree rows often acts as a sediment sink, promoting infiltration and disrupting runoff pathways (Rodríguez Sousa et al., 2023). The spatial arrangement and connectivity of these microenvironments within a plot fundamentally control its overall hydrological response and erosion rates.

The assessment of soil erosion is scale-dependent due to fundamental shifts in dominant hydrological processes (Cammeraat, 2004; De Vente et al., 2013). At the microplot scale (≤1 m^2), processes are confined and dominated by rain splash detachment and sheet flow (interrill erosion), where soil properties like surface cover and resistance directly control particle detachment. In contrast, at the hillslope scale (≥100 m^2), runoff from upslope areas converges, leading to the development of concentrated flow and rill erosion, which typically accounts for the majority of sediment yield (Thomaz and Vestena, 2012; Martínez-Mena et al., 2020). This shift is governed by the concept of sediment connectivity, the physical linkage of different parts of the landscape that determines the efficiency of sediment transport (Neumann et al., 2022). In managed olive orchards, these scale effects are further mediated by the distinct soil microenvironments (tree, rut, vegetation strip), whose spatial arrangement critically controls runoff pathways and connectivity. Therefore, understanding erosion requires a multi-scale approach that captures this process transition, a core complexity our study addresses.

Despite this growing body of knowledge, a critical empirical gap remains in simultaneously quantifying how different vegetation suppression practices affect soil erosion across the distinct microenvironments of an olive orchard and across different spatial scales. Understanding these scale and microenvironment dependent processes is essential to accurately assess the total erosion risk of an orchard and to develop targeted, effective mitigation strategies. Our study directly addresses this gap by providing an integrated, multi-scale, and multi-microenvironment field assessment.

This work addresses the overarching question: How do management practices and spatio-temporal scales influence erosion rates in olive orchards? As a follow-up to Rodríguez Sousa et al. (2023), this study assessed olive orchards in the Alentejo region, Portugal, over two years. The main goal was to evaluate how vegetation management practices (herbicides, plowing, no intervention) affect erosion processes across soil microenvironments (areas under the tree canopy, wheel rut area, vegetation strip) and spatial scales (1 m^2 microplots versus 100–300 m^2 hillslope plots). The specific objectives were to: i) Quantify the temporal erosion patterns from seven olive orchards in both microplots and hillslope plots under different management practices (herbicide, plowing, no intervention); ii) Assess the soil physical (soil roughness, resistance to penetration, soil bulk density) and hydraulic responses (infiltration) to management; iii) Identify key factors explaining the variability of soil erosion (rainfall, cover, microenvironment extent, soil properties).

2. Material and methods

2.1. Study areas

The study areas (commercial olive orchards) were located in the Alentejo region (Fig. 1). The climate of the region can be classified as Mediterranean temperate with a rainy winter and a dry and hot summer (Csa in Köppen classification) with 9–24 °C annual temperature range and an annual rainfall range of 400 to 750 mm (Fraga et al., 2020). The seven study areas include different types of suppression of the vegetation

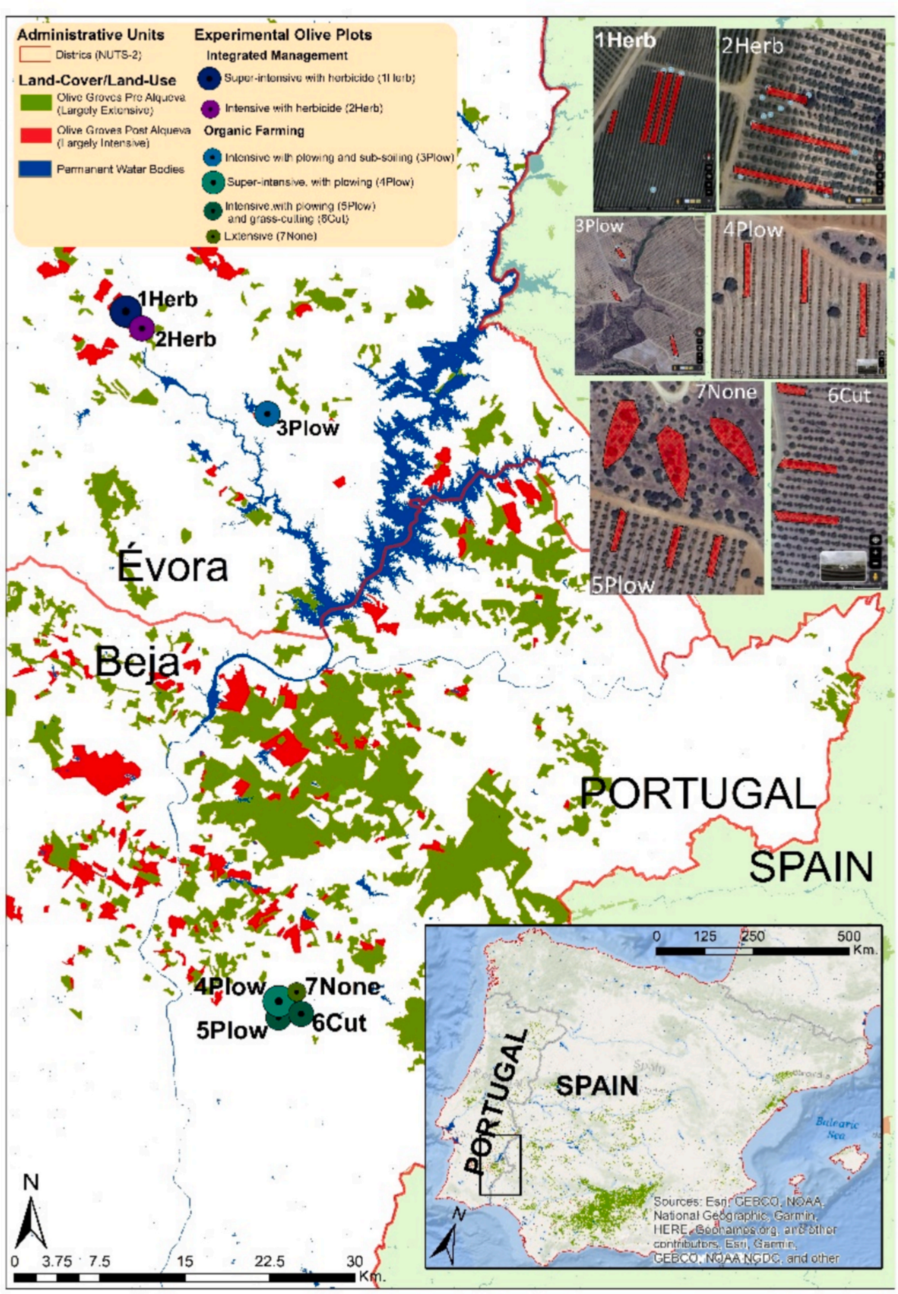

Fig. 1. Location map of olive orchards for the northern (1Herb, 2Herb, 3Plow) and the southern clusters (4Plow, 5Plow, 6Cut, 7None). The small aerial photographs show the hillslope plots (red polygons) installed in the 3–4 sites selected within each study area.

growing directly under the tree rows, in the so-called "*tree microenvironment*": 2 groves applied herbicide, 3 applied plowing, and 2

Table 1
Details of each olive grove, regarding the herb suppression treatment applied under the tree canopy (tree microenvironment), tree density, soil management, number of hillslope plots and mean plot size, slope and percentage of plot surface occupied for each microenvironment ("tree", "rut" or "vegetation" (Veg.)). Abbreviations are: Super: super-intensive, Int: Intensive, Ext: Extensive olive orchard.

Area	Herb clearing	Tree density (tree/ha)	Soil management	Hillslope plots (n; size m^2)	Slope (°)	Tree surface (%)	Rut surface (%)	Veg. surface (%)	Dry biomass (t ha^{-1} yr^{-1})	Olive production (t ha^{-1} yr^{-1})
1Herb	Herbicide	super/1925	Integrated	4; 432	7	51	33	17	0.6	new
2Herb	Herbicide	int/272	Integrated	3; 322	13	66	15	19	2.2	14.2
3Plow	Plowing	int/284	Organic	3; 295	8	33	43	24	3.3	9.0
4Plow	Plowing	super/1186	Organic	3; 107	7	46	24	30	4.8	new
5Plow	Plowing	int/238	Organic	3; 111	9	62	17	21	1.8	7.0
6Cut	Cutting	int/339	Organic	3; 176	8	65	16	19	1.5	2.5
7None	None	ext/104	Organic	3; 481	12	0	0	100	3.8	0.8

groves remained with low disturbance of vegetation and soil (Table 1). The amount of herbicide was consistent across all groves, with two annual glyphosate treatments (autumn and spring) to manage weed proliferation in the tree microenvironment. The plowing treatments in 4Plow and 5Plow were very similar, with two shallow plowings (10–15 cm depth) conducted in autumn and spring under the tree microenvironment to suppress herb growth. However, the area 3Plow underwent only one shallow plowing in year 1 (May 2021) and a second plowing and strong grading in year 2 (May 2022). A crawler tractor equipped with a grading implement was used to ensure soil reconsolidation and protective coverage of the olive root zone, which was being affected by wild boar uprooting. The low-intensity vegetation management strategies included two treatments: 6Cut —a biannual (autumn and spring) vegetation cutting regimen without biomass removal— and 7None, a control group with no vegetation management interventions (Table 1). While the three main vegetation suppression strategies (herbicide, plowing, no intervention) were clearly defined, operational details such as timing, frequency, and intensity of interventions varied between orchards within the same treatment category. A detailed chronological summary of all management actions per orchard is provided in Supplementary Table S1.

Soil management was either integrated, which allowed herbicide use in the tree microenvironment (2 groves) or organically grown, which does not allow herbicide (5 groves). Tree densities ranged from 100 trees/ha (extensive), 300 trees/ha (intensive) and 1000–2000 trees/ha (super-intensive). Areas 1Herb and 4Plow were both super-intensive and were being planted in October 2021. All groves were irrigated except for the extensive 7None, which was rainfed. The soil texture was mainly sandy clay loam, except for area 4NEW, which was sandy loam (Rodríguez Sousa et al., 2023). The parent material consists mainly of either igneous granite (1Herb), metamorphic schists (2Herb, 3Plow), and ultramafic rocks (4Plow, 5Plow, 6Cut, 7None). Other ancillary characteristics were previously described by Rodríguez Sousa et al. (2023).

2.2. Soil erosion and soil properties assessment

One microplot and one larger hillslope plot was installed in each of the three sites selected within each olive grove area (Table 1). A total of 21 bounded microplots (1.4 x 0.7 m) and 22 hillslope plots were installed following Prats et al. (2022). The microplots were bounded with woven fabric fixed with wood stakes and nails, and a sediment fence was constructed at the bottom of the plot to allow runoff water to filter and the sediments to deposit. The hillslope plots collected the natural runoff flowing out from between two olive tree lines and thus had larger sediment fences (3–4 m length, 1–2 m width, 40–50 cm height). The plot contours were delimited by either natural ridges of the hillslopes, roads, or by digging trenches at the top of the plot. The microplots were installed below the olive tree canopy to account for the direct effect of soil management on the tree microenvironment, whereas the hillslope plots included the three microenvironments naturally present in each line: tree, rut and vegetation microenvironments. Thus, all the hillslope plots consistently collected the runoff water flowing from two tree lines, two wheel ruts and one vegetation strip between them. The relative area occupied by each microenvironment (tree, rut, vegetation strip) varied across orchards depending on tree spacing, row width, and management layout (Table 1). This natural variability reflects real-world orchard design, but it means that hillslope erosion integrates differing contributions from each microenvironment. All plots were installed in May-June of 2021 (except for 1herb and 4Plow, two new super- intensive orchards which were being planted and had to be installed in October 2021) and soil erosion was monitored for 2 hydrological years, from June 2021 until July 2023. The sediments deposited in each plot were collected at roughly bimonthly intervals, or depending on the rainfall occurrence, accounting for a total of 9 readouts ("RO"). All the wet sediments were collected and weighed in the field and samples were later dried in the laboratory (60 °C, until weight stabilization). Additionally, sediment and soil samples from RO2, RO3 and RO7 were sent to a commercial laboratory to assess C, N, P, K and organic matter content using a CHNS elemental analyzer (LecoTruSpect Micro).

The soil properties were measured during a single campaign between October-November 2022. Dry bulk density, stone content and soil texture were determined by taking three soil samples from the tree microenvironment using a metal core of 5 cm height (Rodríguez Sousa et al., 2023). Infiltration, roughness and soil resistance were measured for all microenvironments (tree, rut, vegetation) of each one of the three hillslope plots in each area. Infiltration rate was estimated using a Mini Disk Infiltrometer (MDI; Metergroup company, Inc., Pullman, WA, USA) to determine the unsaturated hydraulic conductivity (K, mm h^{-1}). The suction rate was set at −2 cm according to the soil texture (n = 3 on each tree/rut/veg. microenvironment). Soil roughness was estimated by using a 1-cm link, 70 cm-long roller chain (Saleh, 1993), by placing it carefully following the microtopography along the soil surface and subtracting this length from 70 cm (n = 3 on each microenvironment). Soil resistance was determined using a Gilson pocket penetrometer (Gilson Company, Inc., Lewis Center, OH, USA) and the compressive strength of the soil against pressure (range 0–6; ±0.1 kg/cm^2; n = 10 on each microenvironment).

Soil cover percentage was quantified with a 1-m^2 quadrat subdivided into a 10 × 10 cm grid cell placed directly over the microplot, while in the hillslope erosion plots nine systematic placements of the grid were made to account for microenvironment variation (tree, rut, vegetation) and slope position (bottom, middle, top). Four cover classes were considered: green vegetation, bare soil, stones > 1 cm, and litter. The surface of each microenvironment differed between areas, and the contribution to the whole plot cover was calculated accordingly. For example, the surface of the tree microenvironment of 2Herb was maximum at 66 %, while the extensive 7None area consisted entirely of the vegetation microenvironment (Table 1). Cover descriptions were carried out for all the 9 read-outs (RO) in the microplots, and only for the RO2, RO3 and RO4 in the hillslope plots. For the remaining RO in the hillslope plots only the green vegetation cover was estimated, by correlating NDVI values with the vegetation cover values of RO2, RO3 and RO4 using linear regressions. NDVI values were obtained using a Google Earth Engine script (https://code.earthengine.google.com/), which utilized Sentinel-2 satellite imagery to provide one NDVI value per 10x10 m grid cell per month. Rainfall amount and 60-min intensity (I60)in the Évora northern cluster (1Herb, 2Herb, 3Plow) were gathered from an automatic rainfall gauge installed in the 3Plow area, which was also validated with SNIRH rainfall data (R^2 = 0.83) from the São Manços meteorological station (38.460°N, −7.751°W; 5–20 km from the Évora northern areas; Portuguese National System for Water Resources Information; SNIRH, 2024). For the southern cluster near Serpa (4Plow, 5Plow, 6Cut, 7None), SNIRH data were used from the Serpa meteorological station (37.942°N, −7.603°W; 6 km apart).

2.3. Statistical analysis

Pearson's correlation coefficients (r) were calculated between soil erosion and rainfall characteristics (amount, 60-min intensity I60), soil properties (roughness, resistance and infiltration in each microenvironment, as well as bulk density and stoniness), orchard characteristics (plot slope, tree density, surface of each microenvironment) and cover (NDVI, vegetation, vegetation + litter, bare soil cover, stone cover, stone + vegetation cover). This was conducted either statically (for soil properties) or dynamically (for each year), and the significance of the correlation was stated at the 0.05 and 0.01 levels.

Multiple linear regression models were used to assess the relationships between erosion and various environmental predictors, including rainfall variables (amount, I60), ground cover (NDVI, all cover categories for microplots and hillslope plots), soil properties (roughness, resistance, infiltration of different microenvironments, stoniness, bulk density) and orchard characteristics (slope, tree density, microenvironment surface). These models were selected for their interpretability in identifying significant drivers and the direction of their effect, with the primary goal being factor screening rather than achieving high predictive accuracy. To evaluate the relative importance of different predictor variables, a series of hierarchical regression models were constructed. A forward-stepwise selection procedure was used; variables were retained if they contributed significantly ($p < 0.05$) to explained variance. Model fitting was evaluated using R^2, adjusted R^2, and p-values. To provide a more robust assessment of model performance, the Nash-Sutcliffe Efficiency (NSE) and the Mean Absolute Error (MAE) were also calculated. Multicollinearity was checked through variance inflation factors (VIF), ensuring no strong correlations between predictors.

A linear, mixed-effects statistical model with repeated measurements was conducted for soil erosion, with time (year 1 and year 2), treatment (herbicide, plowing, none), and plot size (micro, hillslope), and their interactions as the fixed factors. The olive grove and the erosion plot were considered the random factors and erosion plots were the subject of the repeated measurements (Roy and Khattree 2007). Covariates were also tested and included (e.g., rainfall, I60, slope, cover, soil properties, microenvironment area proportions) if significant (at $p < 0.05$) to examine their potential influence on soil erosion. Soil erosion data was normally distributed according to Kolmogorov-Smirnov (Massey, 1951) and Shapiro-Wilk (Shapiro and Wilk, 1965) statistical tests, and transformations were not needed. Similarly, one-way ANOVA models were constructed for soil resistance, roughness and infiltration for all available microenvironments (tree, rut, veg.) and areas (7 areas). The post-hoc Tukey-Kramer method (Kramer, 1956) was used to rank the differences between all the levels of the factors, and results were reported at a level of significance of $p < 0.05$. Statistical analysis was carried out with IBM SPSS Statistics 25 software.

3. Results

3.1. Rainfall characteristics and sediment yield

In the first hydrologic year, rainfall amount was slightly lower in the Évora northern areas (423 mm) than in the Serpa southern areas (466 mm). However, in the second hydrologic year, rainfall increased in Évora (490 mm) and decreased in Serpa (389 mm; Fig. 2). On the other hand, maximum rainfall intensity in 60 min (I60) was much higher in the Évora areas for both years 1 and 2 (32 and 19 mm/h, respectively) than in the Serpa areas, which only reached 10.6 mm/h. The highest I60 values in the Évora area corresponded to intense rainfall periods of autumn 2021 (100 mm) and autumn 2022 (85 mm). The more abundant periods of spring 2022 (RO05) and winter 2023 (RO08) resulted in copious rainfall volumes of 200–250 mm, but with comparatively much lower I60 values.

The herbicide treatment in the microplots showed moderate erosion (1.5–2.8 t ha^{-1} yr^{-1}), with minimal annual variation (Table 2). Plowed treatments exhibited higher erosion, particularly in year 1 (0.3–10.7 t ha^{-1} yr^{-1}), but rates declined in Year 2 (2.0–6.5 t ha^{-1} yr^{-1}). The 6Cut and 7None groves had the lowest erosion (0.2–1.0 t ha^{-1} yr^{-1}) during the two years (Fig. 2). On the other hand, the herbicide treatment in the hillslope plots showed the highest erosion in year 1 (11.0–22.6 t ha^{-1} yr^{-1}) and halved by year 2 (5.1–6.3 t ha^{-1} yr^{-1}). Conversely, erosion in the hillslope plots under the plowed treatment showed lower erosion, although increasing in year 2, especially in the 3Plow olive grove (0.1 to 5.0 t ha^{-1} yr^{-1}). Cut and None treatments consistently maintained minimal erosion ($\leq$0.139 t ha^{-1} yr^{-1}), reinforcing their sustainability. In fact, the mixed effects statistical models showed a significant effect of the interaction between plot size and treatment to control herbs growth in the tree microenvironment ($F = 19.25$; Table 3). However, the presence of a significant triple interaction between plot size, monitoring year and treatment suggests that some of the levels of these factors played an important role in sharpening the soil erosion response. Detailed model outputs, including parameter estimates with 95 % confidence intervals, are provided in Table S2.

3.2. Soil physical properties and ground cover

Soil infiltration was higher in the tree microenvironments, particularly in 1Herb (1067 mm/h) and 5Plow (563 mm/h), especially compared to the rut microenvironment (Table 4). The two recently planted super-intensive olive groves (1Herb and 4Plow) had the highest infiltration rates in the rut microenvironment (251–106 mm/h), which differed significantly from the other areas (80–20 mm/h). Vegetation

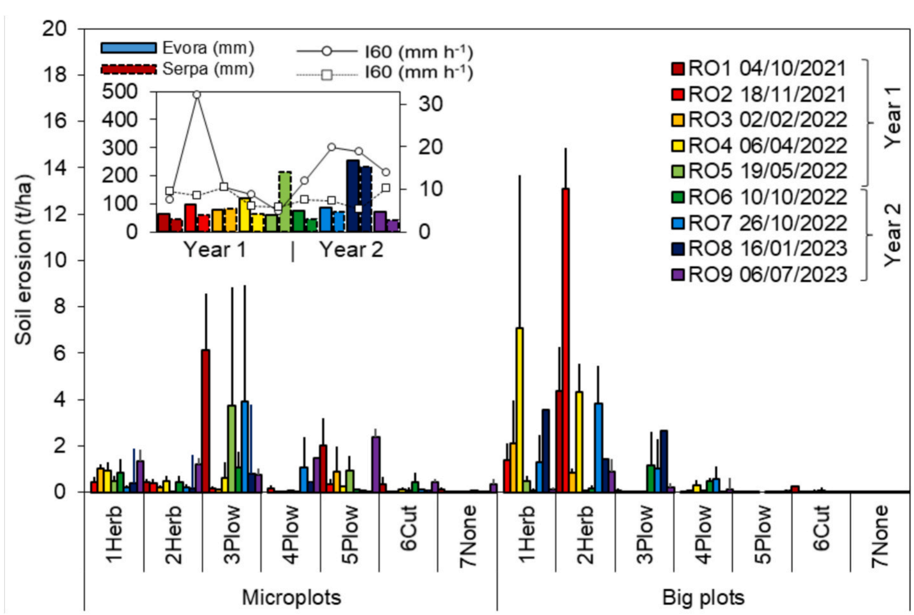

Fig. 2. Mean soil erosion (t/ha) in each readout period for the microplots and big erosion plots of each olive orchard. The inside figure shows rainfall amount (mm, left axis) and maximum rainfall intensity in 60 min (I60 mm/h, right axis) for the olive groves near Evora (1Herb, 2Herb, 3Plow) and the ones near Serpa (4Plow, 5Plow, 6Cut, 7None) during each assessment, read-out (RO) period.

Table 2
Mean annual soil erosion measured during the 2 hydrologic years in the microplots (1 m^2) and hillslope plots (ca. 300 m^2) as well as the dimensionless scale ratios (erosion on the hillslope plot divided by erosion in the microplot). Standard deviation is shown between brackets. Different letters indicate significant differences in soil erosion between the seven areas within the same year and plot size at $p < 0.05$.

Area; plot size	Soil erosion ($t\ ha^{-1}\ yr^{-1}$) Year 1	Year 2
Microplot soil erosion		
1Herb	2.8 (0.4)^{ab}	2.8 (0.7)^{ab}
2Herb	1.5 (0.2)^{b}	2.0 (0.5)^{ab}
3Plow	10.7 (3.6)^{a}	6.5 (3.0)^{ab}
4Plow	0.3 (0.1)^{b}	3.0 (1.0)^{ab}
5Plow	4.4 (1.0)^{ab}	2.5 (1.1)^{ab}
6Cut	0.3 (0.1)^{b}	1.0 (0.3)^{b}
7None	0.2 (0.1)^{b}	0.5 (0.2)^{b}
Hillslope plot soil erosion		
1Herb	11.0 (5.0)^{ab}	5.1 (1.8)^{bc}
2Herb	22.6 (5.0)^{a}	6.3 (1.9)^{bc}
3Plow	0.1 (0.4)^{c}	5.0 (2.1)^{bc}
4Plow	0.4 (0.2)^{bc}	1.1 (0.5)^{bc}
5Plow	0.051 (0.01)^{c}	0.121 (0.2)^{c}
6Cut	0.139 (0.1)^{c}	0.035 (0.005)^{c}
7None	0.003 (0.001)^{c}	0.005 (0.001)^{c}
Scale Ratios (hillslope plots/microplots)		
1Herb	3.93	1.82
2Herb	15.07	3.15
3Plow	0.01	0.77
4Plow	1.33	0.37
5Plow	0.01	0.05
6Cut	0.46	0.04
7None	0.02	0.01

Table 3
Summary of the mixed-effects repeated-measures ANOVA for soil erosion ($t\ ha^{-1}\ yr^{-1}$) with plot size, year, and vegetation suppression treatment as fixed factors Abbreviations: df = degrees of freedom; F = F-value; p = p-value; η^2 = partial eta squared (effect size). Bold p-values indicate significance at $p < 0.05$. Marginal R^2 for the model = 0.298.

Fixed factor	Soil erosion ($t\ ha^{-1}\ yr^{-1}$) df	F-value	p-value	η^2
Plot size	1	7.76	**< 0.05**	0.023
Year	1	3.51	0.062	0.01
Treatment	2	5.39	**< 0.05**	0.031
Plot size * Year	1	2.69	0.102	0.008
Plot size * Treatment	2	19.25	**< 0.05**	0.103
Year * Treatment	2	5.68	**< 0.05**	0.033
Plot size * Year * Treatment	2	6.56	**< 0.05**	0.038
Best covariate				
I60	1	9.96	**< 0.05**	0.029

microenvironments displayed moderate rates, peaking at 1Herb (762 mm/h) but dropping sharply in 6Cut (22 mm/h). Soil roughness was highest in plow orchards, especially 3Plow (14.9 % under Tree). Ruts in 2Herb (14.9 %) and the tree microenvironment in 4Plow (7.6 %) also showed elevated roughness, whereas minimal values occurred in the vegetation microenvironment of 6Cut (2.0 %; Table 4). As expected, soil resistance was consistently higher in the rut area, followed by the vegetation area, and finally the tree area. The orchard 7None had a very high resistance to penetration, while the lowest resistance was recorded in 1Herb and 3Plow, the two recently installed super-intensive orchards.

The bare soil fraction in the second read-out period (Nov 2021) was highest in the two recently established orchards, 1Herb and 4Plow, especially when considering the rut microenvironments (Fig. 3). Bare soil percentage reached 36 % in the rut area of the 2Herb orchard, which had a steepness of 13° (Table 1), but remained lower than 10 % for any other instances. The sum of litter and vegetation cover in the microplots was very low for the herbicide orchards (1Herb, 2Herb), it varied broadly, from 27 to 88 % cover for the plowed sites (3Plow, 4Plow, 5Plow) and it was consistently high for the two orchards with low vegetation and soil disturbance (6Cut and 7None). Litter and vegetation showed similar patterns in hillslope plots for the tree and rut microenvironments, but not for the vegetation microenvironment, where cover exceeded 80 %. Stone cover was highest in the 2Herb and 4Plow microplots, and also reached 50 % in the rut microenvironments of the steeper 2Herb and 7None orchards, and in 3Plow and 6Cut (Fig. 3). Notably, the high stone cover in the rut of the 2Herb orchard did not prevent significant erosion, suggesting that the stone pavement may have been discontinuous or that concentrated flow in the compacted rut was sufficient to mobilize sediment from the remaining bare soil patches.

Vegetation cover, assessed via NDVI, was lowest in 1Herb and 4Plow at the beginning of the study but recovered much faster in the latter (Fig. 4). There were clear seasonal variations, with maximum vegetation cover in January-February of the two monitored years and drops to virtually no vegetation during summer. 3Plow showed a strong drop in vegetation cover for RO5 (May 2022) which recovered slowly after summer 2022. The areas in the Serpa region showed similar evolution, although the 7None showed lower vegetation cover than neighboring areas.

3.3. Main factors affecting soil erosion processes

The performance of the multiple regression models revealed a fundamental contrast in erosion drivers between the two plot scales (Table 5). For the microplots, all models exhibited very low explanatory power, with R^2 values $\leq$ 0.046 and Nash-Sutcliffe efficiency (NSE) values around or below zero. The decline in NSE for the most complex microplot model, despite a slight R^2 increase, indicates issues with overfitting and confirms that a simple linear approach is unsuitable for capturing the dominant, likely stochastic, processes at this scale. The low explanatory power at both scales, particularly for microplots, underscores that additional unmeasured factors (e.g., microtopography, antecedent soil moisture, biological activity) influence erosion, and the models should be interpreted as tools for identifying influential drivers

Table 4
Mean soil infiltration, roughness, resistance for each area in each tree, rut and vegetation (Veg.) microenvironments, as determined in the second assessment period (RO2; 18/11/2021). Different letters indicate significant differences within each variable and microenvironment at a p-value < 0.05. The area 7None has only vegetation microenvironment.

	Area	1Herb	2Herb	3Plow	4Plow	5Plow	6Cut	7None	Mean
Infiltration (mm/h)	Tree	1067^{a}	68^{a}	30^{a}	205^{a}	563^{a}	391^{a}	.	387
	Rut	251^{a}	80^{c}	20^{c}	106^{bc}	40^{c}	42^{c}	.	90
	Veg.	762^{a}	469^{a}	143^{a}	165^{a}	96^{a}	22^{a}	215^{a}	267
Roughness (%)	Tree	2.6^{d}	4.3^{cd}	14.9^{a}	7.6^{b}	5.6^{bcd}	3.9^{d}	.	6.5
	Rut	8.3^{bc}	14.9^{a}	3.1^{d}	10.2^{ab}	3.5^{cd}	3.3^{d}	.	7.3
	Veg.	5.4^{abc}	8.0^{a}	2.7^{c}	3.1^{bc}	4.3^{abc}	2.0^{c}	7.1^{ab}	4.7
Resistance (kg/cm^2)	Tree	0.9^{a}	1.9^{a}	2.5^{a}	0.8^{a}	0.9^{a}	2.3^{a}	.	1.5
	Rut	1.4^{d}	2.3^{d}	5.0^{ab}	3.6^{c}	3.9^{abc}	3.8^{bc}	.	3.4
	Veg.	1.0^{c}	1.6^{c}	3.9^{a}	2.1^{bc}	4.0^{a}	3.7^{ab}	5.1^{a}	2.7

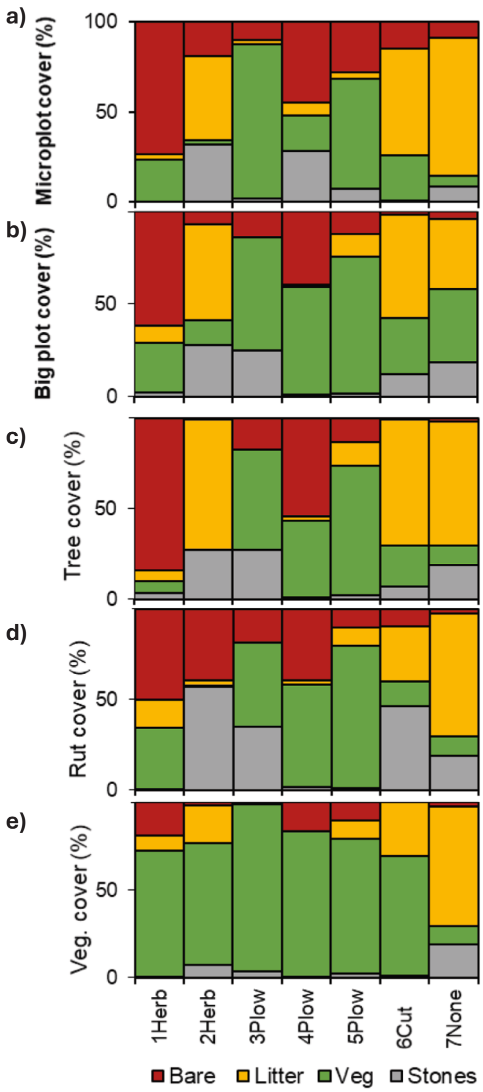

Fig. 3. Ground cover (%) for the second assessment period (RO2; 18/11/2021) for a) the microplots installed in the tree microenvironment, b) for the big plots, summed up to the whole ground cover, and the partial cover on each microenvironment of the big plots: c) Tree, d) Rut and e) Vegetation.

rather than as predictive equations.

In contrast, the models for hillslope plots showed progressively and consistently better performance. R^2 increased from 0.15 to 0.30, the NSE improved substantially from 0.16 to 0.55, and the Mean Absolute Error (MAE) decreased from 1.16 to 0.40. Microenvironment area proportions were considered in the analysis but did not emerge as significant predictors, underscoring the primary role of rainfall, cover, and soil properties in driving hillslope erosion. This coherent improvement across all three metrics confirms that the identified drivers—rainfall intensity (I60), vegetation cover (Veg), and soil surface properties (roughness and resistance)—are meaningful and collectively explain a substantial portion of the erosion variance at the hillslope scale. These findings emphasize the primary role of vegetation and rainfall intensity in controlling hillslope-scale erosion, while orchard characteristics played a more limited role.

Correlation coefficients exhibited contrasting trends across the two scales (Table S3). Hillslope erosion was positively correlated with rainfall intensity (I60; r = 0.523**), while the microplots were not significantly affected by rainfall characteristics. The same was observed in the correlation between soil erosion and vegetation and litter cover. They were significantly and negatively correlated with the erosion in the hillslope plots, underscoring vegetation's protective role (vegetation cover: r = -0.439**; litter + vegetation cover: r = -0.390**; Table S3). In contrast, stone cover in hillslope plots showed a significant positive correlation with erosion (r = 0.465**), while its combination with vegetation was not significant. In microplots, neither stone cover alone (r = 0.100) nor its combination with vegetation (r = -0.040) showed a significant relationship with erosion (all $p > 0.05$; Table S3). However, these correlations were weaker and insignificant for the microplots. This suggests that erosion drivers, such as rainfall intensity and vegetation cover, have a stronger influence on the whole hillslope scale, while microplots capture local runoff-driven processes. Additionally, roughness in the rut and vegetation strip microenvironment showed positive and significant associations with erosion (r = 0.752** and 0.587**, respectively), while resistance had negative relationships (r = -0.553** and −0.555**).

4. Discussion

4.1. Effects of the treatments on soil erosion and soil properties

Herbicide-managed orchards (1Herb and 2Herb) exhibited the highest erosion rates in hillslope plots, which is consistent with their reduced vegetation cover in the tree microenvironment, a direct consequence of herbicide application, and the significant correlation between erosion and rainfall intensity (I60) in our models. The relationship between diminished vegetation cover and elevated erosion is well-documented in Mediterranean olive groves in Spain (Cerdà et al., 2021) and Portugal (Nunes et al., 2023; Santos et al., 2023) as well as other land uses (Prats et al., 2016; 2021; 2022; Nunes et al. 2020). Our measured hillslope erosion under herbicide (11.3 t ha^{-1} yr^{-1}) aligns with other findings reported for intensively managed, bare-soil olive orchards in similar regions, such as soil losses around 7 t ha^{-1} yr^{-1} (Gómez et al., 2009), 8 t ha^{-1} yr^{-1} (Cerdà et al., 2021) or above 10 t ha^{-1} yr^{-1} (Taguas and Gómez, 2015), confirming the high erosion risk of this practice.

Plowed orchards were associated with the highest erosion in the microplots (3Plow and 5Plow). Notably, the hillslope plots were impacted mostly in the 3Plow orchard, where the intensive soil disturbance of mechanized grading operations in May 2022 led to erosion rates of 5 t ha^{-1} yr^{-1} during year 2, a threshold with significant implications for soil conservation (Verheijen et al., 2009). Grading sharply reduced vegetation without improving soil infiltration, conditions that make the soil prone to erosion (Parsakhoo et al., 2009). Tillage practices limit vegetation growth, reduce infiltration, and ultimately increase erosion risk (Palese et al., 2014; Márquez-García et al., 2024). Consistently, the other plowed orchards, 4Plow and 5Plow, only showed erosion in the microplots for some years and areas. This is likely related to the timing of the plowing, which was highly variable across both time and orchards (Table S1). The time of the intervention is crucial, as the tilled soil became highly erodible after the plowing, and soil stability increases with time, due to vegetation development (Malvar et al., 2017) but also depending on soil stone cover and the presence of a stone lag (Verheijen et al., 2009; Nunes et al., 2020).

The orchards without vegetation suppression treatments showed the lowest erosion rates, which has typically been described as a consequence of organic management. For example, Zuazo et al. (2020) found conventional systems to have higher erosion than integrated or organic systems. However, sometimes organic practices alone, while promoting weed growth and ground cover, are insufficient for erosion control without supplemental measures (Arnhold et al., 2014). In our study, organic-intensive and extensive management with vegetation cutting or no treatment (6Cut, 7None) yielded lower erosion rates across plot scales. The vegetation management in 6Cut underscores an effective and strategic erosion control measure, whereas the lowest erosion in 7None, despite steep slopes and sparse vegetation, may reflect prior soil degradation, as evidenced by high stoniness (Table S4) from previous

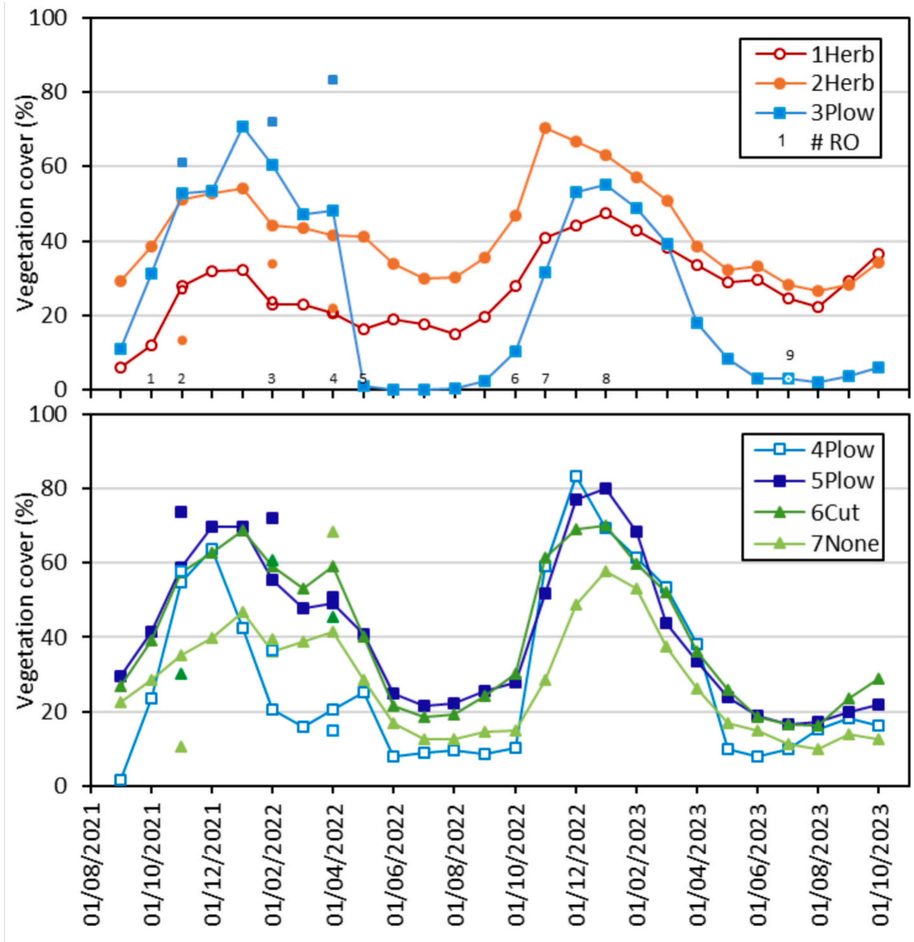

Fig. 4. Monthly mean vegetation cover (%) for the big plots of each olive orchard for the northern olive orchards based on NDVI values and transformed using linear correlations to vegetation cover according to the three read-out (RO) periods (2, 3 and 4) with field cover observations. Symbols were circles for the herbicide orchards (1Herb, 2Herb), squares for the plow orchards (3Plow, 4Plow, 5Plow) and triangles for the low vegetation and soil disturbances (6Cut, 7None). Empty symbols denote recently installed and planted olive orchards (1Herb, 4Plow).

fine-particle loss and the low soil organic matter content, indicating soil exhaustion (Verheijen et al. 2009). This concept of soil exhaustion is further supported by the significant positive correlation found between stone cover and hillslope erosion ($r = 0.465$). This counterintuitive relationship may indicate that in our study system, high surface stone cover is not a stabilizing factor but rather could reflect a severely degraded state where the erodible fine soil fraction has already been removed, leaving behind a stone lag that is linked to historically high erosion rates and continued vulnerability. The near-zero erosion rates in our 6Cut and 7None plots (<0.14 t ha^{-1} yr^{-1}) are lower than those often reported for organically managed groves with spontaneous cover, such as 0.7–0.8 t ha^{-1} yr^{-1} (Gómez et al., 2009; Zuazo et al., 2020). This is potentially due to the specific climatic conditions of our study years or the advanced state of soil exhaustion in 7None.

Our results did not reveal a clear correlation between soil erosion and tree density, suggesting that vegetation suppression methods likely drove the observed differences in erosion rates across sites (Cerdà et al., 2021; Rodríguez Sousa et al., 2023). This finding supports the idea that for erosion control, the specific management of the inter-row space (i.e., vegetation suppression method) is more critical than the absolute number of trees per hectare or their specific in-row spacing. This is also consistent with erosion being primarily driven by runoff detachment and transport in these systems, rather than by splash detachment, which would be more directly mitigated by tree canopy cover. For example, under super-intensive management, erosion outcomes varied markedly between orchards: the integrated 1Herb orchard exhibited high erosion rates, whereas the organic 4Plow showed low erosion rates. Although this effect was only partial in these areas, the recent establishment of these two orchards may have increased erosion rates, as observed in prior studies (Nunes et al., 2020). This reinforces the conclusion of Rodríguez Sousa et al. (2023) that management is a stronger determinant of erosion than planting density in modern Alentejo orchards.

Vegetation suppression treatments were associated with differential soil properties across microenvironments (tree, rut, vegetation). Infiltration rates tended to be highest in the tree microenvironments, possibly due to the absence of machinery passages and organic matter accumulation from olive canopy litterfall. Conversely, rut microenvironments had the lowest infiltration (except for the recently established 1Herb and 4Plow), reflecting porosity loss from tillage and compaction by wheel traffic in the rut area, which is consistent with studies linking plowing to long-term compaction (Bombino et al., 2019). Plowed soil, while initially loosened, can compact over time, reducing its capacity to absorb water (Gómez et al., 2009). The extremely high infiltration in the tree zone of the recently planted 1Herb orchard (>1000 mm h^{-1}) is atypical and likely due to soil disturbance during planting. It contrasts with the much lower values (<100 mm h^{-1}) found in established orchards by Bombino et al. (2019), highlighting how initial conditions can temporarily override typical management effects.

Soil roughness peaked in the tree and rut microenvironments, which could reflect that herbicide use and mechanical disturbance increased surface irregularity, potentially concentrating overland flow and promoting the detachment of soil particles by runoff, which in turn

Table 5
Multiple forward-selection regression models for soil erosion (SE) as explained by rainfall intensity, ground cover categories as well as soil roughness, resistance and infiltration; both in the tree area, in the case of the microplots models, as well as in the vegetation strip area, in the case of the hillslope plot models. Abbreviations are: I60: Rainfall intensity at 60 min; Bare: bare soil cover; Veg: vegetation cover; Ro: soil roughness; Re: soil resistance; Inf: soil infiltration; St: orchard steepness.

Multiple Regression models	n	R^2	F value	p-value	NSE	MAE
Microplot erosion models						
SE = 0.829 – 0.016*I60	189	0.006	1.0	0.319	−0.03	0.6
SE = 0.715 – 0.02*I60 + 0.007*Bare	189	0.022	1.9	0.160	0.02	0.58
SE = 0.267 – 0.022*I60 + 0.01*Bare – 0.051*Ro + 0.04*Re	189	0.046	2.0	0.097	−0.36	0.56
Hillslope plots erosion models						
SE = –0.533 + 0.153*I60	198	0.152	28.8	< 0.001	0.16	1.16
SE = 0.957 + 0.15*I60 – 0.033*Veg	198	0.204	20.5	< 0.001	0.38	0.47
SE = 0.697 + 0.125*I60 – 0.028*Veg + 0.264*Ro – 0.264*Re – 0.001*Inf	198	0.292	13.0	< 0.001	0.51	0.41
SE = –0.134 + 0.125*I60 – 0.028*Veg + 0.136*Ro – 0.365*Re – 0.001*Inf + 0.193*St	198	0.304	11.4	< 0.001	0.55	0.4

facilitated the appearance of rills (Gómez et al., 2009). In contrast, and to a lesser extent, roughness in the vegetation strips also peaked in the orchards with uncut vegetation (1Herb, 2Herb, and 7None), but in this case it should be attributed to the higher vegetation growth, thereby promoting surface stability, and potentially reducing erosion (Lann et al., 2024). The roughness values measured in our wheel ruts (up to 15 %) are comparable to those reported for compacted traffic lines in other orchard systems (Leys et al., 2010), confirming their role as flow paths.

Soil resistance was generally highest in rut and vegetation strips, due to compaction from machinery passage, and minimal in tree-line areas, likely a consequence of organic matter enrichment and limited machinery impact (Gómez et al., 2009; Oliveira et al., 2024). However, it was also high in some instances, such as 7None, likely due to the poor soil conditions of this area (Table S4) where the high stoniness and low carbon content may promote high soil resistance (Shaheb et al., 2021).

Based on our results, we can rank the studied orchards from most to least erosive at the hillslope scale: the herbicide-managed orchards (1Herb, 2Herb) presented the highest erosion risk (11.3 t ha^{-1} yr^{-1}), followed by the plowed orchards with significant disturbance (3Plow; 5 t ha^{-1} yr^{-1}), while the low-disturbance treatments (6Cut, 7None) were effectively non-erosive (<0.14 t ha^{-1} yr^{-1}). This ranking offers clear, evidence-based guidance: minimizing vegetation suppression is the most effective strategy. For sites where suppression is necessary, our data suggests a hierarchy of practices. For herbicide-treated sites, the priority should be to minimize the number of applications and maintain vegetation cover in wheel rut areas to disrupt runoff concentration, potentially supplemented by mulch from organic residues (Prats et al., 2016; Bombino et al., 2021). For plowing treatments, adopting reduced or no-tillage practices is critical to avoid the high detachment observed at the microplot scale (Martínez-Mena et al., 2020; Carretta et al., 2021), with alternatives like mechanical weed control (Fishkis and Koch, 2023) or phytotoxic biochar (Canedo et al., 2025) offering non-chemical options. The confirmed benchmark for sustainability is the low-disturbance practices (6Cut, 7None), which demonstrate that erosion can be virtually eliminated without intensive intervention, though complementary measures to improve soil health may be warranted in exhausted soils like 7None.

To translate these findings into farm–scale management, erosion mitigation should be integrated with olive productivity goals. Maintaining partial ground cover, especially in wheel ruts and between tree rows, can reduce runoff connectivity while minimizing water competition (Gómez et al., 2009; Cerdà et al., 2021). Confining machinery traffic to permanent lanes reduces rut formation and compaction (Leys et al., 2010; Shaheb et al., 2021). Optimizing the timing of weed–control operations to avoid wet periods can lower erosion risk without sacrificing crop performance (Keesstra et al., 2018). Such strategies, tailored to local soil and climate conditions, enable farmers to balance soil conservation with olive yield in Mediterranean intensification contexts.

4.2. *The effect of plot size on soil erosion*

Our results showed that hillslope plots treated with herbicide showed higher erosion rates than microplots, while the opposite was found for most of the other treatments. This scale-dependent response can be explained by the shift in dominant erosion processes and sediment connectivity. Herbicide management, by creating bare and compacted wheel ruts, appears to have promoted hydrological connectivity and rill formation at the hillslope scale, contributing to higher sediment transport (Gómez et al., 2009b; Cerdà et al., 2021). In contrast, plowing was associated with maximized soil detachment at the microplot scale via rain splash and sheet flow (Gómez et al., 2009), but this mobilized sediment seems not to have been efficiently connected for transport at the hillslope scale, potentially due to disruptors like vegetated strips (Keesstra et al., 2018; López-Vicente et al., 2021). The significant three-way interaction between plot size, year, and treatment (Table 3) further indicates that these scale and management dependent responses varied between years. In Year 1, characterized by higher rainfall intensity, herbicide-driven hillslope erosion was most pronounced, while in Year 2, with lower intensity, plowing-induced microplot detachment remained relatively higher. This suggests that both management practice and interannual hydroclimatic variability help shape erosion risk across scales.

These scale-dependent responses underscore why multi-scale assessment is essential for effective erosion management in olive orchards. Interventions that only address micro-scale detachment (e.g., reducing tillage) may still allow connected rill erosion at the hillslope scale if wheel-rut connectivity is not disrupted. Conversely, practices that maintain vegetation strips can trap sediment locally but may not prevent splash erosion under the tree canopy. Therefore, successful soil conservation requires integrated strategies that target both detachment and transport processes across spatial scales, matching the scale of the intervention to the dominant erosion mechanism (De Vente et al., 2013; Bagarello et al., 2018).

Previous research with similar plot sizes in wildfires showed the opposite trends, with scale ratios lower than one (i.e., the microplots produced more erosion than the hillslope plots; Prats et al., 2016), and the authors attributed this to the lack of rill erosion. In fact, hillslope plots have been used because they include rainsplash, interrill, and rill erosion processes, whereas the microplots only accounted for the splash and interrill erosion processes (Thomaz and Vestena, 2012; Prats et al., 2016; Bagarello et al., 2018; Neumann et al., 2022). In our study, herbicide showed evidence of riling and rendered scale ratios slightly higher than one, while plowing remained in a medium position and no-cutting treatments attained no rills and the highest enrichment ratios. Notably, the plots exhibiting rills were the only ones where significant erosion occurred, supporting the view that rill erosion, driven by runoff detachment and transport, is likely the dominant mechanism in these Mediterranean environments. These trends were previously observed by others (Martínez-Mena et al., 2020; Zuazo et al., 2020; Majewski et al., 2023; An et al., 2024; Márquez-García et al., 2024) and were reflected in different key factors explaining soil erosion (Fig. 5): rainfall amount for the herbicide-rilling areas, with an immediate and fast response, independent of rainfall intensity, and rainfall intensity for areas with some buffer effect of the surface, either from mulch or vegetation, in which a

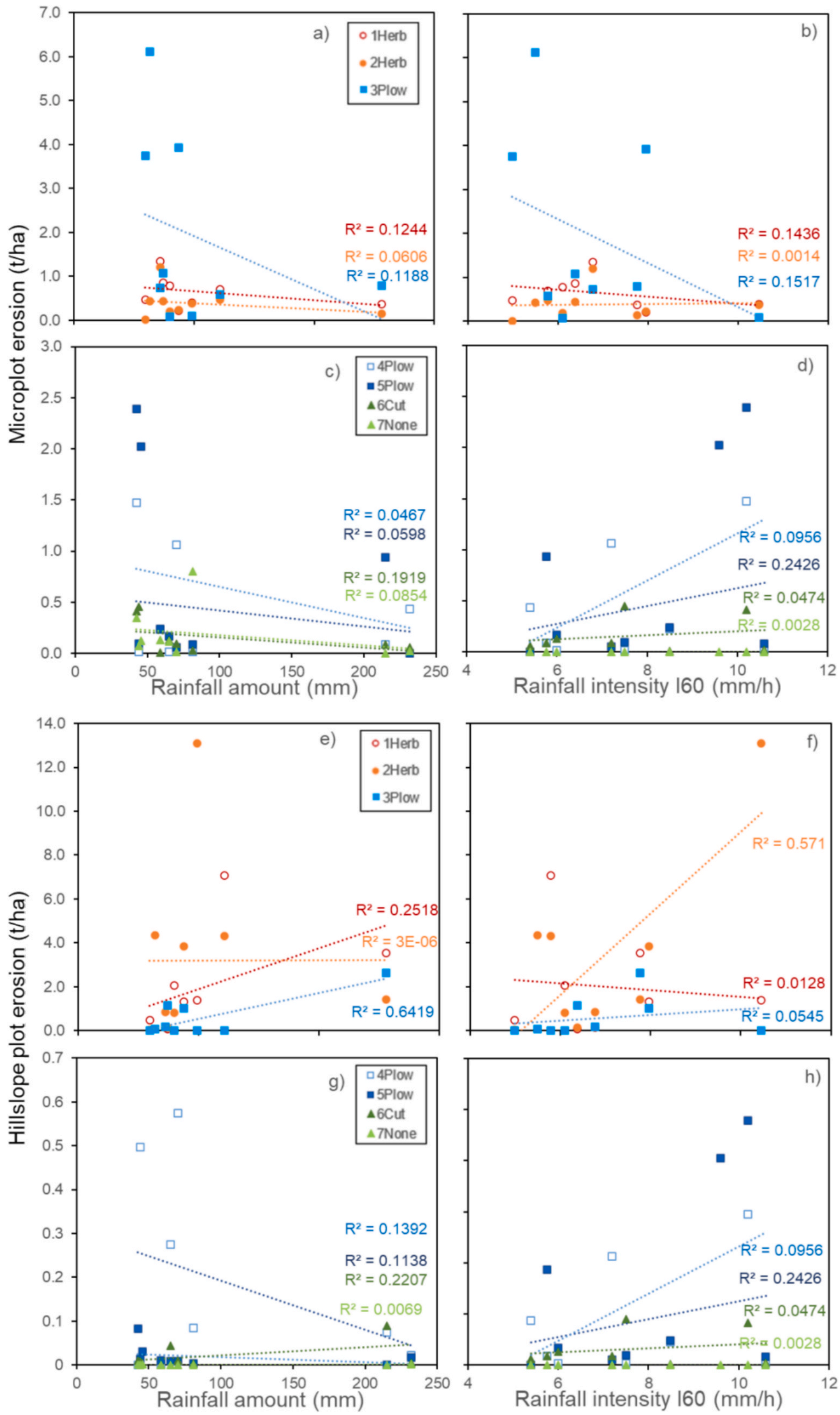

Fig. 5. Linear correlations between soil erosion (t/ha) in the microplots (a-d) and hillslope plots (e-h); and rainfall amount (a, c, e, g) and maximum rainfall intensity in 60 min (I60) (b, d, f, h) in each of the seven olive orchards and measuring periods of this research.

higher rainfall intensity was needed to produce a mild and modest erosion response (Prats et al. 2016).

Our findings have implications for erosion modelling. The contrast in both erosion rates and controlling factors between microplots and hillslope plots underscores a fundamental scaling challenge: models parameterized with data from one scale may perform poorly at another (De Vente et al., 2013; Nunes et al., 2018). Specifically, our results suggest that models applied to managed olive orchards should explicitly account for the role of management in altering sediment connectivity between microenvironments. For example, a model that only incorporates the high detachability of plowed soil (as observed at the microplot scale) could overpredict hillslope erosion if it does not also simulate the disconnectivity caused by vegetated strips (López-Vicente et al., 2021). Conversely, a model not accounting for the creation of bare, compacted wheel ruts by herbicide management might fail to capture the rill-driven connectivity that leads to high hillslope-scale losses (Gómez et al., 2009). Therefore, accurately scaling erosion predictions in these systems would benefit from models that can simulate the shifting dominance of processes (splash vs. rill) with plot size (Wainwright et al., 2000) and the management-driven connectivity of orchard microenvironments, which our data indicates as the primary control on scale-dependent responses. Physically based models that structure the landscape into functional units (e.g., WEPP, SWAT) may be better suited to this task than purely empirical approaches (Alewell et al., 2019), but they require high-resolution input data on management practices and their spatial implementation (Panagos et al., 2014; Ke and Zhang, 2024).

The influence of plot size on erosion highlights that effective conservation strategies should be scale appropriate. Our findings demonstrate that processes dominating at one scale (e.g., detachment in microplots) may not govern outcomes at another (e.g., connected rill transport at hillslopes), necessitating a nested, multi-scale approach. Localized, plot-scale measures such as contour farming (Mondaca et al., 2024) and mulching (Prats et al., 2016) can be effective for controlling interrill processes, but broader strategies are required to mitigate the connected rill erosion that drives major hillslope losses. These include maintaining vegetation strips (Zhang et al., 2024), adopting no-till systems (Skaalsveen et al., 2019), and implementing watershed-scale planning that explicitly considers sediment connectivity (Silva et al., 2024). Such combinations could work synergistically to limit sediment transport across scales (Keesstra et al., 2018). Consequently, erosion control policies and agricultural subsidies should be designed within a multi-scale framework, incentivizing practices that address both detachment and connectivity, and should be adapted to local contexts as no single solution is universally applicable.

When interpreting these results, key methodological aspects should be considered. Soil properties (infiltration, roughness, resistance) were characterized during a single campaign, providing a snapshot of these dynamic characteristics and thus not capturing their potential temporal variability across the two-year study period. Furthermore, microplots were installed under the tree canopy to isolate the management effect in that specific microenvironment; consequently, the microplot-scale data are not directly analogous to the integrated processes captured by the hillslope plots, and our analysis was confined to the plot scale without watershed-level assessment. Additionally, while the three main vegetation suppression strategies were clearly defined, operational heterogeneity in timing, frequency, and intensity of interventions existed within treatment categories (Table S1), reflecting real-world farming conditions but limiting fine-scale comparability across orchards. The varying proportions of tree, rut, and vegetation microenvironments across orchards (Table 1) could also influence cross-site comparisons. However, our multi-scale data indicate that management-induced changes in rut connectivity, not microenvironment area, governed erosion responses. This is evidenced by the reversal in erosion dominance between scales (plowing highest in microplots, herbicide highest in hillslope plots), pointing to activated ruts as the primary driver regardless of their proportional area. Finally, the moderate explanatory power of the regression models ($R2 \leq 0.30$) indicates that other unmeasured factors, such as microtopography, soil moisture, or biological interactions, also influence erosion rates. Our analysis therefore highlights key drivers but does not capture the full complexity of erosion processes. These inherent constraints of the field-based design are balanced by the study's strength in quantifying erosion responses under real, working agricultural conditions.

5. Conclusions

The conclusions regarding the effects of different vegetation suppression treatments (herbicides, plowing, no intervention) on soil erosion processes in the different soil microenvironments (tree, rut, vegetation) at the scale of the microplots of 1 m^2 and hillslope plots of 100–300 m^2 in olive orchards of the Alentejo region during a two-year period are summarized as follows:

- Herbicide application on the tree microenvironment resulted in an average erosion of 2.3 t ha^{-1} yr^{-1} on the microplots, while the plowing treatment doubled this erosion (4.6 t ha^{-1} yr^{-1}), and the low vegetation and soil disturbance treatments decreased erosion by 78 %.
- At the scale of the hillslope, herbicide application in the tree area resulted in an average erosion of 11.3 t ha^{-1} yr^{-1}, while plowing reduced this erosion by 90 %, and low vegetation and soil disturbance were still 99 % lower, compared with the herbicide treatment.
- The two plot sizes allowed us to understand the degradation processes in each management:
  - o Herbicide treatment: Showed low erosion at the microplot scale due to already depleted soils (stone armoring), but the highest erosion at the hillslope scale, indicating strong rill erosion driven by high roughness and bare soil in the rut areas.
  - o Plowing treatment: Resulted in maximum erosion at the microplot scale due to the loosening and detachment of soil particles, making them readily available for transport by rain splash and sheet flow, but low erosion at the hillslope scale, indicating a lack of sediment connectivity or rill formation.
  - o Low vegetation and minimal soil disturbance treatments: Resulted in the lowest erosion rates at both scales, confirming them as the most effective practices, though some sites may require additional measures to improve infiltration and organic matter.
- Rainfall intensity, bare and vegetation soil cover as well as roughness and resistance in the rut and vegetation microenvironments were key factors explaining erosion in the hillslope plots. In the case of the microplots, soil roughness and resistance exerted a stronger effect than the ground cover, indicating local factors affecting the specific conditions of the tree area microsite.

Future research should expand upon these findings by validating plot-scale effects across diverse conditions to improve model calibration and scale-impact assessments. Investigations at the watershed level would provide a more complete understanding of spatial variability in erosion processes, particularly when coupled with the analysis of high-resolution Digital Elevation Models (DEMs) to accurately map microtopography, rill formation, and sediment redistribution pathways. Additionally, incorporating conventionally managed sites would allow for more robust comparisons. Finally, the results of this study could serve as a foundation that ultimately supports more informed decision-making in soil conservation.

6. Declaration of AI technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to improve the readability, clarity and language of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

V. Daimonakos: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **A.Van Zinderen:** Investigation. **J. Muñoz-Rojas:** Writing – review & editing, Visualization, Validation, Investigation, Funding acquisition, Conceptualization. **D. Costa:** Writing – review & editing, Validation, Funding acquisition, Conceptualization. **J.P. Nunes:** Writing – review & editing, Validation. **S.A. Prats:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2026.117673.

Data availability

Data will be made available on request.

References

Alewell, C., Borrelli, P., Meusburger, K., Panagos, P., 2019. Using the USLE: Chances, challenges and limitations of soil erosion modelling. Int. Soil Water Conserv. Res. 7, 203–225. https://doi.org/10.1016/j.iswcr.2019.05.004.

An, M., Wei, C.C., Han, Y., Qu, Z., Wang, X., Zhang, B., 2024. Soil erosion and nutrient loss due to changes in rainfall intensity under different wind directions. Earth Surf. Proc. Land. 49, 291–303. https://doi.org/10.1002/esp.5674.

Arnhold, S., Lindner, S., Lee, B., Martin, E., Kettering, J., Nguyen, T.T., Koellner, T., Ok, Y.S., Huwe, B., 2014. Conventional and organic farming: Soil erosion and conservation potential for row crop cultivation. Geoderma 219–220, 89–105. https://doi.org/10.1016/j.geoderma.2013.12.023.

Bagarello, V., Ferro, V., Keesstra, S., Comino, J.R., Pulido, M., Cerdà, A., 2018. Testing simple scaling in soil erosion processes at plot scale. Catena 167, 171–180. https://doi.org/10.1016/j.catena.2018.04.035.

Beniaich, A., Guimarães, D.V., Avanzi, J.C., Silva, B.M., Acuña-Guzman, S.F., Dos Santos, W.P., Silva, M.L.N., 2023. Spontaneous vegetation as an alternative to cover crops in olive orchards reduces water erosion and improves soil physical properties under tropical conditions. Agric Water Manag 279, 108186. https://doi.org/10.1016/j.agwat.2023.108186.

Berger, A., Friedrich, T., Kienzle, J., 2010. Soils, plant growth and crop production. Conserv. Agric. 1, 108–112.

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.

Bombino, G., Denisi, P., Gómez, J.A., Zema, D.A., 2019. Water infiltration and surface runoff in steep clayey soils of olive groves under different management practices. Water 11, 240. https://doi.org/10.3390/w11020240.

Cammeraat, E.L.H., 2004. Scale dependent thresholds in hydrological and erosion response of a semi-arid catchment in southeast Spain. Agric. Ecosyst. Environ. 104, 317–332. https://doi.org/10.1016/j.agee.2004.01.032.

Canedo, J.N.G.V., Coelho, L., Castro, L., Verheijen, F.G.A., Prats, S., 2025. Biochar and Mulch: hydrologic, erosive, and phytotoxic responses across different application strategies and agricultural soils. Agronomy 15, 926. https://doi.org/10.3390/agronomy15040926.

Carretta, L., Tarolli, P., Cardinali, A., Nasta, P., Romano, N., Masin, R., 2021. Evaluation of runoff and soil erosion under conventional tillage and no-till management: A case study in northeast Italy. Catena 197, 104972. https://doi.org/10.1016/j.catena.2020.104972.

Cerdà, A., Terol, E., Daliakopoulos, I.N., 2021. Weed cover controls soil and water losses in rainfed olive groves in Sierra de Enguera, eastern Iberian Peninsula. J. Environ. Manage. 290, 112516. https://doi.org/10.1016/j.jenvman.2021.112516.

De La Rosa, J.M., Campos, P., Diaz-Espejo, A., 2022. Soil Biochar Application: Assessment of the Effects on Soil Water Properties, Plant Physiological Status, and Yield of Super-Intensive Olive Groves under Controlled Irrigation Conditions. Agronomy 12, 2321. https://doi.org/10.3390/agronomy12102321.

De Vente, J., Poesen, J., Verstraeten, G., Govers, G., Vanmaercke, M., Van Rompaey, A., Arabkhedri, M., Boix-Fayos, C., 2013. Predicting soil erosion and sediment yield at regional scales: Where do we stand? Earth Sci. Rev. 127, 16–29. https://doi.org/10.1016/j.earscirev.2013.08.014.

Fishkis, O., Koch, H.J., 2023. Effect of mechanical weeding on soil erosion and earthworm abundance in sugar beet (Beta vulgaris L.). Soil Tillage Res. 225, 105548. https://doi.org/10.1016/j.still.2022.105548.

Fraga, H., Pinto, J.G., Santos, J.A., 2020. Olive tree irrigation as a climate change adaptation measure in Alentejo. Portugal. Agric. Water Manag. 237, 106193. https://doi.org/10.1016/j.agwat.2020.106193.

Gómez, J.A., Guzmán, M.G., Giráldez, J.V., Fereres, E., 2009. 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., Sobrinho, T., Giraldez, J., Fereres, E., 2009. 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.

González-Rosado, M., Parras-Alcántara, L., Aguilera-Huertas, J., Lozano-García, B., 2021. Soil productivity degradation in a long-term eroded olive orchard under semiarid mediterranean conditions. Agronomy 11, 812. https://doi.org/10.3390/agronomy11040812.

González-Sánchez, E.J., Ordóñez-Fernández, R., Carbonell-Bojollo, R., Veroz-González, O., Gil-Ribes, J.A., 2012. Meta-analysis on atmospheric carbon capture in Spain through the use of conservation agriculture. Soil Tillage Res. 122, 52–60. https://doi.org/10.1016/j.still.2012.03.001.

Ke, Q., Zhang, K., 2024. Scale issues in runoff and sediment delivery (SIRSD): A systematic review and bibliometric analysis. Earth Sci. Rev. 251, 104729. https://doi.org/10.1016/j.earscirev.2024.104729.

Keesstra, S., Nunes, J., Novara, A., Finger, D., Avelar, D., Kalantari, Z., Cerdà, A., 2018. The superior effect of nature-based solutions in land management for enhancing ecosystem services. Sci. Total Environ. 610–611, 997–1009. https://doi.org/10.1016/j.scitotenv.2017.08.077.

Keesstra, S., Pereira, P., Novara, A., Brevik, E.C., Azorin-Molina, C., Parras-Alcántara, L., Jordán, A., Cerdà, A., 2016. Effects of soil management techniques on soil water erosion in apricot orchards. Sci. Total Environ. 551–552, 357–366. https://doi.org/10.1016/j.scitotenv.2016.01.182.

Kramer, C.Y., 1956. Extension of multiple range tests to group means with unequal numbers of replications. Biometrics 12, 307–310. https://doi.org/10.2307/3001469.

Lann, T., Bao, H., Lan, H., Zheng, H., Yan, C., Peng, J., 2024. Hydro-mechanical effects of vegetation on slope stability: A review. Sci. Total Environ. 926, 171691. https://doi.org/10.1016/j.scitotenv.2024.171691.

Leys, A., Govers, G., Gillijns, K., Berckmoes, E., Takken, I., 2010. Scale effects on runoff and erosion losses from arable land under conservation and conventional tillage: The role of residue cover. J. Hydrol. 390, 143–154. https://doi.org/10.1016/j.jhydrol.2010.06.034.

Liu, H., Blagodatsky, S., Giese, M., Liu, F., Xu, J., Cadisch, G., 2016. Impact of herbicide application on soil erosion and induced carbon loss in a rubber plantation of Southwest China. Catena 145, 180–192. https://doi.org/10.1016/j.catena.2016.06.007.

López-Vicente, M., Gómez, J.A., Guzmán, G., Calero, J., García-Ruiz, R., 2021. The role of cover crops in the loss of protected and non-protected soil organic carbon fractions due to water erosion in a Mediterranean olive grove. Soil Tillage Res. 213, 105119. https://doi.org/10.1016/j.still.2021.105119.

Malvar, M.C., Silva, F.C., Prats, S.A., Vieira, D.C., Coelho, C.O., Keizer, J.J., 2017. Short-term effects of post-fire salvage logging on runoff and soil erosion. For. Ecol. Manag. 400, 555–567. https://doi.org/10.1016/j.foreco.2017.06.031.

Majewski, M., Czuchaj, A., Marciniak, M., 2023. Impact of rainfall intensity on soil erosion based on experimental research. Landf. Anal. 42, 25–36. https://doi.org/10.12657/landfana-042-002.

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.

Martínez-Mena, M., Carrillo-López, E., Boix-Fayos, C., Almagro, M., García Franco, N., Díaz-Pereira, E., Montoya, I., De Vente, J., 2020. Long-term effectiveness of sustainable land management practices to control runoff, soil erosion, and nutrient loss and the role of rainfall intensity in Mediterranean rainfed agroecosystems. Catena 187, 104352. https://doi.org/10.1016/j.catena.2019.104352.

Massey Jr., F.J., 1951. The Kolmogorov-Smirnov test for goodness of fit. J. Am. Stat. Assoc. 46, 68–78. https://doi.org/10.2307/2280095.

Mondaca, P., Lebuy, R., Rojas, S., Aguas, J., Celis-Diez, J.L., Díaz-Siefer, P., 2024. Contour furrowing reduces erosion and enhances soil moisture on semiarid hillslopes. Geoderma Reg. 38, e00826. https://doi.org/10.1016/j.geodrs.2024.e00826.

Nachtergaele, J., Poesen, J., Vandekerckhove, L., Oostwoud Wijdenes, D., Roxo, M., 2001. Testing the ephemeral gully erosion model (EGEM) for two mediterranean environments. Earth Surf. Proc. Land. 26, 17–30. https://doi.org/10.1002/1096-9837(200101)26:1 17::AID-ESP149 3.0.CO;2-7.

Neumann, M., Kavka, P., Devátý, J., Stašek, J., Strouhal, L., Tejkl, A., Kubínová, R., Rodrigo-Comino, J., 2022. Effect of plot size and precipitation magnitudes on the activation of soil erosion processes using simulated rainfall experiments in vineyards. Front. Environ. Sci. 10, 949774. https://doi.org/10.3389/fenvs.2022.949774.

Novara, A., Gristina, L., Saladino, S.S., Santoro, A., Cerdà, A., 2011. Soil erosion assessment on tillage and alternative soil managements in a Sicilian vineyard. Soil Tillage Res. 117, 140–147. https://doi.org/10.1016/j.still.2011.09.007.

Nunes, A.N., Gonçalves, J.P., Figueiredo, A., 2023. Soil erosion in extensive versus intensive land uses in areas sensitive to desertification: A case study in beira baixa. Portugal. Land 12, 1591. https://doi.org/10.3390/land12081591.

Nunes, J.P., Bernard-Jannin, L., Rodríguez Blanco, M.L., Boulet, A.-K., Santos, J.M., Keizer, J.J., 2020. Impacts of wildfire and post-fire land management on hydrological and sediment processes in a humid Mediterranean headwater catchment. Hydrol. Process. 34, 5210–5228. https://doi.org/10.1002/hyp.13926.

Nunes, J.P., Wainwright, J., Bielders, C.L., Darboux, F., Fiener, P., Finger, D., Turnbull, L., 2018. Better models are more effectively connected models. Earth Surf. Process. Landforms 43, 1355–1360. https://doi.org/10.1002/esp.4323.

Oliveira, E.M.D., Hermógenes, G.M., Brito, L.D.C., Silva, B.M., Avanzi, J.C., Beniaich, A., Silva, M.L.N., 2024. Cover crop management systems improves soil quality and mitigate water erosion in tropical olive orchards. Sci. Hortic. 330, 113092. https://doi.org/10.1016/j.scienta.2024.113092.

Palese, A.M., Vignozzi, N., Celano, G., Agnelli, A.E., Pagliai, M., Xiloyannis, C., 2014. Influence of soil management on soil physical characteristics and water storage in a mature rainfed olive orchard. Soil Tillage Res. 144, 96–109. https://doi.org/10.1016/j.still.2014.07.010.

Panagos, P., Karydas, C., Borrelli, P., Ballabio, C., Meusburger, K., 2014. Advances in soil erosion modelling through remote sensing data availability at European scale. In: Hadjimitsis, D.G., Themistocleous, K., Michaelides, S., Papadavid, G. (Eds.), Presented at the Second International Conference on Remote Sensing and Geoinformation of the Environment (RSCy2014). https://doi.org/10.1117/12.2066383.

Pareja-Sánchez, E., Calero, J., García-Ruiz, R., 2024. Does spontaneous cover crop increase the stocks of soil organic carbon and nitrogen in commercial olive orchard? Soil Tillage Res. 244, 106237. https://doi.org/10.1016/j.still.2024.106237.

Parsakhoo, A., Hosseini, S.A., Lotfalian, M., Jalilvand, H., 2009. Soil loss and displacement by heavy equipment in forest road subgrading projects. Int. J. Sedim. Res. 24, 227–235. https://doi.org/10.1016/S1001-6279(09)60029-9.

Prats, S.A., Sierra-Abraín, P., Moraña-Fontán, A., Zas, R., 2022. Effectiveness of community-based initiatives for mitigation of land degradation after wildfires. Sci. Total Environ. 810, 152232. https://doi.org/10.1016/j.scitotenv.2021.152232.

Prats, S.A., Malvar, M.C., Wagenbrenner, J.W., 2020. Compaction and cover effects on runoff and erosion in post-fire salvage logged areas in the Valley Fire. California. Hydrol. Process. 35, e13997. https://doi.org/10.1002/hyp.13997.

Prats, S.A., Wagenbrenner, J.W., Martins, M.A.S., Malvar, M.C., Keizer, J.J., 2016. Mid-term and scaling effects of forest residue mulching on post-fire runoff and soil erosion. Sci. Total Environ. 573, 1242–1254. https://doi.org/10.1016/j.scitotenv.2016.04.064.

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.

Rodríguez Sousa, A.A., Parra-López, C., Sayadi-Gmada, S., Barandica, J.M., Rescia, A.J., 2021. Impacts of erosion on the sustainability of organic olive groves: A case study (Estepa Region, Southwestern Spain). Sustainability 13, 7983. https://doi.org/10.3390/su13147983.

Roy, A., Khattree, R., 2007. Classification of multivariate repeated measures data with temporal autocorrelation. J. Appl. Stat. Sci. 15, 283–294.

Santos, R., Fonseca, F., Baptista, P., Paz-González, A., De Figueiredo, T., 2023. Erosion control performance of improved soil management in olive groves: A field experimental study in NE portugal. Land 12, 1700. https://doi.org/10.3390/land12091700.

Saleh, A., 1993. Soil roughness measurement: Chain method. J. Soil Water Conserv. 48, 527–529. https://doi.org/10.1080/00224561.1993.12456826.

Shaheb, M.R., Venkatesh, R., Shearer, S.A., 2021. A Review on the effect of soil compaction and its management for sustainable crop production. J. Biosyst. Eng. 46, 417–439. https://doi.org/10.1007/s42853-021-00117-7.

Shapiro, S.S., Wilk, M.B., 1965. An analysis of variance test for normality (complete samples). Biometrika 52, 591–611. https://doi.org/10.2307/2333709.

Silva, T.P., Bressiani, D., Ebling, É.D., Reichert, J.M., 2024. Best management practices to reduce soil erosion and change water balance components in watersheds under grain and dairy production. Int. Soil Water Conserv. Res. 12, 121–136. https://doi.org/10.1016/j.iswcr.2023.06.003.

Skaalsveen, K., Ingram, J., Clarke, L.E., 2019. The effect of no-till farming on the soil functions of water purification and retention in north-western Europe: A literature review. Soil Tillage Res. 189, 98–109. https://doi.org/10.1016/j.still.2019.01.004.

Taguas, E.V., Gómez, J.A., 2015. Vulnerability of olive orchards under the current CAP (Common Agricultural Policy) regulations on soil erosion: a study case in Southern Spain. Land Use Policy 42, 683–694. https://doi.org/10.1016/j.landusepol.2014.09.001.

Thomaz, E.L., Vestena, L.R., 2012. Measurement of runoff and soil loss from two differently sized plots in a subtropical environment (Brazil). Earth Surf. Proc. Land. 37, 363–373. https://doi.org/10.1002/esp.2242.

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., Jones, R., Rickson, R., Smith, C., 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.

Vicente-Vicente, J.L., García-Ruiz, R., Francaviglia, R., Aguilera, E., Smith, P., 2016. Soil carbon sequestration rates under Mediterranean woody crops using recommended management practices: A meta-analysis. Agric. Ecosyst. Environ. 235, 204–214. https://doi.org/10.1016/j.agee.2016.10.024.

Wainwright, J., Parsons, A.J., Abrahams, A.D., 2000. Plot-scale studies of vegetation, overland flow and erosion interactions: case studies from Arizona and New Mexico. Hydrol. Process. 14, 2921–2943. https://doi.org/10.1002/1099-1085(200011/12)14:16/17 2921::AID-HYP127 3.0.CO;2-7.

Zhang, X., Li, P., Bin Li, Z., Qiang, Yu., G.,, 2024. Effects of grass strips distribution on soil erosion and its optimal configuration on hillslopes. Catena 238, 107882. https://doi.org/10.1016/j.catena.2024.107882.

Zuazo, V.H.D., Rodríguez, B.C., García-Tejero, I.F., Ruiz, B.G., Tavira, S.C., 2020. Benefits of organic olive rainfed systems to control soil erosion and runoff and improve soil health restoration. Agron. Sustain. Dev. 40, 41. https://doi.org/10.1007/s13593-020-00644-1.