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Biochar

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Soil conservation benefits of biochar in Mediterranean vineyards: enhancing the soil sponge function and mitigating water erosion

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Abstract

Soil erosion by water poses major environmental challenges to the European viticulture sector. Biochar is recognised as a sustainable tool for combating land degradation, but few studies on the effect of biochar on soil erosion have been conducted in Mediterranean vineyards with hilly terrain and heavy rainfall. This study assesses the potential of biochar to support soil conservation by enhancing sponge function, i.e. water retention and infiltration, and reducing erodibility in sloping sandy loam soil under natural rainfall conditions. An 18-month outdoor box lysimeter experiment was conducted using bare soil, including soil amended with 4% (w/w) biochar from a Portuguese vineyard. Over the monitoring period, biochar application significantly ($p < 0.001$) reduced the runoff coefficient by an average of 45%. Biochar reduced coarse fragment erosion by 67%, fine-earth erosion by 43%, and splash erosion by 34%, all affected ($p < 0.05$) by rainfall intensity. The erosion rate in vineyard soil was 3 times lower ($p < 0.001$) in biochar-amended soil than in the control (3.7 vs. 11.1 t ha^{-1} yr^{-1}). Improved soil structure led to a 7% reduction in bulk density, an average increase of 73% in stored water, and a 28% increase in infiltration. During drier periods, the biochar-amended soil stored 171–303% more water than the control soil. We recommend a minimum monitoring period of a full hydrological cycle under natural rainfall to comprehensively capture the effect of biochar on the soil sponge function. Observed seasonal trends and atmospheric river (AR) events suggest that studies using rainfall simulations without considering antecedent soil moisture and AR variations will yield skewed data on effects. From a practical standpoint, this study showed that biochar could be a sustainable soil management solution to enhancing long-term vineyard resilience and productivity in the Mediterranean.

Highlights

- Biochar strongly reduced the runoff coefficient and doubled or tripled the stored water during dry periods.
- Biochar decreased erosion in this order: splash erosion < fine-earth erosion < coarse fragment (gravel) erosion.
- Rainfall simulations have limitations in accurately showing the variability of real rainfall patterns.

Keywords Biochar, Rock fragment erosion, Surface runoff, Water retention, Atmospheric river, Combating desertification

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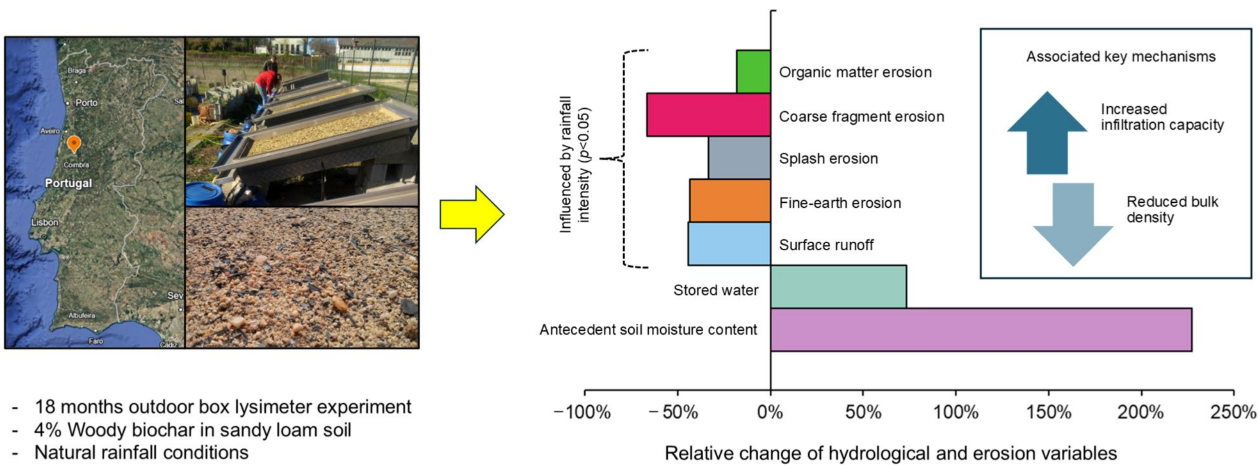
Graphical Abstract



1 Introduction

The Mediterranean is the most susceptible region in Europe to land degradation and desertification (Ferreira et al. 2022; Gholamahmadi 2024), resulting in the loss of soil ecosystem services (Hugo and Rocío 2009; Verheijen et al. 2009; Borrelli et al. 2017; Eswaran et al. 2019), such as food production (Lal 2008). Globally, soil erosion by water is predicted to increase by 30–66% by 2070 (The baseline year 2015) (Borrelli et al. 2020). In Europe, water is one of the main agents responsible for soil erosion (Borrelli et al. 2020). In the Mediterranean region, heavy rains are often recorded after prolonged dry periods when the infiltration rate drops dramatically (Ferreira et al. 2015). Accelerated soil erosion poses a significant challenge for Mediterranean vineyards. The average erosion rate in Mediterranean vineyards is 9.3 t ha^{-1} yr^{-1} (Prosdocimi et al. 2016). This is primarily due to the hilly terrain, bare cultivation, and increasingly drier climate conditions (Figueiredo et al. 2013; Ferreira et al. 2018; Gholamahmadi et al. 2025). The conditions that increase Hortonian overland flow, i.e., infiltration-excess overland flow, include high-intensity rainfall, sparse vegetation, sloped terrain, and low soil permeability (Horton 1933; Corradini et al. 1998; Beven 2012). Thus, enhancing the soil sponge function, i.e. water infiltration, retention, and slow release of water, and decreasing runoff is critical to preventing the force of running water from dislodging and carrying away the topsoil (Visconti et al. 2024) in vineyards.

Biochar is a carbon-rich product resulting from the thermal conversion of biomass in the absence of (or with limited) oxygen and high temperatures, a process called charring or pyrolysis (Lehmann and Joseph 2012). A recent meta-analysis by Gholamahmadi et al. (2023) showed that on average, biochar application to soil reduces runoff by 25% and erosion by 16%. Biochar enhances soil water retention by altering the shape of soil pores and augmenting overall porosity (Edeh and Masek 2022; Singh et al. 2022) or their spatial arrangement (Blanco-Canqui 2017). Biochar can adsorb and retain water and gases proportionally linked to its structural pore geometry, size, and pore size distribution (Atkinson 2018). By improving soil structure and porosity, biochar application to soil decreases bulk density (Siedt et al. 2021) and reduces compaction (Blanco-Canqui 2021). Based on meta-analyses, biochar reduces bulk density by 9% (Razzaghi et al. 2020) and 7.6% (Omondi et al. 2016). This discrepancy was explained by soil texture and biochar particle sizes, but indicates a benefit to ameliorating soil compaction.

Biochar is known to have a high water-holding capacity due to its porous structure (Tomczyk et al. 2020). Razzaghi et al. (2020) highlighted that when biochar is incorporated into the soil, it can improve the soil ability to retain water (available water content) by 45% in coarse-texture soil, 21% in medium-texture soil, and 14% in fine-texture soil. In another global meta-analysis by Gholamahmadi et al. (2023), the result showed there is a mean reduction in runoff by 31% in coarse-texture soil, 9% in medium-texture soil, and 20% in fine-texture soil. They reported that soil erosion is reduced by 21% in coarse-textured soil, 16% in medium-textured soil, and 9% in fine-textured soil. The way biochar affects runoff and soil erosion can vary depending on factors such as soil type, climate conditions, biochar type, age and concentration, and application methods (Joseph et al.

2021). Biochar application, combined with other soil conservation practices, can be an effective tool in reducing runoff and soil erosion in agricultural and environmental contexts (Woolf 2008). However, there is scarce published work on the potential of biochar to improve the soil sponge function and soil erodibility parameters in Mediterranean vineyard soils under natural rainfall conditions. Most studies on the effects of biochar on soil water retention report soil moisture contents measured with bulk density rings as a snapshot in time, leaving a key knowledge gap on temporal patterns of the soil sponge function. To contribute to closing this knowledge gap, this study aims to (i) test the long-term effects of biochar application on runoff and runoff coefficient, fine-earth erosion, coarse fragments erosion, splash erosion, soil organic matter erosion (export of particulate SOM in runoff), and stored water in rainfall events; and (ii) define the main runoff/erosion explanatory variables (i.e. rainfall amount, rainfall intensity) throughout the experiment.

2 Materials and methods

2.1 Study area

The outdoor box lysimeter experiment was conducted at Escola Superior Agrária de Coimbra (ESAC), in Coimbra, Portugal (40°12′44.49”N, 8°27′2.52”W), approximately 30 km from the selected site for soil collection. The site is a traditionally managed commercial vineyard in Vilarinha do Bairro, central-north mainland Portugal (40°28′14.63"N, 8°32′59.68"W) (Fig. 1A). The mentioned vineyard is located in the Bairrada wine region and has a gentle (< 10%) slope where soils are typically Calcaric Cambisols with a clay texture and are vulnerable to erosion by water (Ferreira et al. 2018). In addition, Coimbra has a warm-summer Mediterranean climate (Köppen: Csb) but is located in a transition area to a hot-summer (Csa) climate recorded in the interior of Central Portugal (Kottek et al. 2006). The study site has a mean annual temperature of 13.1 °C and an average yearly rainfall of 881 mm, with rainfall occurring mainly during the winter months (IPMA 2018).

2.2 Experimental setup

2.2.1 Soil and biochar

The collected soil (topsoil 0–15 cm) is classified as an Eutric Regosol (IUSS Working Group WRB 2015). It has a sandy loam texture, rock fragments in gravel sizes of 2–19 mm, a pH of 5.4, and a 4.0% soil organic matter content. Biochar was acquired from Swiss Biochar GmbH (Switzerland), where it was produced through slow pyrolysis at 620 °C using pine wood chip feedstock, with ash content of 18.6%, organic carbon of 75%, and a pH of 10.1. The particle size distribution was as follows: 4% of particles were smaller than 0.1 mm, 25% ranged from 0.1 to 0.5 mm, 34% from 0.5 to 2 mm, and 37% were larger than 2 mm. Prodana et al. (2019) report the full physicochemical characterisation of biochar. Both the soil and the biochar were wettable by the Water Drop Penetration test.

2.2.2 Experimental design

The two treatments, control and 4% (gravimetric) biochar-amended soils, with 3 replicates each, were set up in a randomised design (Fig. 1). The outdoor box lysimeters are unobstructed by tall buildings or trees and face southwards at a slope angle of 15˚. Each lysimeter is 35 cm deep, 78 cm wide, and 156 cm long (total soil surface area

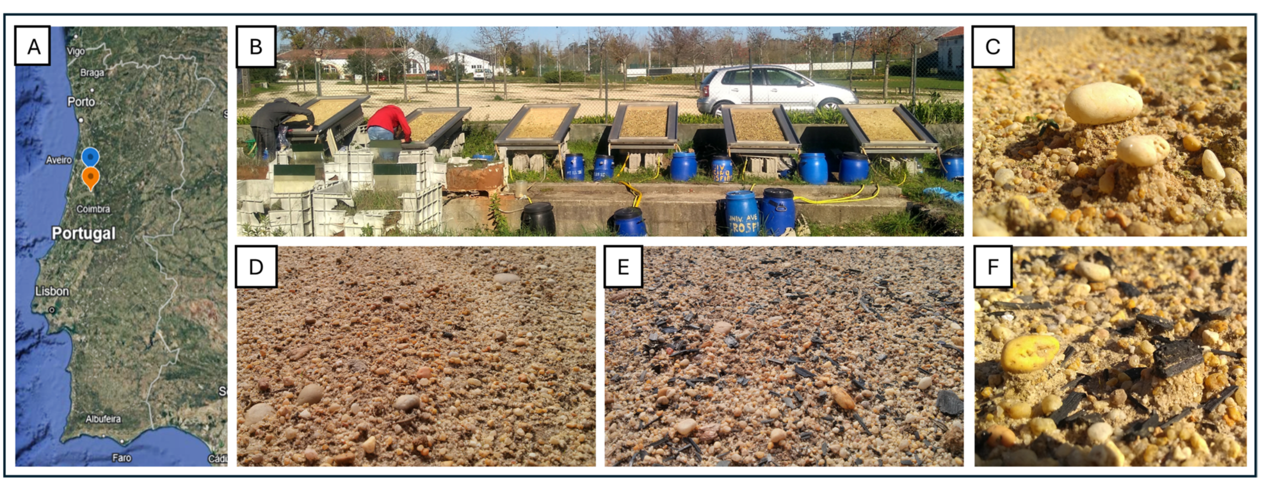


Fig. 1 Map, overview, and soil surface status during the experiment. **A** Geographic locations of ESAC (orange pin), and vineyard in Vilarinha do Bairro (blue pin) in Portugal, **B** The outdoor box lysimeter experiment, including six lysimeters and collection tanks, **C** soil pedestals with a capstone in control soil, **D** the surface of control soil, **E** the surface of biochar-amended soil, and **F** soil pedestals with a capstone (left) and a biochar particle (right) in biochar-amended soil

is 1.22 m^2), with a 15 cm wide splash gutter around the edge. Box lysimeters were filled with a 21–23 cm layer of gravel at the bottom, a 2 cm layer of acid-washed sand, and a 13 cm layer of control topsoil or a 15 cm layer of biochar-amended topsoil on the top. The sand layer prevents the soil particles from washing down into the gravel layer. The gravel layer allows free drainage. Soil, or biochar-amended soil, was added layer by layer, with each layer being consolidated by placing a concrete block (17 kg) on all parts of the soil surface inside the lysimeter. The setup allowed the collection of runoff and leachates in individual collection tanks (Fig. 1B). The experiment ran from November 2016 to June 2018, during which 29 rainfall events were recorded. The soil surface of the box lysimeters was kept bare by continuous removal of any vegetation at every field visit.

2.2.3 Sample collection and analysis

After each rainfall event (with a measurable amount), the volume of runoff and leachate was measured in the collection tanks, and 1.5 L samples were taken (after agitation to resuspend the sediments) to the laboratory. Subsequently, the runoff tanks were carefully tipped over to drain the water, and the coarse sediments were collected from the bottom. Splashed sediments were removed from the gutter around the edge of the lysimeters by brushing to estimate splash erosion, specifically those particles that splashed over the threshold, i.e. the 4 cm distance from the soil surface to the rim of the splash gutter (for a discussion on splash erosion factors, see Fernández-Raga et al. 2017).

Runoff and leachate samples were analysed for electrical conductivity (EC) and pH. Subsequently, samples were agitated, and a 50 ml sub-sample was oven-dried at 105 °C for 24 h to remove all water content to determine the fine-earth erosion. After that, the soil organic matter (SOM) content was measured by loss-on-ignition at 550 °C for 2 h (Heiri et al. 2001). This was used to measure the soil organic matter erosion, i.e. the export of particulate SOM in runoff. The splash erosion and coarse sediment were oven-dried in the laboratory at 105 °C for 24 h and weighed.

In the context of this work, coarse sediments refer to both large particles of sand (0.5–2 mm) and the ≥ 2 mm of gravel-sized rock fragments. The gravel-sized rock fragments include angular and rounded shapes of fine and medium sizes. Fine gravel size refers to 2–4.75 mm of rock, and medium gravel size refers to 4.75–19 mm of rock. These categorisations are based on the American Society for Testing and Materials (ASTM 2017) and the LUCAS soil monitoring database (Orgiazzi et al. 2018). Hereafter, they are referred to as coarse fragment erosion.

The soil used to fill in the lysimeters was sampled destructively on 12th June 2018 (See Supplementary Fig. 1), after the end of the experiment. The soil at the top, middle, and bottom third of the sloping box lysimeters was sampled separately for dry bulk density (using steel rings). The soil depth was measured in these three locations of the box lysimeters (See Supplementary Result 1).

2.2.4 Soil probes data

One volumetric soil moisture-content probe (Decagon 5TE) was inserted horizontally in the middle part of each box lysimeter, at 5 cm depth. Soil moisture content (SMC) data were logged every 5 min and stored on a Decagon EM50 datalogger. After each significant rainfall event, the data were downloaded onto a laptop and erased from the data logger. The recorded soil moisture data (in m^3/m^3) was multiplied by 1000 to achieve the value in mm. Stored water (SW) is calculated by subtracting the SMC value 49 h after a rainfall event (a) from the SMC value 1 h before the rainfall event (b) (i.e. antecedent soil moisture content) calculated as:

$$SW = SMCa - SMCb$$

The soil moisture data recorded had an interruption due to a hardware problem in the data logger, and no data were collected from 15th December 2017 until 30th January 2018.

2.3 Data analysis

All statistical analyses were conducted with SPSS 29.0 (IBM Corporation, 2022). The data were analysed in absolute terms, including runoff (mm), runoff coefficient, stored water in the soil (mm), splash erosion (g m^{-2}), fine-earth erosion (g m^{-2}), coarse fragment erosion (g m^{-2}), total soil erosion (fine-earth + coarse fragments), and organic matter erosion (g m^{-2}). The runoff, the abovementioned erosion parameters, and stored water were analysed in cumulative terms for each storm event to align with the frequency of sponge function measurements. Additionally, we calculated the runoff coefficient (mm of runoff per mm of rainfall). Significant differences between control and biochar-amended soils were assessed using the Mann–Whitney U test. This test was used after checking the normality of data distribution through the Shapiro–Wilk test. Multivariate Analysis of Covariance (MANCOVA) was applied to examine multiple dependent variables (i.e. runoff and erosion data) simultaneously while controlling for covariates (i.e. rainfall amount and rainfall intensity). The relative change (*RC*) was calculated using the following formula between the means of the biochar-amended (*Mbiochar*) and control (*Mcontrol*) groups for each variable for whole measurement events:

$$RC = \frac{Mbiochar - Mcontrol}{Mcontrol}$$

Cohen's d (Cohen 1988) was calculated to quantify the effect size of biochar. Cohen's d is given by:

$$d = \frac{M_1 - M_2}{SD_{pooled}}$$

Where M_1 and M_2 are the means of the two groups, and SD_{pooled} is the pooled standard deviation of the two groups. Cohen's d effect sizes were interpreted as a small effect when $d \approx 0.2$, a medium effect when $d \approx 0.5$, a large effect when $d \approx 0.8$, and a very large effect when $d \geq 1.3$. Cohen's d was considered since our sample size is small (three replicates for each treatment group) and there is variability within the groups. Effect size refers to the raw difference between group means, or absolute effect size, as well as standardised measures of effect (Sullivan and Feinn 2012).

Atmospheric rivers (AR) are relatively long, narrow regions in the atmosphere that transport most of the water vapour outside of the tropics (NOAA 2024) and they play important roles in the global water cycle and regional weather/hydrology (Guan and Waliser 2015), especially in the west of Europe (Eiras-Barca et al. 2021). Only 6–9% of rainfall events in mainland Portugal are ARs (IPMA 2 2024). In our experiment, 1–3 events were likely AR events. The AR event on 13th March 2018 was omitted only from the regressions in Supplementary Fig. 6 and Supplementary Fig. 7.

3 Results

3.1 Hydrological-related variables

3.1.1 Rainfall amount and intensity

We identified the AR events, such as 13th March 2018, during the experiment. The total rainfall amount recorded during the monitoring period (11/11/2016 to 26/03/2018) was 937 mm. Approximately 40% of the rainfall (i.e. 382 mm) fell in the last three months, mostly because of an extreme rainfall event of 173 mm recorded on 13/03/2018. Four events had markedly greater rainfall intensities (I30 values): 19.2 mm h^{-1} on 09/05/2017 and 27/11/2017; 18 mm h^{-1} on 15/05/2017; and 13/03/2018 (Fig. 2A). Generally, rainfall amounts ranged from 1.80 mm to 173 mm, with an average of 33.5 mm, and rainfall intensities (I30 values) ranged from 0.80 to 19.2 mm h^{-1}, with an average of 7.7 mm h^{-1}. Furthermore, readout number 12 (14/03/2017) was excluded from the rainfall data analysis due to the missing value of the rainfall amount.

See Supplementary Result 2 for the influence of rainfall amount and rainfall intensity on all hydrological and erosion variables. We discussed this topic and its relation in Supplementary Discussion 1.

3.1.2 Runoff and runoff coefficient

Based on the average values of all events, biochar amendment significantly ($p < 0.05$) reduced runoff by 44%, as defined by a "very large" effect, $d = 2.8$ (See Table 1). For individual events, 12 out of 28 had significantly lower runoff values for the biochar-amended treatment (Fig. 2B). The remaining events showed no significant change in runoff between control and biochar-amended soils. The relative change in runoff due to biochar application was from + 17 to − 83% (Supplementary Fig. 2 Panel H), denoting a reverse U shape in the correlation between the biochar effect and observed rainfall amount (Supplementary Fig. 3 Panel A). Findings showed the impact of biochar on runoff, with relative changes ranging from 11% to 83% for rainfall events of 40–5 mm and 9–53% for rainfall events higher than 40–80 mm (Supplementary Fig. 3 Panel A). Furthermore, biochar significantly ($p < 0.001$) reduced the runoff coefficient by 45% ($d = 2.7$) (See Table 1). Thirteen events had significantly lower runoff coefficient values for the biochar-amended treatment (Fig. 2C). Runoff coefficients were, on average, 0.27 for biochar-amended and 0.5 for the control over the study period.

3.1.3 Topsoil stored water

On average for all the rainfall events observed, biochar-amended treatment increased stored water, i.e. measured 49 h after the end of the rainfall event to allow macropore drainage by gravity, throughout the experiment by 73% ($d = 2$), with a relative change ranging from − 40% to 303% (Supplementary Fig. 2 Panel F). Stored water in the control ranged from 1.8 to 59.3 mm, while the biochar-amended values ranged from 1.8 to 72 mm (Fig. 2D). Eleven out of 24 events had significantly higher stored water values for the biochar-amended treatment ($p < 0.05$). Biochar increased the average antecedent soil moisture content by 227%. Increased soil water retention upon biochar amendment was most pronounced during the drier months (i.e. July 303%, August 290%).

Figure 3 shows the daily volumetric soil moisture content (SMC) for the observation period, except for 45 days in December 2017 to January 2018 due to unforeseen data overwriting. Overall, biochar increased daily SMC by 215%. A minimum SMC increase was recorded in the initial three days of the experiment, and a maximum of 437% increase on September 10, 2017. The strongest immediate effect was observed in a rainfall event at the end of a long dry period, i.e. 8.8 mm of precipitation with

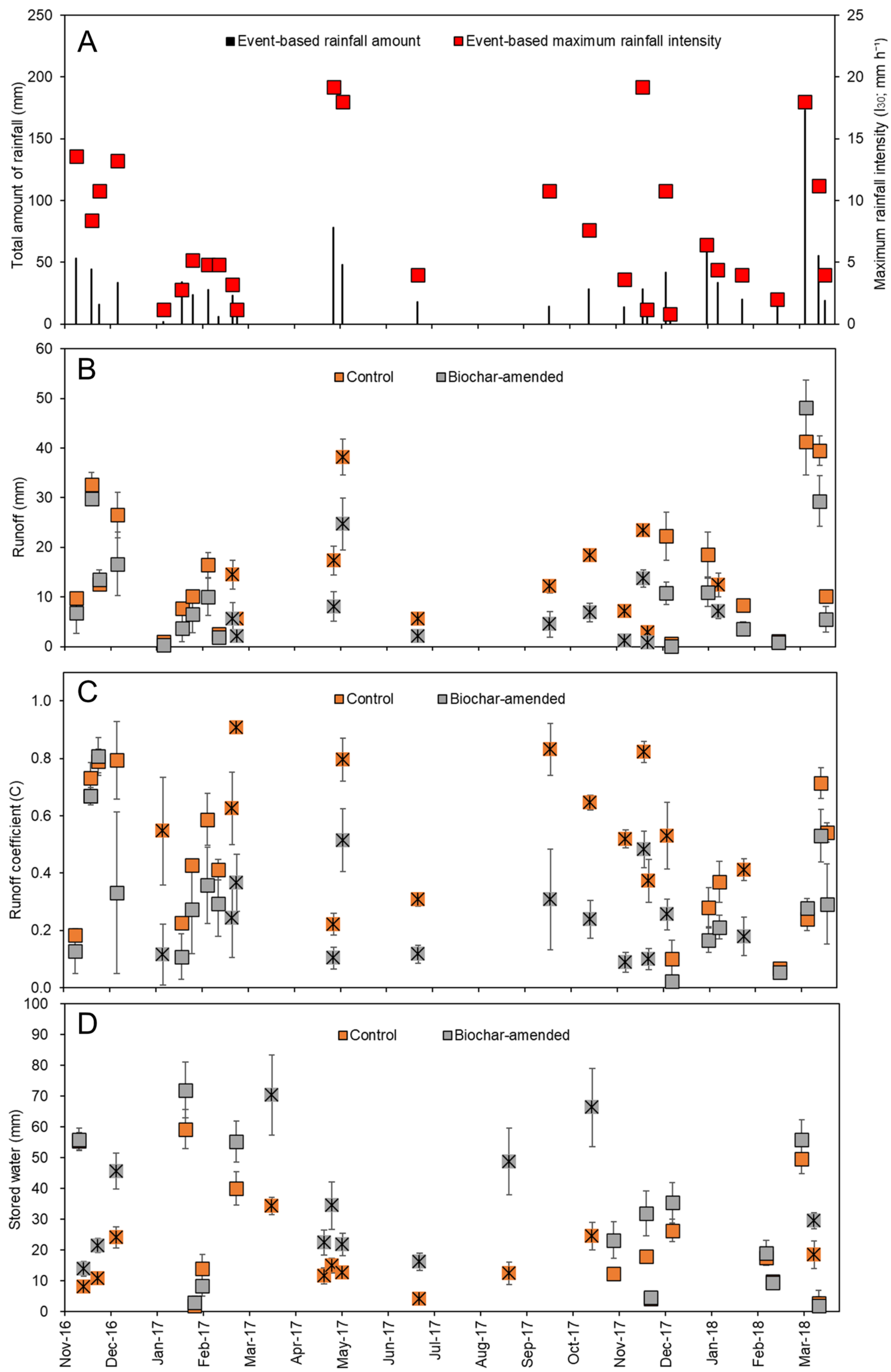


Fig. 2 Hydrological-related variables variations. **A** event-based total rainfall amount (dark columns) and event-based maximum 30-min rainfall intensity (red squares). For both treatments, **B** runoff (squares), **C** runoff coefficient (squares), and **D** stored water (squares) represents the end of the total rainfall amount measurement period. Squares with a mark (on both control and biochar-amended) showed statistically significant events from the biochar effect on runoff and stored water. The significance level is 0.050. Error bars represent standard deviation. $n = 3$

Table 1 Summary of biochar effects on the monitored hydrological and erosion variables

Dependent variable	Unit	Number of events	RC %	Cohen's *d*	Cohen's effect size category	*p*-value
Runoff	mm	28	−44	2.8	Very large	0.042*
Runoff coefficient	ratio	28	−45	2.7	Very large	0.001**
Stored water	mm	24	+73	2.0	Very large	0.058
Total soil erosion	$g\ m^{-2}$	19	−55	2.8	Very large	0.173
Fine-earth erosion	$g\ m^{-2}$	24	−43	1.9	Very large	0.083
Coarse fragment erosion	$g\ m^{-2}$	19	−67	2.7	Very large	0.053
Splash erosion	$g\ m^{-2}$	22	−34	2.2	Very large	0.139
Organic matter erosion	$g\ m^{-2}$	23	−18	1.2	Large	0.231

The number of events refers to rainfall events with data available on that specific variable. Cohen's *d* is the average of the *d* values of all events. The statistically significant effect sizes for the entire experiment are mentioned with the *p*-value (Mann–Whitney U test). RC refers to the relative change. Total soil erosion refers to fine-earth + coarse fragments. The marks refer to the levels of statistical significance: *$p < 0.05$, and **$p < 0.001$. (n = 3)

a maximum intensity of 10.8 mm h^{-1} from 27th until 29th August 2017. For this 3-day rainfall event, SMC increased from 1.0% to 2.7% in the control (1.7% increase) and from 4.1% to 9.5% in the biochar-amended treatment (5.4% increase), i.e. 3 times more. The post-event processes also showed that the biochar-amended treatment retained SMC effectively.

3.2 Erosion-related variables

3.2.1 Splash erosion

The application of biochar effectively reduced splash erosion throughout the experiment, with an average decrease of 34% ($d = 2.2$) (Table 1). In nine out of 21 monitored events, splash erosion was significantly lower in the biochar-amended treatment compared to the control ($p < 0.05$) (Fig. 4A). The extent of impact of biochar varied between a 21% to 68% reduction (Supplementary Fig. 2, Panel C).

3.2.2 Fine-earth erosion

Biochar treatment led to a significant decline in fine-earth erosion ($d = 1.9$), resulting in an overall reduction of 43% during the study period (Table 1). Seven out of 24 observed events exhibited a statistically significant decrease in fine-earth erosion due to biochar amendment ($p < 0.05$) (Fig. 4B), while the remaining events showed no notable difference between treatments. The effectiveness of biochar varied widely, ranging from an 83% decrease to a 17% increase (Supplementary Fig. 2, Panel B).

3.2.3 Coarse fragment erosion

The presence of biochar substantially mitigated coarse fragment erosion, with a recorded reduction of 67% throughout the experiment. This effect was classified as "very large" ($d = 2.7$, Table 1). In nine out of 20 events, coarse fragment erosion was significantly lower in the biochar-amended plots compared to the control ($p < 0.05$) (Fig. 4C), while the remaining events showed no significant differences. The relative impact of biochar on coarse fragment erosion ranged from a 40% to 96% reduction (Supplementary Fig. 2, Panel A).

3.2.4 Organic matter erosion

Biochar application contributed to an 18% reduction in organic matter erosion over the study period ($d = 1.9$) (Table 1). In two out of 24 events, organic matter erosion was significantly lower in the biochar-treated soil ($p < 0.05$) (Fig. 4D), whereas in the remaining events, no statistically significant differences were observed between treatments. The effectiveness of biochar in modifying organic matter erosion fluctuated widely, with changes ranging from a decrease of 83% to an increase of 154% (Supplementary Fig. 2, Panel E).

4 Erosion rate vs. infiltration

Figure 5 shows a trend of accelerating erosion, including accumulated erosion of fine-earth and coarse fragments, in the control. Biochar-amended treatment showed a flatter line, indicating stabilisation or reduction of erosion rate during the experiment. The trend of accelerating infiltration (accumulated infiltrated water) lines showed that water infiltrated better into biochar-amended soil compared to the control. Overall, biochar significantly reduced the accumulated erosion by 65% (6.7 t ha^{-1} vs. 19 t ha^{-1}, $d = 1.04$, $p < 0.001$) and resulted in an annual reduction of 67%, from 11.1 t ha^{-1} yr^{-1} in the control to 3.7 t ha^{-1} yr^{-1} in the biochar-amended treatment. Biochar significantly increased the infiltration by 28% (663 mm vs. 519 mm, $d \approx 0.5$) over the 18-month experiment. The reduction in erosion rate was over 19 t ha^{-1} and around 6.7 t ha^{-1} for the control and biochar-amended treatments, respectively. This large difference was caused disproportionately by

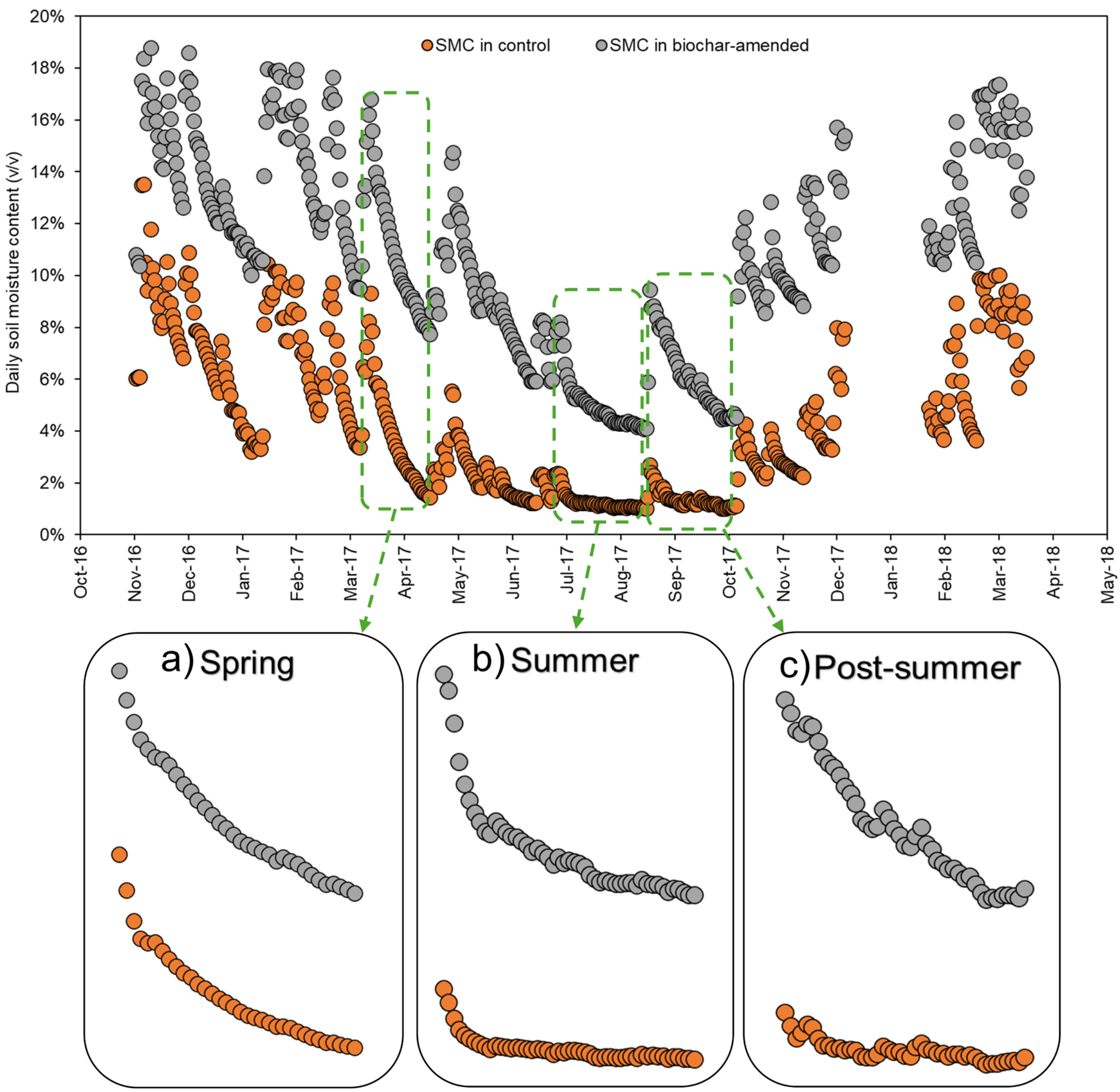


Fig. 3 Daily soil moisture content (SMC) variations. SMC is represented by circles and calculated by the daily average. The state of SMC in three key periods is shown as **a** spring, **b** summer, and **c** post-summer, for both control (orange circles) and biochar treatment (grey circles). *n* = 3

four events, i.e. one event in May 2017, one event in September 2018 and two events in March 2018. During the specified period, the erosion rate in the control soil was more than three times higher than in the biochar-amended treatment, at 14.8 t ha^{-1} compared to 4.6 t ha^{-1}. Furthermore, the infiltration was 1.3 times greater in biochar-amended soil compared to the control (Fig. 5). Refer to Sect. 4.4 of the discussion for a comparison of erosion rates in Mediterranean vineyards.

5 Discussion

5.1 Effect of biochar on soil sponge function

Based on a lysimeter scale, this study explored the effect of biochar on soil sponge function in sandy loam soil under natural rainfall conditions. We measured this effect after every rainfall event (e.g. stored water) and during a rainfall event. The stored water content was determined

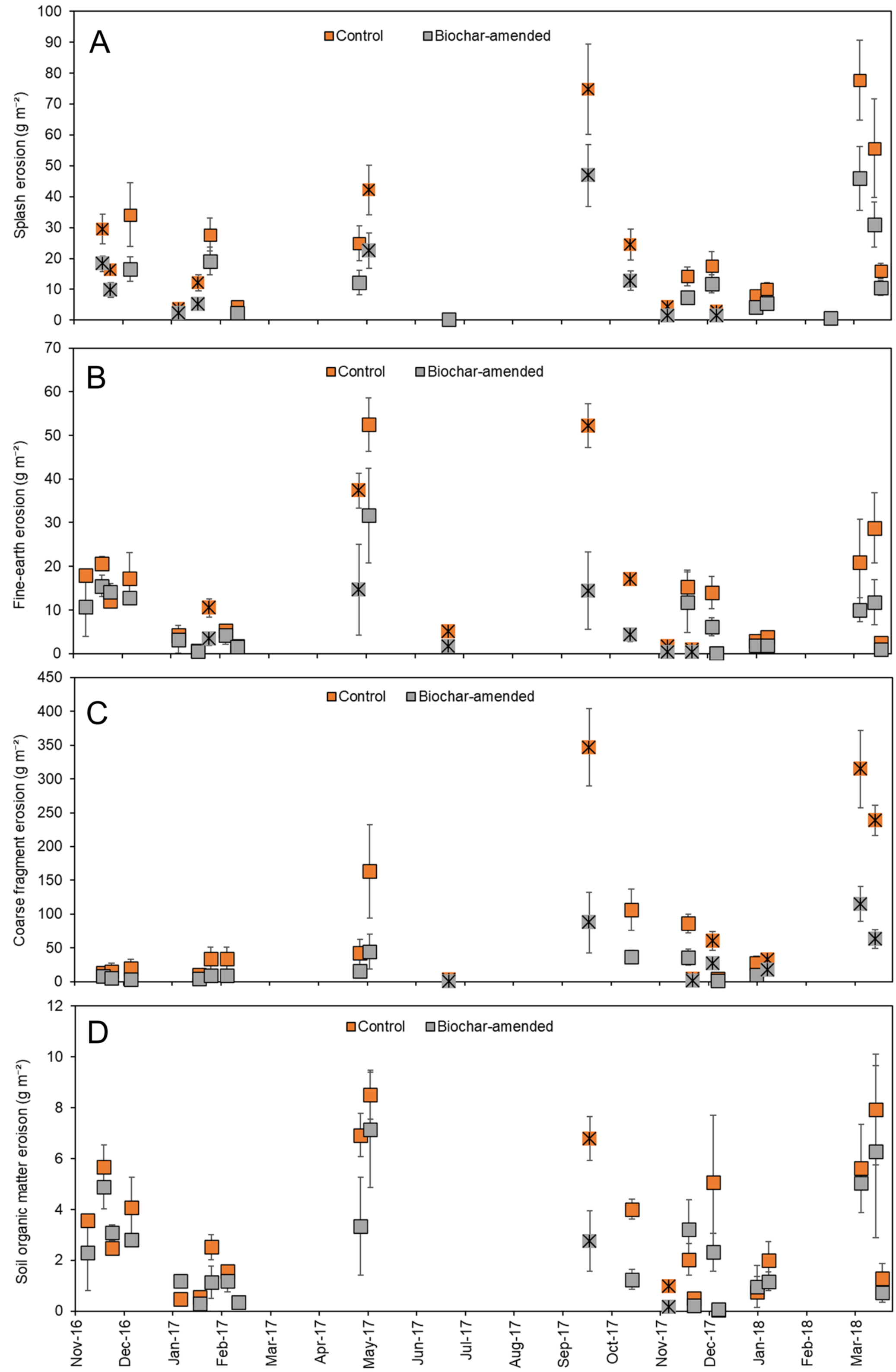


Fig. 4 Erosion-related variables variations. **A** splash erosion, **B** fine-earth erosion, **C** coarse fragment erosion, and **D** organic matter erosion. Both treatments represent the end of the total rainfall amount measurement over the study period. Squares with a mark showed statistically significant events of the biochar effect on erosion-related variables. The significance level is 0.050. Error bars represent standard deviation. $n = 3$

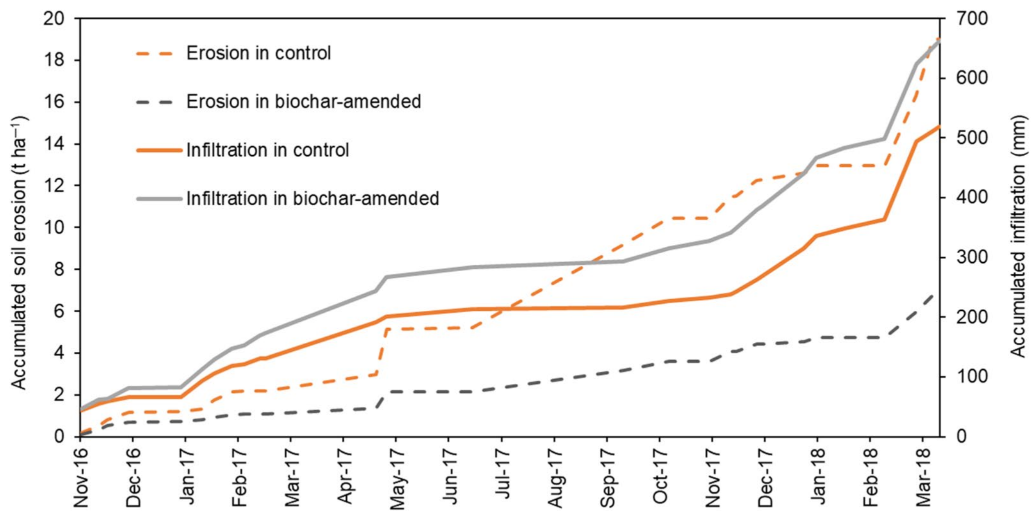


Fig. 5 Accumulated erosion and infiltration throughout the experiment. The erosion in the figure is accumulated soil erosion in fine-earth and coarse fragments, and the infiltration is accumulated infiltrated water for the control and biochar-amended treatments

using the gravity-drained equilibrium method since we took the soil moisture content values 49 h after the rain had stopped. This lysimeter study had a slope angle and surface properties that affected infiltration close to real-world conditions. Our results highlight that laboratory analyses of water holding capacity increase following biochar application may underestimate the "real world" impacts on the soil sponge function. For example, Edeh et al. (2020) found that the effect of biochar on soil water properties was greater in lab studies than in field studies, which they attributed to by soil heterogeneity. Our outdoor lysimeter methodology was representative of real weather conditions similar to those in the field while allowing for soil and biochar homogenisation in controlled lab experiments.

Our findings showed a higher water storage capacity compared to the literature. After biochar application in sandy loam soil, stored water increased by 73%, and the average daily soil moisture content increased by 215%. Similarly, Verheijen et al. (2019) reported a positive effect of biochar on water-holding capacity by > 60% in a column experiment. However, in a recent meta-analysis, Razzaghi et al. (2020) found that for 82 studies, there was a grand mean increase of 51% in field capacity in coarse-textured soil. Furthermore, Edeh et al. (2020) found a reduction in saturated hydraulic conductivity (K_{sat}) by 38.7% among 37 studies without waterlogging. The reduction in runoff and soil erosion, coupled with the 7% reduction in bulk density (See Supplementary Result 1) in biochar-amended soil, could be explained by the ability of biochar to improve water infiltration. The 28% increased infiltration in biochar-amended soils could have a particularly important contribution to preventing runoff and erosion in sloping areas, as shown by Blanco-Canqui (2017) and Gholamahmadi et al. (2023). In our study, biochar with moderately coarse particle size (i.e. 71% > 0.5 mm with a proportion of 37% > 2 mm) was added to sandy loam soil, which typically has a high drainage capacity but poor water retention. We speculate that the larger particle size of biochar enhances soil structure by creating more macropores, which helps retain water and slows the percolation rate through the soil. This is consistent with the 10% increase in porosity reported by Gamage et al. (2016) in sandy loam soil at 0.5% and 1% biochar concentrations. Verheijen et al. (2019) reported that biochar incorporation (5% w/w) led to decreased bulk density and increased maximum water-holding capacity in sandy loam soil, enhancing total soil water storage by 15%. However, our results indicated significantly higher soil water storage in biochar-amended medium-textured soils compared to the application rates used in these studies, as well as an increased field capacity of 13%, as reported by Razzaghi et al. (2020). Some of the proposed underlying mechanisms include (a) increasing soil micropores due to the high internal microporosity of biochar (Razzaghi et al. 2020); (b) smaller biochar particle size interposing between coarse soil particles, decreasing the average pore size (Liu et al. 2017); (c) improving soil physical properties, such as increasing pore space or increasing infiltration capacity (reducing infiltration excess) of the topsoil (Li et al. 2020). We concluded that this phenomenon is particularly accentuated in drier seasons and dry spells, as indicated by the variations in biochar effect on antecedent moisture content compared to its effect on runoff generation.

5.2 Effect of biochar on surface runoff processes

The 44% significant reduction in runoff observed in our study is substantially larger than the 28% reduction in runoff in the temperate zone that was found in a global meta-analysis (Gholamahmadi et al. 2023). However, for similar texture soils, larger effects have been reported. For instance, Gholami et al. (2019) also studied biochar application to sandy loam soil and reported runoff coefficient reductions ranging from 23% to 59% depending on initial soil moisture contents at a biochar concentration of 1.6 t ha^{-1} with particles < 2 mm. Although their size effect was in the same range as ours, the study by Gholami et al. (2019) only monitored one rainfall simulation at 50 mm h^{-1} in the lab. The results for bare soil are consistent with the 48% reduction in runoff rate reported by Zanutel and Bielders (2023), which was achieved through the application of aged biochar. In similar textured soils, our results were substantially higher than the overall runoff reduction of 37% in Bashagaluke et al. (2019), and 13% in Smetanová et al. (2013).

Compared to real-world conditions, we monitored the variation of maximum rainfall intensity (I_{30}) throughout 28 natural rainfall events, ranging from 0.8 to 19.2 mm h^{-1}. Our results showed that biochar significantly reduced runoff by 44% throughout the experiment under a variety of rainfall conditions. Event-based reductions in runoff in biochar-amended soils ranged from 35% to 83% and were mostly significant in the dry periods, which was similar to increases in stored water. In addition, Cohen's d indicated that in 22 out of 28 events, the biochar effect size was "very large". Runoff decreased by 33% until pre-spring 2017, and as precipitation patterns shifted to a more intensive regime, biochar demonstrated a significantly greater effect ($d = 3.8$), reducing runoff by 53% by summer. Two intensive rainfall events with 18 mm h^{-1} and 19.2 mm h^{-1} occurred in that period. However, the most important part of our experiment was observing the completely different rainfall patterns and soil conditions between the summer and winter of 2017. Runoff reduction remained at 64% until winter, with biochar achieving the highest effect size, $d = 5.2$, ranging from 1.4 to 11. Until spring 2018, biochar showed a "very large" effect with a similar reduction in runoff (e.g. 31%) compared to the same period in 2017. The biochar effect in reducing runoff showed a reverse U shape in relation ($R^2 = 0.33$) to rainfall amount (See Supplementary Fig. 3 Panel A). This indicates that the effect of biochar in reducing runoff is negatively correlated with rainfall amounts up to 50 mm. However, for rainfall amounts over 50 mm, the biochar effect was higher with increasing rainfall amounts. Furthermore, biochar linearly reduced runoff as antecedent soil moisture improved during this period (See Supplementary Fig. 4). These interactions showed that soil conditions in biochar amendment could deal with dry periods and immediate intensive rainfall events. This evidence suggests that biochar amendment could be an effective tool for enhancing soil conditions in response to climate change in the Mediterranean region. It is important to acknowledge that the effectiveness of biochar may be limited during the initial "soil equilibration" period, which occurs in the primary weeks or months following biochar addition, depending on the weather, as well as for events with runoff values less than 5 mm or during AR events.

5.3 Effect of biochar on soil erosion processes

Soil erosion is a selective process as it systematically sorts out soil primary and secondary particles. It preferentially removes fine inorganic and organic particles and leaves coarse particles and gravel. Furthermore, natural erosion is gradual and does not cause an abrupt disappearance of the whole topsoil, unlike artificial removal (Blanco-Canqui and Lal 2010). To provide real-world conditions, this study is evidence regarding biochar's impact on erosion in sloping sandy loam soil under natural rainfall conditions. We observed a 43% reduction in fine-earth erosion, which is substantially larger than the 16% global mean found in a recent meta-analysis (Gholamahmadi et al. 2023). That same study found an average reduction in soil erosion caused by biochar in the temperate zone of 9%, i.e. 4 times lower than what we observed. This may be because of the application depth, biochar ash content, pyrolysis temperature, and biochar concentration in this study. Gholamahmadi et al. (2023) found that biochar with an ash content of less than 30%, pyrolysed at temperatures above 500 °C and applied to the topsoil, exhibited a higher effect size. However, other potential factors may cause differences in results, such as methodologies (lab vs field), study duration, soil types, bare soil vs vegetated soil, biochar concentrations, and biochar types. For instance, in sandy loam soil subjected to simulated rainfall in a flume, Zanutel and Bielders (2023) observed a 39% reduction in soil erosion with the application of 2% fresh biochar, which was lower than the erosion reduction reported by Khademalrasul et al. (2019) using woody biochar in laboratory conditions. For a similar texture, Bashagaluke et al. (2019) found that rice husk biochar reduced erosion by 37% in bare soil after three years of field study.

Throughout the experiment, significant differences were observed in erosion patterns between the control and biochar-amended treatments, with reductions of 43% in fine-earth erosion and 67% in coarse soil erosion in the biochar-amended treatment compared to the control. In some cases, abundant gravel, stones, and other coarse materials in the soil reduce sediment loss in contrast with loose topsoil materials (Blanco-Canqui and Lal 2010), depending on rainfall conditions. We observed an overall 67% reduction in coarse erosion, which was 1.5 times stronger than the effect on fine-earth erosion. The additional effect on the coarse erosion that contained a majority of gravel-sized rock fragments could potentially have been caused by: (i) reduced velocity of the overland flow, because of the increased surface roughness in the biochar-amended treatment, i.e. coarse biochar particles sticking out of the soil surface, which may have reduced the mobility of the gravel-sized rock fragments more than the fine-earth particles; and (ii) higher detachment energy for gravel-sized rock fragments caused by the increased surface roughness (See Fig. 1B, E). To our understanding, this study facilitated the observation of the biochar effect on gravel-sized rock fragment erosion. We recommend future studies to monitor both the gravel in the collected sediments as well as the gravel cover at the soil surface as suggested by Arnaez et al. (2007) to control erosion after each rainfall event. This supports an understanding of the selective process mechanisms of soil erosion by water. In the Mediterranean, where approximately 60% of soils are thought to contain rock fragments, gravel "plays a pivotal role in influencing slope erosion processes" (Ni et al. 2024).

Statistically significant splash erosion reduction (53–77%) occurred, particularly in the summer period. Splash erosion, particularly prominent during intensive rainfall, showed a 34% overall reduction for biochar-amended soil, including fine-earth, but not in coarser fragments. The absence of gravel-size rock fragments may be due to our experimental design, as the splash gutter was 5–7 cm above the soil surface. This splash of gravel-sized rock fragments is essential for investigation using methods that keep the gutter at the same level or lower than the soil surface. However, despite an extensive search, no relevant literature was found on investigating the effects of biochar on splash erosion in similar soil textures and under natural rainfall conditions. This presents an important area for future investigation. For example, regarding studies under simulated rainfall, Sadeghi et al. (2021) found that biochar exhibited the maximum reduction in splash erosion, with a reduction rate of 74% in silty clay loam. In coarse sand closer to our study's soil texture, Seitz et al. (2020) reported that pyrochar reduced 43% of sand loss by splash erosion measurement.

5.4 Soil erosion rates in comparison to Mediterranean vineyards

In this study, biochar significantly ($p < 0.001$) reduced the annual erosion rate by 67% (i.e. 3.7 t ha^{-1} yr^{-1} vs. 11.1 t ha^{-1} yr^{-1}) in sloping bare vineyard soil. Panagos et al. (2015) reported soil erosion rates in Mediterranean vineyards to range from 4 to 80 t ha^{-1} yr^{-1}. This shows that the higher rates in Mediterranean vineyards depend on management practices and environmental conditions. It is evident that vineyards, especially those on steeper slopes or without adequate conservation practices, are more vulnerable to land degradation. Since the tolerable soil erosion rate is generally around 1–2 t ha^{-1} yr^{-1} (Verheijen et al. 2009) in European agricultural soil, an urgent need for effective soil conservation is necessary.

It is important to note that exceeding the tolerable soil erosion rate can lead to reduced crop yields, loss of arable land, and increased need for input fertilisers (Verheijen et al. 2009). Over time, this can result in land degradation, desertification, and loss of soil ecosystem services. Our study showed that biochar has the potential to control the erosion rate in vineyard soils without the indirect effect of plant growth. Biochar application in vineyards helps soil erosion become sustainable and does not lead to the degradation of soil quality, reducing agricultural productivity.

Research on biochar in sloping sandy loam soils is limited. See Supplementary Discussion 2 for further insights on this issue. In addition, see Supplementary Discussions 3 and 4, where we explored (i) biochar effects on soil organic matter erosion and (ii) the implications and future directions.

6 Conclusions

During an outdoor box lysimeter experiment, we investigated the impact of biochar application on various soil hydrological and erosion parameters in bare soil within a vineyard. We found that biochar reduced bulk density, indicating improved soil porosity and structure. This led to a significant 73% increase in stored water, suggesting that the ability of soil to absorb, retain, and distribute moisture (i.e. sponge function) was enhanced. This effect was larger (e.g. 171–303% increase) during dry periods. Furthermore, biochar application resulted in significant reductions in runoff and erosion. We investigated the biochar effect on gravel-sized rock fragments since this is a crucial component in Mediterranean soil erosion by water. Compared to the control soil, the biochar-amended soil experienced a 1.7-fold reduction in the annual erosion rate throughout the experiment. These reductions were closely linked to the rainfall intensity and amount during 28 events. This emphasises the importance of long-term monitoring of the relationship between biochar-soil interactions, ideally in conjunction with various surface covers such as vegetation and gravel. These findings suggest that biochar may be a viable soil management tool for Mediterranean vineyards to reduce or negate climate change impacts.

Supplementary Information

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Supplementary material 1.

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Author contributions

BG: Conceptualization, Data curation, Data Analysis, Investigation, Software, Visualization, Writing the original draft, Review and editing, Funding acquisition. CF: Project administration, Conceptualization, Data curation, Investigation, Methodology, Review and editing, Funding acquisition. OGP: Review & editing. ACB: Review and editing, Funding acquisition. FV: Project administration, Conceptualization, Data curation, Investigation, Methodology, Supervision, Review and editing, and Funding acquisition. All authors contributed to the article and approved the submitted version.

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Data availability

The datasets used or analysed during the current study are available from the corresponding author upon reasonable request.

Declarations

Competing interests

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