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Case Study

Evaluating soil respiration and water infiltration in esparto grasslands: the effects of hillslope position and soil management in arid, human-affected Mediterranean environments

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Abstract

Stipa tenacissima L., commonly known as esparto grass, is a key species in semi-arid Mediterranean ecosystems, historically valued for its use in crafts and agriculture. However, the widespread abandonment of esparto grasslands has led to significant soil degradation, including erosion, reduced water retention, and nutrient loss. In Benamaurel, Granada (Southern Spain), where these grasslands once thrived, abandonment has exacerbated soil degradation, driven by the region's distinct geomorphological and climatic conditions, such as saline soils, gypsum deposits, and extreme temperatures. This study aims to assess soil infiltration and respiration dynamics in both cultivated and abandoned esparto grasslands in Benamaurel, considering different hillslope positions (upper, backslope, and footslope). Our results demonstrate significant variability in soil infiltration (differences between 0.5 and 1.5 mm h^{-1}) and respiration (difference of -9.17 µg m^2 hr^{-1} in CO_2 emissions), with no consistent trends identified across different hillslope positions or types of land management. Key soil properties, including bulk density, organic matter, and soil water retention capacity (SWRC), play a critical role in these processes, though their effects vary. Long-term monitoring is essential for understanding these dynamics, especially in the context of climate change. Our findings highlight the need for conservation strategies to prevent further soil degradation, promote landscape restoration, and reduce environmental risks. Gaining insight into the effects of abandonment on soil quality in this region is crucial for developing effective land management practices.

Keywords *Stipa tenacissima* · Environmental degradation · Ecosystem management · Conventional agriculture · Soil management · Sustainable practices

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1 Introduction

Stipa tenacissima L., commonly known as alfa fiber or esparto grass, is a herbaceous plant belonging to the Poaceae family [28]. The leaves of esparto grass are estimated to take approximately 6 months to reach full development. After this growth period, their longevity allows them to persist for 12–24 months. Historically, during fiber harvesting, nearby shrubs that could interfere with esparto grass growth were removed to enhance production. Esparto grass is one of the most widespread plant formations in the semi-arid western Mediterranean. Estimates suggest its current distribution covers approximately 32,000 km^2, though historically, it may have spanned over 86,500 km^2. This species is prevalent in the Iberian steppes, including provinces such as Murcia, Albacete, Almería, and Granada, as well as in North Africa [30, 55]. However, its significant decline is attributed to a combination of factors, including shifts in land use toward more profitable crops, periods of adverse climatic conditions [39], and the abandonment of agricultural land [13, 38].

Esparto grasslands are typically found on nutrient-poor, rocky soils, often characterized by carbonate or gypsum substrates, which contribute to their salinity [37, 44, 48]. Soil erosion continues to intensify, primarily due to the nature of calcareous soils, which support only sparse vegetation cover, offering minimal protection against degradation [9, 10]. The deterioration of soil quality has led to widespread land abandonment, a trend frequently observed in geomorphological landscapes such as badlands [45].

In these soils, water scarcity is severely exacerbated. As a result, atmospheric humidity and water vapor play a crucial role in the survival of *Stipa tenacissima* [58], directly influencing its germination and growth [37, 38]. These environmental variations, combined with human management and arid climatic conditions, shape both abandoned and cultivated lands. Notably, organic matter levels in cultivated lands are often significantly lower than in abandoned areas [33, 50, 75]. This decline is attributed to practices such as shrub clearance and the maintenance of esparto grass, which remove barriers to the plant's growth [13]. Regarding the climatic conditions required for *Stipa tenacissima*, various authors have identified an annual average precipitation range of 200–400 mm, with significant temperature fluctuations from 0 to 40 °C, and an average of around 14 °C, alongside high soil salinity. To withstand these extreme conditions, the species has developed several morphophysiological adaptations [29, 55].

Esparto (*Stipa tenacissima*) has been documented as a valuable resource since prehistoric times and continues to be used today, particularly as a substitute for synthetic fibers and plastics. Traditionally, it has been utilized for thermal insulation in roofs, crafting domestic items, rustic decorations, and agricultural tools [3], such as baskets, ropes, espadrilles, and rugs. It has also been combined with clay to reinforce ceramic elements. During the Roman era, esparto-made materials were widely exported and traded beyond the western Mediterranean. From the 5th to the fifteenth centuries, small guilds specializing in esparto crafts emerged, including esparto workers, spinners, and espadrille makers [56].

Since the 1960s, esparto has been increasingly replaced by jute and sisal, leading to the disappearance of the Esparto Service and a subsequent decline in prices. This decline has also been driven by industrial mechanization, which has had a direct impact on the esparto sector, as its collection remains highly labor-intensive, expensive, and nearly impossible to mechanize. As a result, widespread abandonment of esparto grasslands has contributed to environmental degradation, negatively impacting the land [21]. For example, increased desertification has led to reduced water retention and infiltration capacity, causing productivity losses due to nutrient depletion. Additionally, changes in soil respiration can alter carbon levels, affecting the sustainability and ecological function of esparto grass ecosystems.

In the province of Granada, esparto grasslands cover a total of 51,314 hectares. One of the most notable municipalities is Benamaurel, where a significant portion of agricultural land—34.4% of the total—is still devoted to esparto, amounting to 4,382 hectares out of the 12,819 hectares registered for crops (Consejería de Agricultura, Ganadería, Pesca y Desarrollo Sostenible, Spain). However, the abandonment of esparto grasslands in Benamaurel poses a serious threat to soil quality due to the absence of a recovery plan (Fig. 1). A review of the existing literature on abandoned versus cultivated esparto grasslands suggests that abandonment may lead to significant soil degradation. However, there is currently a lack of research in the Mediterranean region that integrates both laboratory analysis and field experiments to determine whether soil degradation is more severe in abandoned esparto grasslands than in cultivated ones, or if allowing the land to rest could facilitate soil recovery [49]. The primary objective of this study is to analyze key soil properties in both cultivated and abandoned esparto plots to assess the severity of soil degradation, particularly its effects on soil respiration and infiltration. To achieve this, multiple field campaigns have been conducted, along with the development of a structured sampling and experimental protocol that includes selective soil sampling and field experiments. The findings could provide valuable insights for land managers, aiding in the development of conservation practices for abandoned esparto grasslands. Implementing such measures could help prevent irreversible soil degradation, enhance landscape resilience,

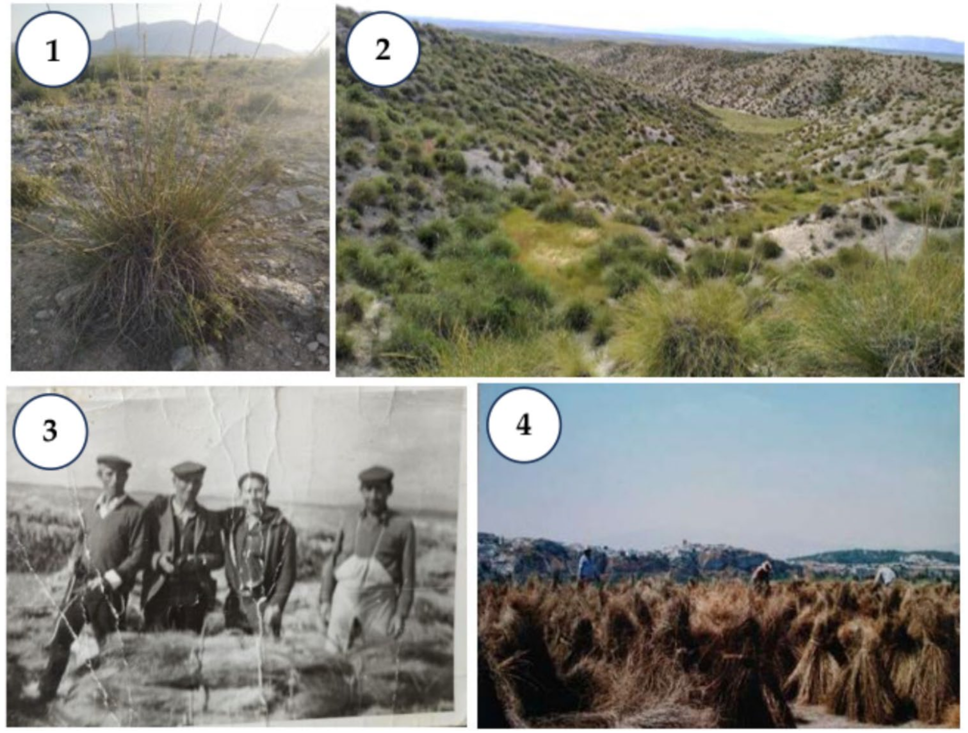


Fig. 1 Esparto grass abandoned in steep slopes (1 and 2), historical pictures of old farmers working on past plantations (3 and 4)

and mitigate environmental risks such as wildfires, runoff peaks, and erosion. We hypothesize that abandoned *Stipa tenacissima* grasslands in Benamaurel will exhibit higher soil infiltration and respiration rates compared to cultivated grasslands due to the re-establishment of spontaneous vegetation cover. We further hypothesize that the impact of land management (cultivated vs. abandoned) on soil infiltration and respiration will vary across different hillslope positions, influenced by local geomorphological and soil characteristics.

2 Materials and methods

2.1 Study area

Benamaurel is a municipality located in the northeast of the Granada province, within the Baza region. It lies within the geomorphological unit known as the Hoya de Baza, covering an area of 127.8 km^2 at an altitude of 719 m above sea level. The municipality is part of the Granada Geopark (UNESCO) and is situated on a vast, arid plain primarily traversed by the Guardal River valley. The geomorphological unit in which Benamaurel is located dates back to the Miocene. With the formation of the Betic Cordillera, a series of depressions emerged, leading to the deposition of Neogene materials following the Alpine Orogeny [16]. The region's landscape is characterized as a floodplain within the Baza depression (IGME—Spanish Geological Survey: MAGNA 50—Hoja 972, CÚLLAR-BAZA). Due to the area's gentle slopes, detrital covers and glacis formations have developed [17]. The selected study plots are situated between 689 and 715 m above sea level.

Intense precipitation events contribute to the formation of concentrated runoff streams, which have shaped the incised slopes commonly known as badlands. As Benamaurel is located on a plain within a depression where runoff water carries soluble salts, the area is characterized by Solonchak-type soils [32]. These soils develop over materials rich in gypsum and salts [31]. While they can be cultivated when properly drained, their high salinity significantly influences the types of crops that can be grown [18]. Regarding climatic conditions, winter temperatures in the study area typically range between 0 and 2 °C, while summer highs can reach up to 39 °C (AEMET, 2023. The average annual temperature is 14 °C, and total annual precipitation is approximately 300 mm, with peaks occurring in the spring months (Proyecto LUCDEME, 2006, Portal Rediam).

2.2 Soil sampling strategy

A sampling campaign was carried out across multiple plots in the locality of Benamaurel (Fig. 2). Four plot types were selected: two abandoned plots (1 and 4) and two cultivated esparto plots (2 and 3). Sampling locations were carefully chosen, with a total of three composite samples collected per hillslope position (upper, back, and footslope), each consisting of five sub-samples (Fig. 3). The specific sampling points have been marked in green on the provided map for reference. Subsequent laboratory analyses were conducted to evaluate the collected samples.

2.3 Selected key soil properties and laboratory analysis

To estimate antecedent soil moisture (ASM) during sample collection, three soil samples were extracted, labeled, and numbered with the corresponding extraction date. The samples were then spread on an aluminum tray, weighed, and dried in an oven at a constant temperature of 60 °C for several days. After drying, they were weighed again to determine the moisture loss by calculating the difference between the initial and final weights. Following this process, the soil was separated based on particle size. Coarser material was sieved first, with gravel fractions classified using 8 mm, 5 mm, and 2 mm sieves [63]. The remaining finer material was passed through a < 2 mm sieve and used for further soil property analyses. Organic matter content was determined using the loss on ignition (LOI) method, with triplicate samples placed in a muffle furnace at 430 °C for 24 h to combust the organic matter [5, 59]. After this period, the crucibles were removed from the furnace and placed in a desiccator for an additional 24 h. To accurately determine the percentage of organic matter burned, the Schulte and Hopkins equation was applied [67] (Eq. 1).

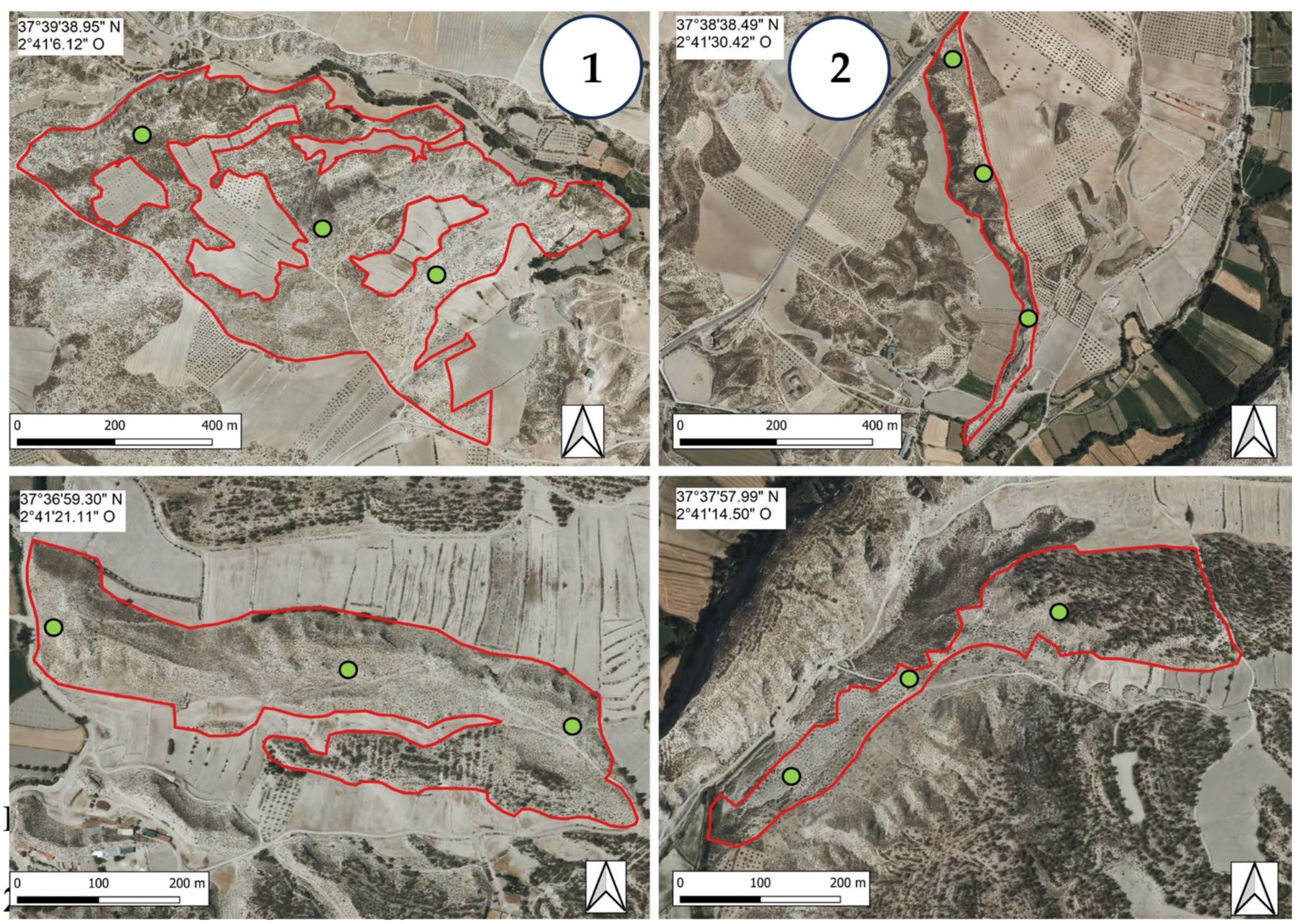


Fig. 2 Study areas and sampling points (1 and 4: abandoned; 2 and 3: cultivated)

Fig. 3 Fieldwork campaigns using plastic bags and rings to collect soil samples (above), mini-disc infiltrometers (middle) and EGM-5 gas analyzer (below)

$$SOMLOI = \left[(soil\ weight\ after\ combustion - oven - dry\ soil\ weight)/\ oven - dry\ soil\ weight\right] \times 100pH \quad (1)$$

Soil pH was determined using a pH meter following the method outlined by Schofield and Taylor [66] and Thomas [71]. A 12.5 ml aliquot of distilled water was added to the soil sample and stirred until a uniform solution was achieved. Aggregate stability was assessed using a wet sieving method. Distilled water was used for Soil 1, while a 2 g/l sodium hexametaphosphate solution was used for Soil 2 [2, 23, 26]. Following the sieving procedure with both solutions, the weight loss of the aggregates was determined. This value was then used to calculate the stability index according to Eq. 2. The resulting stability index ranges from 0 to 1.

$$\text{Aggregate stability index} = \frac{\boldsymbol{Soil}2}{\boldsymbol{Soil}1 + \boldsymbol{Soil}2} \quad (2)$$

To determine water retention capacity, 24 rings were collected concurrently with the soil samples. These rings were then saturated with distilled water using a laboratory pipette [34, 57].

2.4 Soil infiltration

Infiltration rate was measured using an Eijkelkamp mini-disk infiltrometer, a widely used and effective tool for field measurements (Fig. 3) [14, 25, 52]. The infiltrometer was placed on the soil surface, and a known volume of water was applied. The infiltration rate was then determined by monitoring the water level in the cylinder over time. Each measurement typically lasted 30 min, though some were shorter due to rapid soil infiltration. To ensure accuracy and comparability, two replicates were performed at each sampling point using separate infiltrometer placements. The average of these two measurements was taken as the final infiltration rate for that location.

2.5 Soil respiration

Soil respiration was measured using an EGM-5 gas analyzer (PP Systems, Amesbury, USA; Fig. 3), which quantifies carbon dioxide (CO_2) content. CO_2 emissions are a key indicator of soil biological activity [47, 53]. Data was recorded on a USB device. The soil respiration chamber (SRC, 1171 ml), connected to the gas analyzer, measures soil CO_2 fluxes over 78 cm^2

in 60 s, calculating both linear and quadratic fits [43]. The system operates in a closed environment with continuous gas circulation between the chamber and the infrared gas analyzer (IRGA) where measurements are taken.

The EGM-5 utilizes a non-dispersive infrared (NDIR) sensor to detect CO_2 absorption at 4.26 µm, providing high selectivity and minimizing interference from other gases. An integrated infrared light source and optical filter precisely tune the wavelength. The detector measures the decrease in light intensity due to CO_2 absorption, enabling concentration calculations based on the Lambert–Beer law. Five replicate measurements were taken, yielding a total of 60 data points, which are presented in ppm (Fig. 3).

2.6 Statistical analysis

Data was initially organized in a Excel sheet, and descriptive statistics (mean, standard deviation, minimum, and maximum values) were calculated. Box plots of key soil properties and infiltration rates were generated using SigmaPlot v.14. A Mann–Whitney Rank Sum Test was used to compare the data, as a Shapiro–Wilk test indicated a non-normal distribution for all variables. Data transformation was performed to achieve normality prior to this test. Interactive graphs comparing bulk density (BD), organic matter (OM), pH, soil water retention capacity (SWRC), respiration, and infiltration characteristics across different slope positions (land uses) were generated using the "ggplot2," "plotly," and "gapminder" packages within the R Core Environment (Version 4.2.1) and RStudio IDE (Version 2024.09.0 Build 375). A Pearson correlation analysis, using the "corrplot" package in R, was performed to assess linear correlations between soil properties. Finally, Canonical Discriminant Analysis (CDA) results were visualized to illustrate the relationships between soil properties and field experiments. This visualization allows for the differentiation of data point groups, representing various combinations of management practices, hillslope positions, soil properties, and experimental measurements. The proximity of data points in the CDA plot suggests potential correlations between specific soil attributes, providing insights into the complex relationships within this multivariate dataset.

3 Results

3.1 Key soil properties

Table 1 presents selected key soil properties. The field campaign took place during the dry season, following a 2-week period without rain, resulting in low antecedent soil moisture (ASM) levels. Average ASM was 3.1 ± 2.3% in abandoned plots and 2.7 ± 0.8% in cultivated plots, with maximum values observed in the upper slope positions of both areas. Abandoned areas exhibited a high content of coarse gravels (5–8 cm and 2–5 cm), reaching 20.2 ± 10.1% and 8.1 ± 3.4%,

Table 1 Soil properties in abandoned and cultivated esparto grasslands per hillslope positions

ID	ASM	Gravels (%)			Fine particles	BD	OM	pH	SWRC	AS
	(%)	5–8 cm	2–5 cm	2 mm-2 cm	< 2 mm	g cm^{-3}	%		%	
AB_A1	2.6	32.2	13.7	18.5	35.6	1.24	3.15	8.7	25.5	0.2
AB_M1	1.9	16.1	8.1	7.4	68.4	1.07	8.52	8.1	29.4	0.2
AB_F1	2.7	23.3	7.1	9.0	60.6	1.10	5.08	8.3	29.4	0.2
AB2_A2	7.6	3.2	4.0	8.7	84.1	0.90	15.35	9.9	32.9	0.1
AB2_M2	2.6	19.4	9.9	18.3	52.4	1.07	9.13	8.3	28.7	0.1
AB2_F2	1.2	27.2	5.5	5.7	61.5	1.08	4.92	8.3	35.3	0.4
CU_A1	4.1	21.7	7.0	8.6	62.7	1.26	7.29	8.2	24.5	0.4
CU_M1	2.7	18.6	5.8	12.8	62.8	1.19	3.42	8.8	27.7	0.2
CU_FI	2.5	15.8	5.2	9.3	17.3	1.25	3.56	8.8	24.5	0.2
CU2_A2	2.5	11.5	8.9	12.3	67.3	1.29	8.69	8.3	25.3	0.4
CU2_M2	1.7	9.5	7.0	12.3	71.2	1.17	3.86	8.2	28.1	0.2
CU2_F2	2.6	29.2	9.0	13.1	48.7	1.23	3.70	8.3	24.9	0.3

AB abandoned, *Cu* Cultivated, *A* upper part, *M* backslope, *F* footslope: 1: plot 1; 2: plot 2, *ASM* antecedent soil moisture, *< 2 mm* fine materials, *BD* Bulk density, *OM* Organic matter, *SWRC* soil water retention capacity, *AS* Aggregate stability respectively. Fine gravel content (11%) was similar between the two plot types but showed greater variability within the cultivated areas. No clear trends were observed across hillslope positions for gravel content. Soils in abandoned areas had a higher fine material (< 2 mm) content (60.4 ± 16.2%) compared to cultivated areas (55 ± 20%), which also exhibited substantial variability. As with coarse materials, no relationship was found between fine texture and hillslope position. Bulk density (BD) was higher in cultivated plots (1.23 ± 0.04 g cm^{-3}) with the highest values in upper slope positions, compared to abandoned plots (1.08 ± 0.11 g cm^{-3}), although no consistent trends were observed across hillslope positions in either plot type.

Organic matter (OM) content was greater in abandoned plots (7.7 ± 4.4%) than in cultivated plots (5.1 ± 2.3%), likely due to the removal of understory vegetation beneath the esparto grass in the cultivated areas. No clear trends were observed for OM across hillslope positions in either management type. Soil pH was similar between the two plot types, averaging 8.6 ± 0.7 in abandoned plots and 8.4 ± 0.3 in cultivated plots, with the highest values observed in the upper slope positions of both. Soil water retention capacity (SWRC) in the saturated steel rings was higher in abandoned plots (30.2 ± 3.4%, with maximum values in the footslope) than in cultivated plots (25.8 ± 1.6%, with maximum values in the backslope). Aggregate stability (AS) was similar between the two plot types, averaging 0.27 ± 0.12 in cultivated plots and 0.21 ± 0.09 in abandoned plots. No clear trends were observed for AS across hillslope positions.

3.2 Soil infiltration

Figures 4 and 5 shows the total average infiltration rates in relation to selected key soil properties. Figure 6 presents box plots of infiltration measurements per interval, soil management type, and overall. The results reveal considerable variability, with no discernible trends observed between hillslope position, infiltration rates, and the measured soil properties.

In abandoned areas (Fig. 4), the highest infiltration rates (yellow) are associated with the lowest bulk density, highest pH, and highest organic matter content in the upper part of plot 2. This also coincides with the second highest soil water retention capacity within this area. Conversely, low infiltration rates (dark blue and purple) generally correspond to areas with lower soil water retention capacity, pH, and organic matter content, and higher bulk density. This pattern is primarily observed in the backslope and footslope positions, particularly in plot 1.

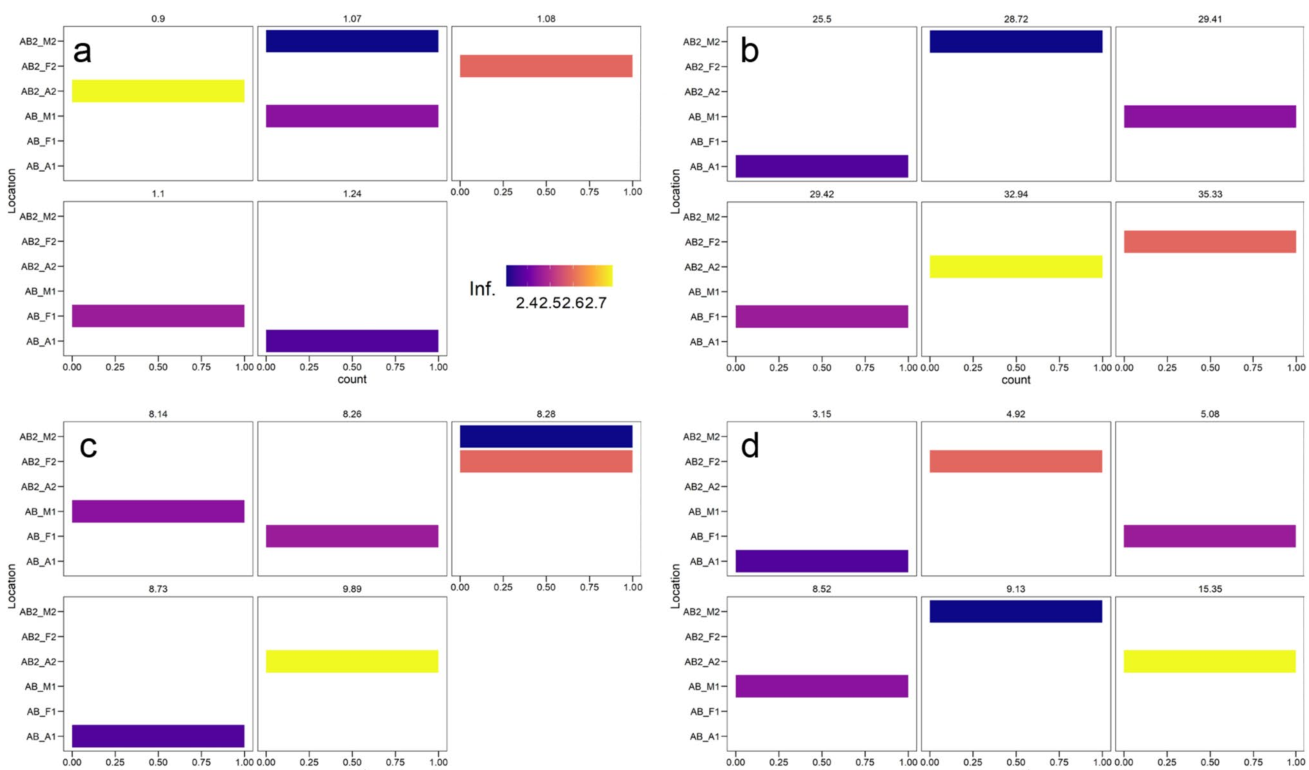


Fig. 4 Total infiltration rates per hillslope position in the abandoned plots crossed with key soil properties. *AB* abandoned, *Cu* Cultivated, *A* upper part, *M* backslope, *F* footslope: 1: plot 1; 2: plot 2. **a** bulk density; **b** soil water retention capacity; **c** pH; **d** Organic matter

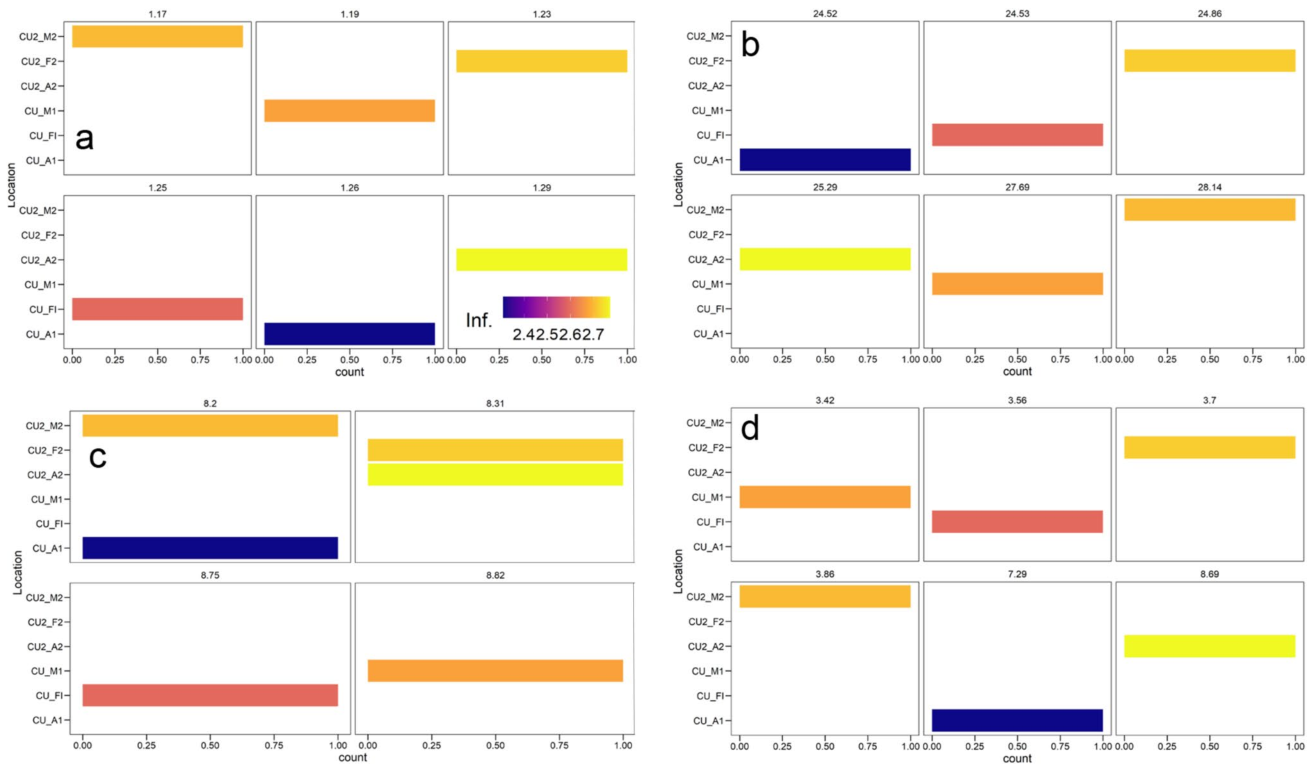


Fig. 5 Total infiltration rates per hillslope position in the cultivated plots crossed with key soil properties. *AB* abandoned, *Cu* Cultivated, *A* upper part, *M* backslope, *F* footslope: 1: plot 1; 2: plot 2. **a** bulk density; **b** soil water retention capacity; **c** pH; **d** Organic matter

A Mann–Whitney Rank Sum test and Shapiro–Wilk normality test revealed no statistically significant difference ($P = 0.105$) between abandoned plots 1 and 2 (Fig. 6).

In cultivated areas (Fig. 5), the highest infiltration rates (yellow) are associated with the highest bulk density and organic matter content in the upper part of plot 2. This also coincides with the second lowest soil water retention capacity and pH. Low infiltration rates (dark blue and purple) are generally associated with the lowest pH values, mainly in the upper part of plot 1. No clear trends are apparent in other hillslope positions. Similarly, a Mann–Whitney Rank Sum test and Shapiro–Wilk normality test showed no statistically significant difference ($P = 0.276$) between cultivated plots 1 and 2 (Fig. 6). Finally, when comparing all data from paired plots in both abandoned and cultivated areas, no statistically significant difference in infiltration rates was found ($P = 0.47$).

3.3 Soil respiration considering both soil management types and hillslope positions

The analysis of CO_2 emissions across treatments (cultivated vs. abandoned) and hillslope positions (footslope, backslope, and upper part) revealed no statistically significant effects. Neither treatment, hillslope position, nor their interaction had a significant influence on CO_2 emissions ($p > 0.05$). This suggests that observed variations in CO_2 emissions are likely due to random variability rather than specific management practices or topographic position.

Specifically, the comparison between cultivated and abandoned treatments showed a small, non-significant difference of −9.17 μg m^2 hr^{-1} in CO_2 emissions ($p = 0.477$). Similarly, comparisons across hillslope positions, such as the difference between footslope and backslope (−3 μg m^2 hr^{-1}), were also not significant ($p = 0.977$). Furthermore, no significant interaction was found between treatment and hillslope position; for example, the difference between cultivated and abandoned areas at a given hillslope position was approximately −11 μg m^2 hr^{-1}, with a p-value of 0.993 (Fig. 7).

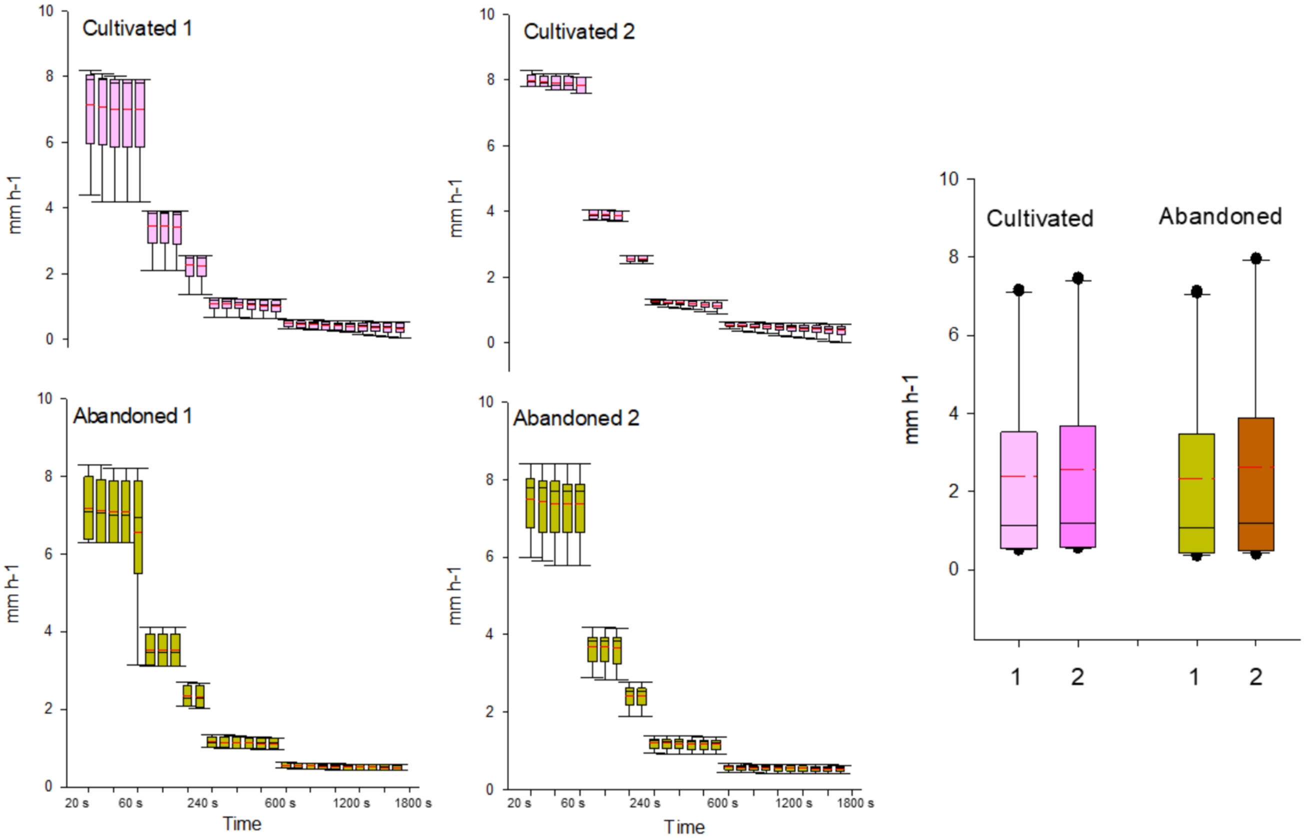


Fig. 6 Infiltration rates per intervals (seconds) and complete measurements using a mini-disc infiltrometer in both soil managements: cultivated and abandoned with two different repeatitions (1 and 2)

3.4 Investigating possible explicative factors

To explore the relationships between soil variables and infiltration/respiration processes in cultivated and abandoned esparto grass fields, Pearson correlation (Fig. 8) and canonical analyses (Fig. 9) were conducted. Given the lack of statistically significant differences among plots based on hillslope position or plot type in previous analyses, these analyses aimed to identify specific variables influencing or differentiating these processes between the two field types. In abandoned areas, bulk density (BD) was negatively correlated with organic matter (OM) and soil infiltration, but positively correlated with soil respiration. OM was negatively correlated with large gravels and soil respiration, but positively correlated with fine particles and aggregate stability (AS). pH was negatively correlated with soil respiration but positively correlated with soil infiltration. Soil respiration was negatively correlated with soil infiltration and antecedent soil moisture (ASM), but positively correlated with large gravels. In cultivated plots, soil respiration was positively correlated with coarse gravels and soil infiltration. pH was negatively correlated with AS and soil respiration, which, in turn, was positively correlated with fine gravels but negatively correlated with ASM.

The canonical analysis revealed that cultivated plots in the upper and footslope positions were most similar, their distribution influenced by bulk density, AS, and coarse gravels. Abandoned plots demonstrated greater variability in the relationships between soil variables and processes. Soil respiration was closely associated with gravels, OM, and ASM, while soil infiltration was associated with fine materials and soil water retention capacity (SWRC).

4 Discussion

The analysis of soil properties and their relationships with infiltration and soil respiration revealed a complex interplay of factors, with substantial variability observed across both cultivated and abandoned plots, as well as among different hillslope positions. The study's findings partially contradict our initial hypothesis that abandonment would lead to soil

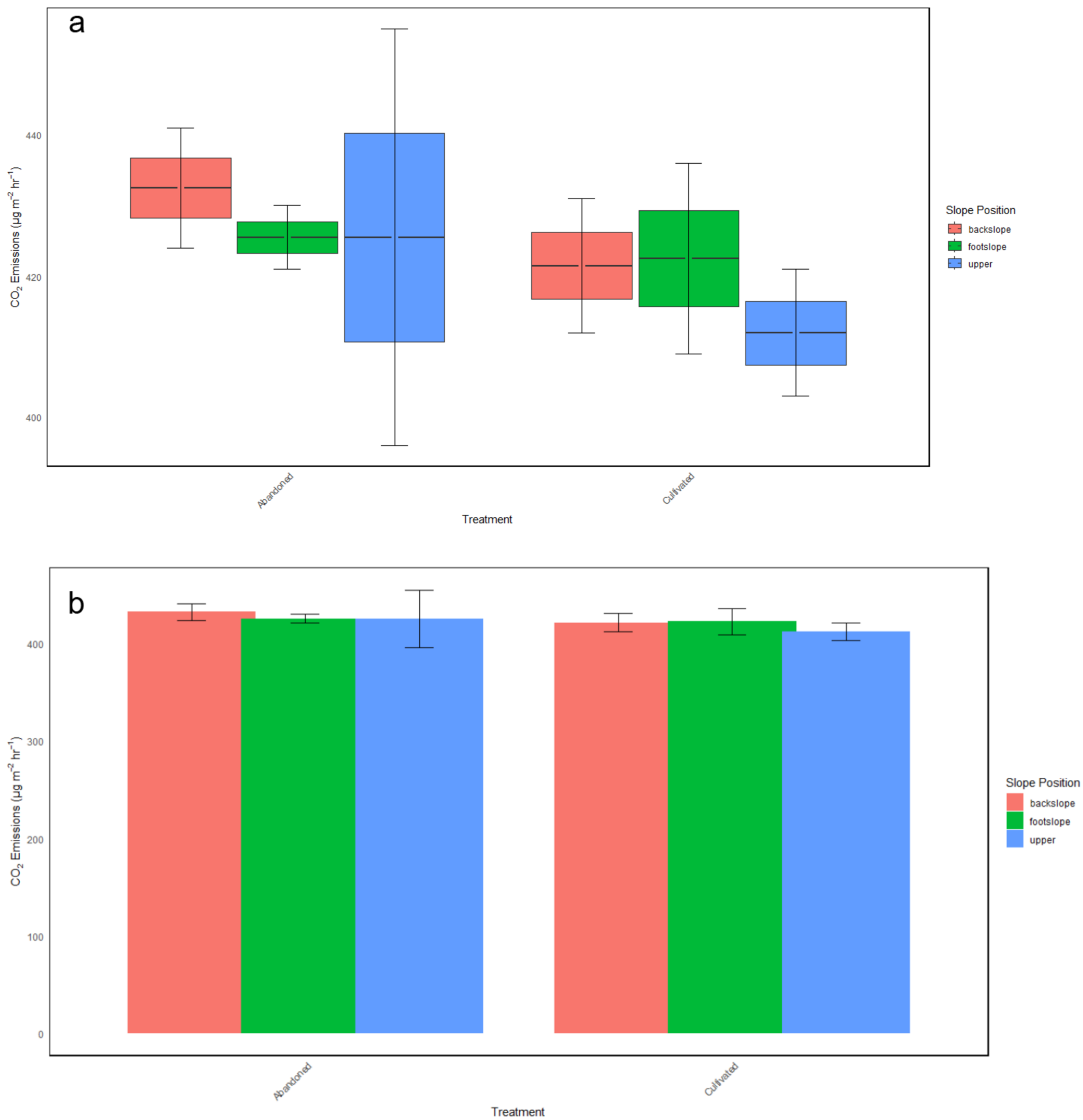


Fig. 7 CO2 emissions across treatments (cultivated vs. Abandoned; **a**) and hillslope positions (footslope, backslope, upper parts; **b**)

degradation. Instead, the observed higher soil infiltration and respiration rates in abandoned grasslands suggest that the re-establishment of spontaneous vegetation has a positive effect on soil health, likely by providing soil cover and organic matter input. Conversely, the cultivated areas, characterized by bare soil, appear to be more susceptible to degradation. The lack of consistent trends across hillslope positions indicates that local factors, as suggested in our second hypothesis, play a significant role in modulating the effects of land management on soil processes. This observation aligns with findings from other studies conducted in Mediterranean, human-affected environments [36, 41]. While localized patterns in infiltration rates were observed, no statistically significant trends were registered across hillslope positions. In abandoned areas, higher infiltration rates were noted in areas with lower bulk density and higher organic matter content, particularly in the upper part of plot 2. However, this trend lacked consistency, as no significant correlation was

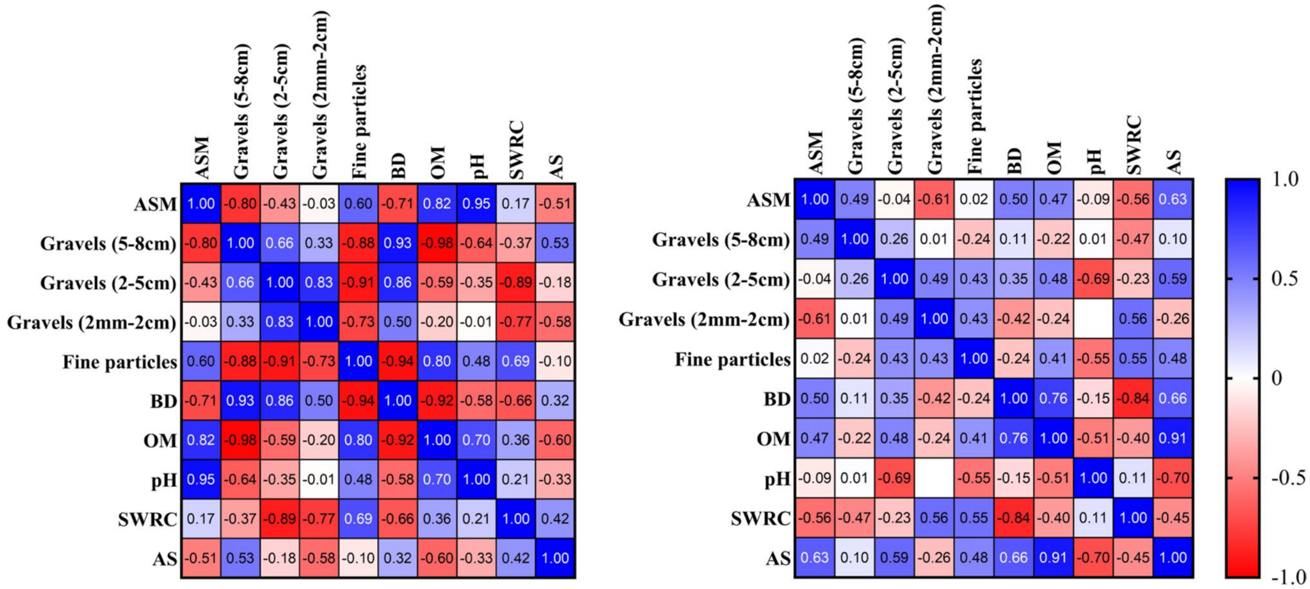
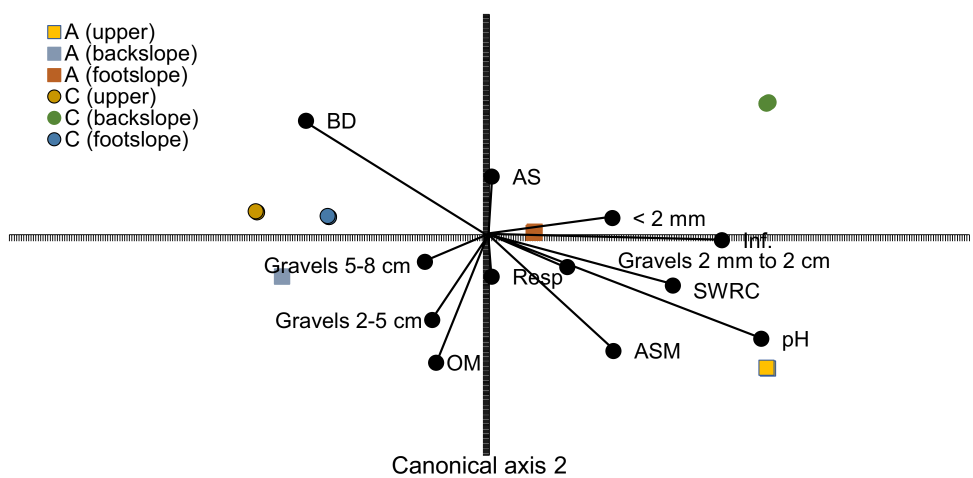


Fig. 8 Pearson correlations considering key soil properties, infiltration and soil respiration in abandoned and cultivated plots. *ASM* antecedent soil moisture, < *2 mm* fine materials, *BD* Bulk density, *OM* Organic matter, *SWRC* soil water retention capacity, *AS* Aggregate stability, *Resp* Soil respiration, *Inf* Infiltration

Fig. 9 Canonical analysis considering hillslope positions and soil management



found between infiltration rates and any single variable when considering the entire dataset. This result is consistent with other research conducted in areas with high rock fragment content, steep slopes, and Mediterranean grass and scrub vegetation [11, 62]. Similarly, soil respiration, measured across different treatments and topographical positions, showed no statistically significant differences, suggesting that neither environmental nor soil management factors had a directly measurable effect on this variable. These findings are in agreement with other studies conducted at the national [74], field [24, 54], and modeling scales [20, 60].

The high variability observed in key soil properties, including bulk density, soil organic matter, and gravel content, underscores the challenge in establishing clear trends between soil management types and hillslope positions [35, 72]. For instance, although cultivated plots exhibited higher bulk density and organic matter content, these differences were not consistently reflected in infiltration or respiration rates across different slope positions. This suggests that localized factors, such as soil texture, microtopography, and soil erosion, might play a substantial role in modulating infiltration and respiration, further complicating the ability to draw general conclusions based on broader landscape or management differences [4, 68].

Soil infiltration appeared to be most strongly correlated with SWRC and pH, particularly in abandoned areas, where higher infiltration rates were associated with higher SWRC and pH levels. The highest infiltration rates in cultivated plots coincided with higher BD, a somewhat counterintuitive result [6, 15]. This suggests that factors such as soil compaction and management practices (e.g., tilling or grazing) may influence water movement through the soil in complex ways, potentially altering soil structure or pore space distribution [1, 7, 8]. The lack of significant differences in infiltration between cultivated and abandoned areas, as revealed by statistical tests, highlights the difficulty in predicting hydrological behavior in Mediterranean environments characterized by highly variable soils and land management practices [40, 42].

Regarding soil respiration, no clear relationships were found with soil management or hillslope position, despite observed differences in soil organic matter content and bulk density between cultivated and abandoned plots. Pearson correlation and canonical analysis revealed that soil respiration was negatively correlated with infiltration and antecedent soil moisture (ASM), while positively correlated with gravel content. This suggests that coarse soils with lower moisture content might promote soil respiration, potentially due to higher air-filled pore space enhancing microbial activity. However, the absence of statistically significant differences between plots suggests that soil respiration in these Mediterranean landscapes may be driven more by stochastic processes or subtle, unmeasured environmental variables than by land management or topography. Alternatively, the sampling strategy, such as increasing the number of measurements or comparing different devices, may need to be revisited [61].

The variability in soil properties and the lack of clear trends across treatments and hillslope positions can be attributed to the inherent complexity of Mediterranean environments [13, 44], often characterized by erodible soils [46, 73], steep slopes [51], and human disturbances such as agriculture [12] and fire [22]. These landscapes are also highly sensitive to climatic fluctuations, particularly water availability, which can mask potentially significant trends [65]. For example, while soil moisture levels were low during the study period, they can fluctuate considerably throughout the year, further complicating the interpretation of short-term infiltration and respiration measurements. This inherent variability presents a significant challenge in predicting soil processes, as the interactions between soil, vegetation, and climate are highly dynamic and spatially heterogeneous.

The challenges encountered in studying soil processes in Mediterranean environments, and grasslands in other arid regions, highlight several gaps and opportunities for future research [27, 64]. First, improving the temporal resolution of soil moisture, infiltration, and respiration measurements could provide greater insight into how these processes respond to seasonal changes. Second, incorporating more detailed measurements of soil structure, such as pore size distribution or soil aggregation dynamics, could help clarify how management practices influence soil hydraulic properties [69]. Finally, considering the impacts of climate change, including increasing temperatures and altered precipitation patterns [70], future studies should investigate how these shifts will affect soil–water-plant interactions, particularly regarding water erosion, carbon sequestration, and ecosystem sustainability [19]. Addressing these knowledge gaps will be crucial for developing adaptive soil management strategies to maintain ecosystem function in Mediterranean landscapes.

5 Conclusions

This study highlights the complexity and variability of soil processes, particularly infiltration and soil respiration, in Mediterranean environments. No significant trends were observed across hillslope positions or land management types, with both processes strongly influenced by soil properties such as bulk density (BD), organic matter (OM), and soil water retention capacity (SWRC). However, the relationships between these variables were inconsistent, reflecting the challenges posed by erodible soils, human disturbances, and climatic variability. This lack of clear trends could indicate that, within the parameters of this study, the examined treatments and hillslope positions do not have a measurable impact on CO_2 emissions or infiltration. The correlations observed between soil properties, infiltration, and respiration suggest complex interactions, but the observed variability limits the ability to draw broad conclusions. Future research should prioritize long-term monitoring and more detailed analyses of soil structure to better understand these intricate processes. Given the sensitivity of Mediterranean soils to climate change, investigating how these dynamics will evolve in the future will be crucial.

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