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DOI link to the version of record on the publisher's site

Gholamahmadi, B., Jeffery, S., Gonzalez-Pelayo, O., Prats, S., Bastos, A.C., Keizer, J.J. and Verheijen, F.G. (2023) 'Biochar impacts on runoff and soil erosion by water: a systematic global scale meta-analysis', *Science of The Total Environment*, 871, article number 161860.

Science of the Total Environment 871 (2023) 161860

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Biochar impacts on runoff and soil erosion by water: A systematic global scale meta-analysis

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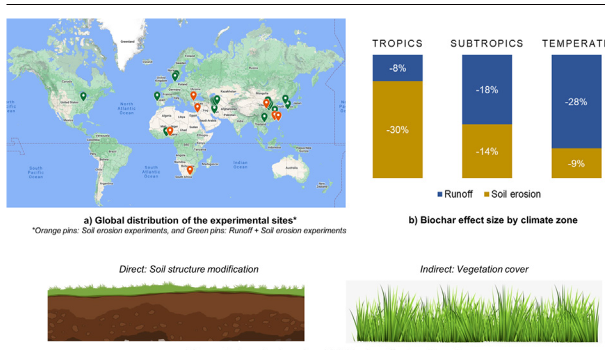
HIGHLIGHTS

- On average, biochar application to soil reduced runoff by 25 % and erosion by 16 %.
- Soil erosion in the tropics was reduced 3 times more than in the temperate zone.
- Biochar effect was strongest at intermediate biochar concentrations (0.6–2.5 %, m/m).
- Vegetated biochar experiments resulted in double erosion reduction than bare soil.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Manuel Esteban Lucas-Borja

Keywords:
Biochar
Soil hydrology
Soil mechanism
Overland flow
Land degradation
Desertification

ABSTRACT

Biochar application to soil has the potential to affect soil and vegetation properties that are key for the processes of runoff and soil erosion. However, both field and pot experiments show a vast range of effects, from strong reductions to strong increases in runoff and/or soil erosion. Therefore, this study aimed to quantify and interpret the impacts of biochar on runoff and soil erosion through the first systematic meta-analysis on this topic. The developed dataset consists of 184 pairwise observations for runoff and soil erosion from 30 independent studies but 8 of which just focused on soil erosion. Overall, biochar application to soil significantly reduced runoff by 25 % and erosion by 16 %. Mitigation of soil erosion in the tropics was approximately three times stronger (30 %) than at temperate latitudes (9 %); erosion reduction in the subtropical zone was 14 %, but not significantly different from either the tropical or temperate zones. Fewer reported field observations for runoff resulted in larger confidence intervals and only the temperate latitudes showed a significant effect (i.e. a 28 % reduction). At topsoil gravimetric biochar concentrations between 0.6 % and 2.5 %, significant reductions occurred in soil erosion, with no effect at lower and higher concentrations. Biochar experiments that included a vegetation cover reduced soil erosion more than twice as much as bare soil experiments, i.e. 27 % vs 12 %, respectively. This suggests that soil infiltration, canopy interception, and soil cohesion mechanisms may have synergistic effects. Soil amended with biochar pyrolyzed at >500 °C was associated with roughly double the erosion reduction than soil amended with biochar produced at 300–500 °C, which potentially could be related to the

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http://dx.doi.org/10.1016/j.scitotenv.2023.161860
Received 11 November 2022; Received in revised form 23 January 2023; Accepted 23 January 2023
Available online 8 February 2023

enhancement of hydrophobicity in the latter case. Our results demonstrate substantial potential for biochar to improve ecosystem services that are affected by increased infiltration and reduced erosion, while mechanistic understanding needs to be improved.

Contents

1. Introduction

Accelerated soil erosion and land degradation are pressing environmental challenges, resulting in the degradation of ecosystem services (Hugo and Roćio, 2009; Verheijen et al., 2009; Borrelli et al., 2017; Eswaran et al., 2019), such as the reduction in soil productivity and sustainability of agricultural lands (Lal, 2008, 2010). Globally, soil erosion by water is predicted to increase by 30 % to 66 % by 2070 (Borrelli et al., 2020). Solely in the EU and UK, the mean soil erosion rate is estimated to increase by 13 % to 22.5 % from an estimated 3.07 t ha^{-1} yr^{-1} (representative baseline, 2016) to between 3.46 t ha^{-1} yr^{-1} and 3.76 t ha^{-1} yr^{-1} by 2050 (Panagos et al., 2021). Biochar is the residual carbon (C)-rich by-product of the pyrolytic conversion of biomass for bioenergy production (Lehmann and Joseph, 2015). Soil application of biochar as a legal soil amendment (EU – The European Union, 2019), is considered a strategy for countering land degradation and supporting global agricultural soils (Barrow, 2012) while representing a potential geoengineering tool for climate change mitigation and through C sequestration in soil (The Royal Society, 2009; Bruckman et al., 2015; IPCC - The Intergovernmental Panel on Climate Change, 2021). In a recent systematic review of 26 meta-analyses, Schmidt et al. (2021) highlight that biochar use in agriculture has the potential to combine carbon dioxide removal with significant agronomic and/or environmental co-benefits, if biochar type, application rate, and method, are suitably selected given the application aim and site-specific environmental and crop requirement combinations (Verheijen et al., 2015, 2019). It has been gaining substantial research interest (Verheijen et al., 2014; Jiao et al., 2021), in both public and private sectors because of its potential to reduce soil erosion (Blanco-Canqui, 2019), land degradation by sequestering organic carbon (C), while also being a more generally acceptable environmental management tool from a public point of view (Glaser et al., 2002; Beesley et al., 2011; Zhang et al., 2016).

One of the main mechanisms by which biochar may affect erosion rates is by improving soil structure, i.e. the size, stability, and spatial arrangement of soil aggregates (Blanco-Canqui, 2017), and thereby changing time-to-runoff (infiltration capacity), runoff duration/amount, and soil erodibility. Several meta-analyses have shown a positive correlation between topsoil biochar concentration and soil physical-hydrological properties, i.e. saturated hydraulic conductivity, available water capacity, bulk density, and porosity (Omondi et al., 2016; Razzaghi et al., 2019; Edeh et al., 2020). For Hortonian (infiltration-excess) overland flow, the soil structure in the topsoil layer is a key determinant factor, in which soil surface sealing or crusting in the top centimetres, drastically reduces the soil infiltration capacity (Nciizah and Wakindiki, 2015). For saturation-excess overland flow, the soil structure throughout the soil profile is key. Commonly, a deterioration in soil structure in a finer textured and/or compacted subsoil causes a sudden and strong decrease in (un)saturated hydraulic conductivity.

Li et al. (2019a,b) found that biochar addition decreased the total runoff volume by 12.2 % and generally inhibited soil loss under lower biochar concentrations (1 % and 3 %) while promoting soil loss under higher biochar concentrations (5 % and 7 %). In the study of Lee et al. (2018), the co-application of biochar and compost was the most effective in decreasing runoff (by around 17 %). However, Vilayvong et al. (2016) showed that a combination of organic amendment with biochar could increase soil erosion by an average of 60 % (i.e. 30 % to 100 %). Prats et al. (2018) reported a 59 % increase in soil erosion after applying charcoal on the soil surface (i.e. <7 mm), while a straw-biochar co-application significantly reduced soil erosion by an average of 70 % in two burnt areas with different burn severity classes (Prats et al., 2021).

Biochar may affect soil erosion indirectly by i) changing plant growth and, thereby, the raindrop impact on the soil surface, which in turn, affects the mobilisation of soil particles by rain splash erosion; ii) changing root growth and architecture, thereby affecting aggregation and cohesion between aggregates; and iii) increasing soil roughness by forming physical impediments to overland flow and affecting its velocity (Zuazo and Pleguezuelo, 2008). Since biochar has been shown to generally increase plant growth in soils with a pH below the optimum (Jeffery et al., 2017), this indirect plant growth mechanism may be expected to contribute to any potential mitigation of soil erosion. However, Jeffery et al. (2017) also identified a contrast between biochar effects in tropical and temperate latitudes, i.e. in the tropics, crop yield increased by 19 % for biochar made from "Structure" feedstocks (e.g. wood or straw) and by 70 % for biochar made from a "Nutrient" feedstock (e.g. manures), while in the temperate zone there was no significant effect for either feedstock category. This finding implies that the indirect effect of biochar in reducing soil erosion via increasing soil cover with enhanced crop growth may be stronger in the tropics than in the temperate zone. In summary, evidence from the literature shows multiple potential mechanisms of how runoff and erosion may increase or decrease following biochar application. There are currently no syntheses that quantify the effects of biochar application to soil on such processes. We aimed to help bridge this knowledge gap through a systematic and comprehensive quantitative meta-analysis that explores climate, biochar, soil, precipitation, terrain, and methodological predictor variables. We explore the causes and mechanisms of how biochar application to soils affects runoff and erosion to inform both future research and policy development.

2. Materials and methods

2.1. What is a meta-analysis?

Meta-analysis is a quantitative statistical analysis of several separate but similar scientific experiments or studies addressing the same question, to test the pooled data for statistically significant.

2.2. Data sources and treatment

A literature search was performed on Scopus, ScienceDirect, and Google Scholar databases, using the search string "(soil AND biochar OR charcoal OR black carbon) AND runoff AND erosion". A total of 70 studies were found that were published/available before the cut-off date of 1st July 2020. Among such studies, 40 contained insufficient information on environmental or experimental parameters (21 out of 40) and/or on the variance in runoff and erosion results (14 out of 40) or were considered not relevant in the context of the present study (5 out of 40). Furthermore, only studies with trials comprising at least three replicates measurement units per treatment were included. Both laboratory/greenhouse experiments (i.e. 97 out of 184 pairwise) and field experiments (i.e. 87 out of 184 pairwise comparisons) were considered. All of these 184 pairwise observations from 30 independent studies included soil erosion and runoff experiments. And among them, the 55 pairwise observations from 8 independent studies just included soil erosion experiments. Studies that did not consider quantitative results were excluded from the building process of the meta-analysis dataset. Also, Nyambo et al. (2018) paper was excluded because the confidence intervals (CIs) for the >120 in rainfall intensity categories were out of range. When no measures of variance were given, efforts were made to obtain these directly from the corresponding authors, which was successful on two occasions (Li et al., 2019a,b). If not, those studies were also excluded from the analysis (Lee et al., 2015). To try to have an unbiased meta-analysis, efforts were also made to contact lead researchers on the topic of biochar for the inclusion of unpublished data (as listed in Supplementary material), which has been successful. This was a recommended strategy by Cooper (2010) for any data that are not presented in the format needed to calculate the effect sizes.

Auxiliary variables are presented in the Supplementary material (see Fig. S1–S13). Graphical data were extracted using a web-based tool, WebPlotDigitizer (Version 4.2). The dataset was built in Excel (Microsoft Corporation, 2018), with each row representing a 'treatment', and then exported to MetaWin Version 2.1 statistical software.

2.3. Data processing

Auxiliary variables consisting of continuous data were grouped aiming for maximal in-group homogenization. Ranges for grouping variables are shown in Table 1. For example, biochar application rates were divided into three categories; <10, 11–50, and >50 (t ha^{-1}); soil texture was grouped into three classes based on the USDA classification: fine, medium, and coarse; climatic zones were grouped based on longitude: tropical (0 to 23.5°), subtropical (23.5 to 35°) and temperate (>35° (excluding polar zone)). All grouping information, alongside other related tables, are shown as Supplementary material (see Table S1). Results with associated error bars >500 % were excluded from the initial dataset to increase the resolution for the remaining categories.

2.4. Data visualization

All figures were produced in Excel (Microsoft Corporation, 2018), where numbers in parentheses indicate the number of pairwise comparisons on which the erosion (left) and runoff (right) statistics are based. The grand mean represents the mean effect size of all studies that reported data in any specific category. Although erosion and runoff analysis use studies from the same dataset (Table S1), the number of studies and/or the specific studies for erosion and runoff, or a partition therein, may not be the same. See Table S1 for specific study contributions.

2.5. Comparisons using meta-analysis

In this meta-analysis, the missing measures of variance were calculated as double the means of the standard deviations of the selected studies (Weir et al., 2018). A categorical meta-analysis using a random-effects model (Tufanaru et al., 2015) was applied with 9999 iterations using MetaWin Version 2.1 statistical software. The effect size was calculated by unlogging the response ratio, which was calculated as (Hedges et al., 1999):

$$ln\ RR = ln\left(\frac{\bar{x}^E}{\bar{x}^C}\right)$$

Table 1
Experimental comparison between tropical and temperate zones (subtropical zone was omitted for the reasons explained in Discussion). C = coarse; M = medium; F = fine; AL = Application Layer.

Climatic zones	Soil texture category			Median application depth (cm)	Median application rate (t ha^{-1})	Median [biochar] in AL (%)	Median biochar ash (%)	Median soil pH	Median biochar pH
	%C	%M	%F						
Temperate	58	26	17	5	7.5	1	60	6.3	8.5
Tropical	65	18	16	20	5	0.2	6	5.7	8.8

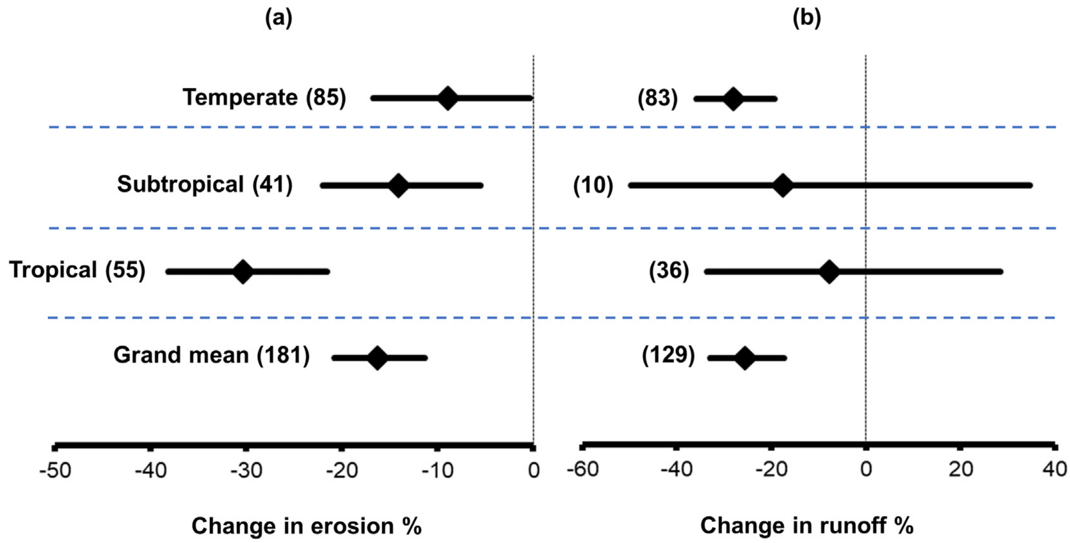

Fig. 1. The effect size of biochar application on erosion (panel a), and runoff (panel b) (%) by the major climatic zones. Data points (diamonds) show means, with bars representing 95 % confidence intervals. The number in parentheses is the number of pairwise comparisons on which the statistic is based. See Supplementary Tables 4 and 5 for more details on this categorisation.

where: $\bar{x}^E$ = mean of experimental treatment; $\bar{x}^C$ = mean of control treatment.

The control treatment was defined as being identical to the experimental treatment concerning all other variables, excluding the addition of biochar. Therefore, data were extracted from treatments in each study, where control with zero biochar input could be compared to an equivalent treatment with biochar, at either single or multiple application rates, with all other factors unchanged. Results were reported at the level of single comparisons (Jeffery et al., 2017).

3. Results

3.1. Predictor variables related to climate zones

Overall, biochar application to soil reduced runoff by 25 % and erosion by 16 % (Fig. 1). However, both results contrasted strongly across latitudinal zones. Soil erosion (Fig. 1a) in the tropics was reduced by 30 %, in the subtropics by 14 %, and in the temperate zone by 9 %. The opposite pattern was observed for runoff (Fig. 1b), i.e. a 28 % reduction in the temperate, while no significant effects were observed across studies in the tropics or subtropics.

3.2. Predictor variables related to biochar characteristics

3.2.1. pH

The use of neutral to very alkaline biochar reduced erosion and runoff by 19 % and 16 %, respectively. In terms of changes in soil erosion, alkaline biochar was associated with a 2.3 times stronger reduction in erosion, compared to very alkaline biochar (Fig. 2a). The neutral biochar category showed no significant effect.

3.2.2. Pyrolysis temperature

Biochar pyrolyzed at temperatures higher than 500 °C was associated with 1.9 times a greater reduction in soil erosion than when pyrolyzed at 300–500 °C (Fig. 3a). Also, a 30 % effect size in runoff reduction is observed

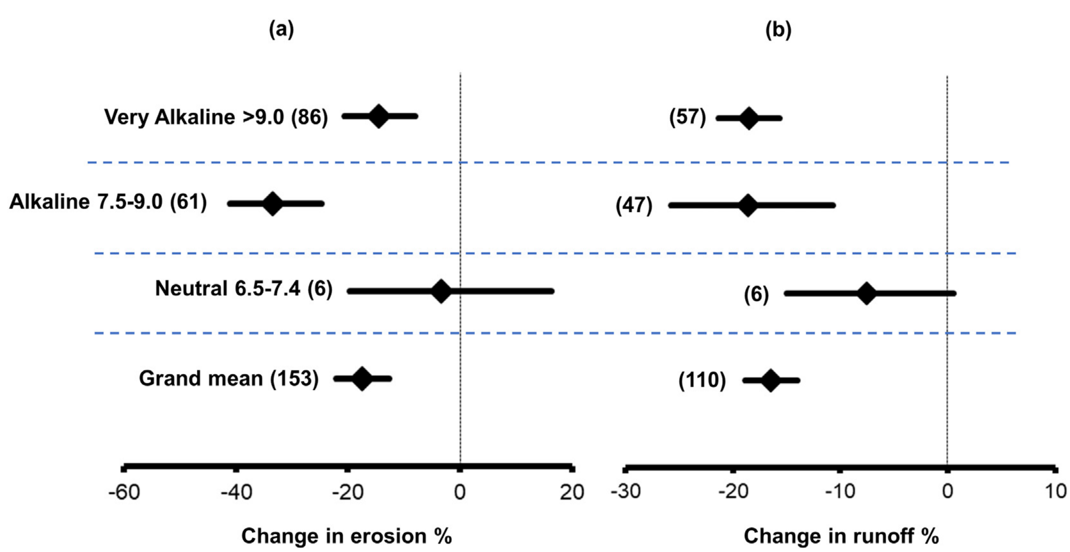

Fig. 2. The effect size of biochar application on erosion (panel a), and runoff (panel b) (%) by biochar pH category. Data points (diamonds) show means, with bars representing 95 % confidence intervals. The number in parentheses is the number of pairwise comparisons on which the statistic is based. See Supplementary Tables 4 and 5 for more details on this categorisation.

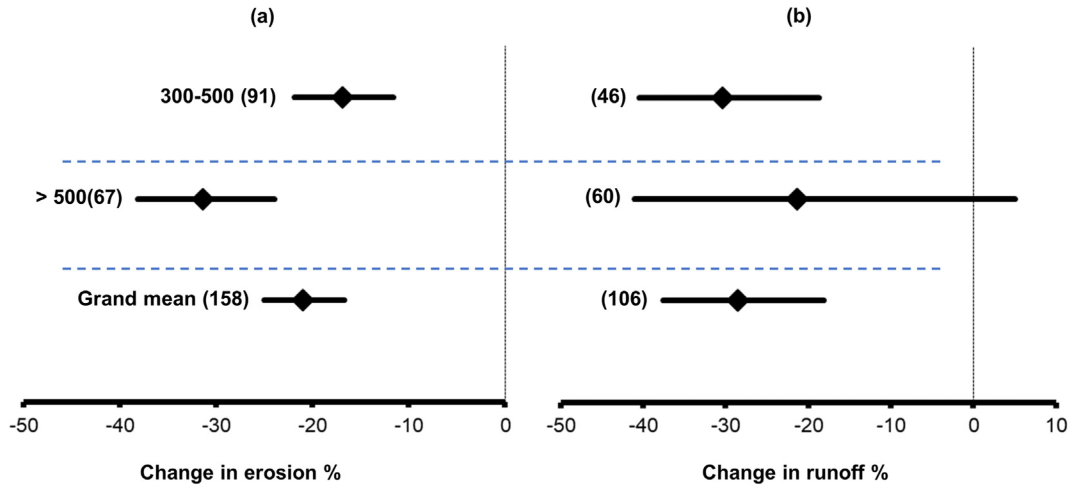

Fig. 3. The effect size of biochar application on erosion (panel a), and runoff (panel b) (%) by pyrolysis temperature (°C) category. Points (diamonds) show means, with bars representing 95 % confidence intervals. The number in parentheses is the number of pairwise comparisons on which the statistic is based. See Supplementary Tables 4 and 5 for more details on this categorisation.

with biochar pyrolyzed at 300–500 °C, compared to a 20 % reduction at pyrolysis temperatures higher than 500 °C.

3.3. Biochar application predictor variables

3.3.1. Topsoil biochar concentration

Soils with biochar concentrations of 0.6 % to 2.5 % (m/m) exhibited erosion reduction of just over 20 %, compared to when no biochar was included, while the effect size was roughly halved for smaller concentrations (0–0.5 %), and not significant for larger concentrations (>2.5 %; Fig. 4a). Biochar reduced runoff (by 35 %) only up to 1 % biochar (m/m), with no significant effects at higher biochar concentrations.

3.3.2. Biochar application depth

Biochar application to maximum depths of either 5 cm or 15 cm, showed a greater reduction in soil erosion of approximately 22 %. Applications to a depth of 30 cm were shown to reduce erosion only by 6 % (Fig. 5a). In turn, application depths of 5 cm showed a reduction in the runoff by 31 % when compared to other application depths, i.e. 15 cm by 19 %, and 30 cm by 12 % (Fig. 5b).

3.3.3. Soil cover

Erosion was significantly halved (i.e. 27 % vs. 12 %) when biochar experiments included vegetation cover (VC) compared to biochar experiments using bare soil (BS) surface (Fig. 6a). No significance was observed in runoff while biochar experiments using bare soil (BS) exhibited a greater reduction in runoff compared to experiments that included vegetation cover (VC), i.e. 30 % against 20 %.

3.3.4. Soil texture

Biochar addition to medium and coarse-textured soils had reduced erosion by 16 % and 21 % respectively (Fig. 7a), while biochar addition to fine-textured soils did not result in a significant change in the runoff (Fig. 7b). The confidence intervals for runoff in the medium soil texture category are five times larger than those for erosion, indicating a substantially more variable runoff than erosion response.

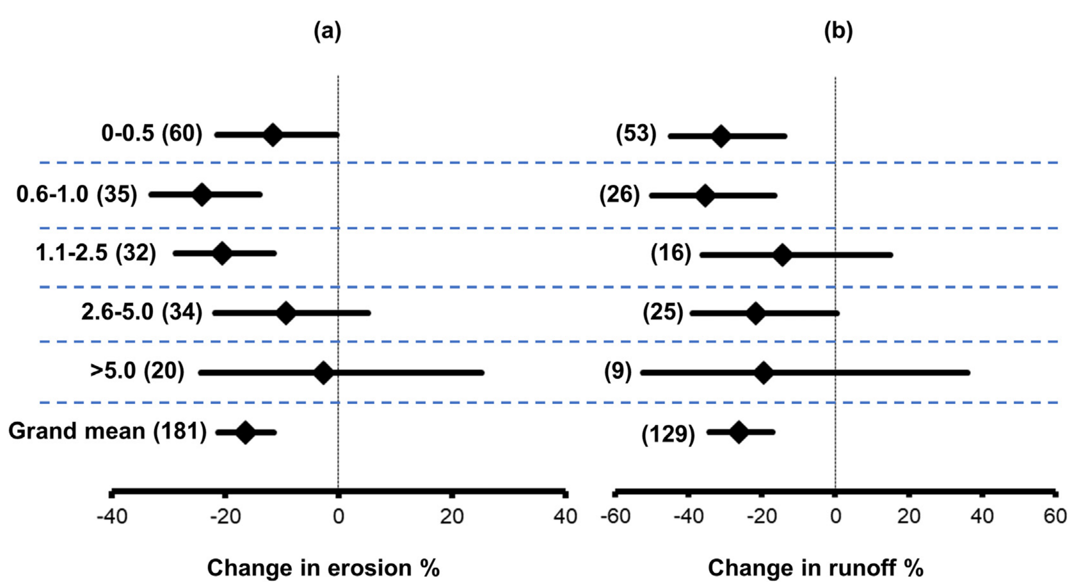

Fig. 4. The effect size of biochar application on erosion (panel a), and runoff (panel b) (%) by biochar concentration (%, m/m) category. Points (diamonds) show means, while bars represent 95 % confidence intervals. The number in parentheses is the number of pairwise comparisons on which the statistic is based. See Supplementary Tables 4 and 5 for more details on this categorisation.

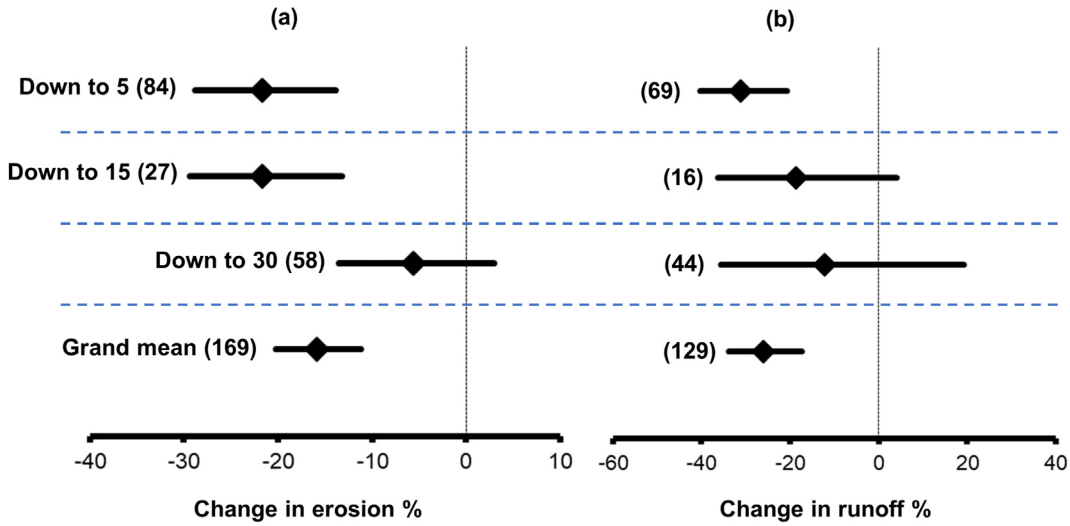

Fig. 5. The effect size of biochar application on erosion (panel a), and runoff (panel b) (%) by biochar application depth (cm) category. Points (diamonds) show means, while bars represent 95 % confidence intervals. The number in parentheses is the number of pairwise comparisons on which the statistic is based. See Supplementary Tables 4 and 5 for more details on this categorisation.

4. Discussion

Considering that our results showed the strongest changes occurring between tropical and temperate zones, which have also been found for biochar effects on crop yield (Jeffery et al., 2017), we have structured the discussion of the predictor variables by climatic zones (Subsection 4.1), before unravelling the main causal mechanisms (Subsection 4.2) and contextualising our main observations (Subsection 4.3). However, because of the relatively reduced number of observations in the subtropical zone for both erosion and runoff, combined with large confidence intervals and lack of significant differences between that and the other two main climatic zones, we have not included the subtropical zone separately in the discussion. Further, for consistency, the main predictor variables are discussed below following a similar structure to that used in the Results section.

4.1. Tropics vs. temperate comparisons: main factors

Table 1 compared and summarised the main predictor variables between the tropical and temperate zones. While soil texture, soil pH, and biochar pH were comparable between climatic regions, biochar in the temperate zone had a ten times greater ash content, and the amended-soil layers had a five times greater biochar concentration, because of higher application rates and shallower application depths.

The highest biochar pH category (very alkaline) was less often used in the tropics (4.3 % of pairwise comparisons) than in the temperate zone (76.7 % of pairwise comparisons). Interestingly, the neutral biochar category showed no significant effect. However, this statistic is based on a reduced number of observations (i.e. 6) suggesting that more observations are required in this category before any conclusions can be drawn. Although ash content was reported for almost one third of the pairwise comparisons (i.e. 68), differences in feedstock type and availability in the two climatic zones are likely to explain differential results, despite suggesting a smaller contrast in median values. Nutrient feedstocks, which are generally high in ash content, were used in 21 % of pairwise comparisons in the temperate zone, but only 4 % of that in the tropics. Furthermore, 60 % of tropical pairwise comparisons used rice husk as the main biochar feedstock, and although rice husk has a relatively high ash content, the proportion of Ca^{2+}, K^{+}, and Mg^{2+} that is water-soluble are low (Prakongkep

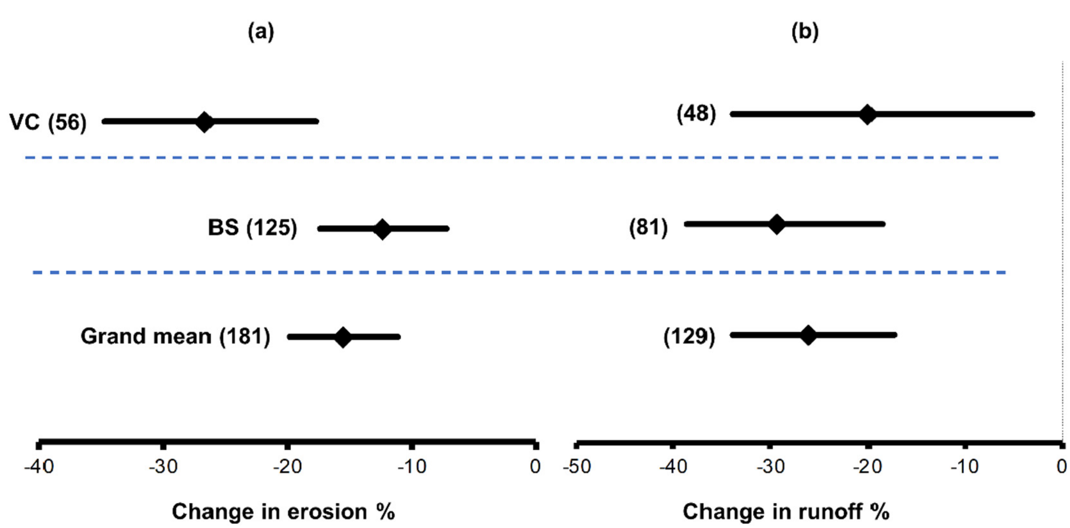

Fig. 6. The effect size of biochar application on erosion (panel a), and runoff (panel b) (%) by soil cover category. VC = vegetation cover; BS = bare soil. Points (diamonds) show means, while bars represent 95 % confidence intervals. The number in parentheses is the number of pairwise comparisons on which the statistic is based. See Supplementary Tables 4 and 5 for more details on this categorisation.

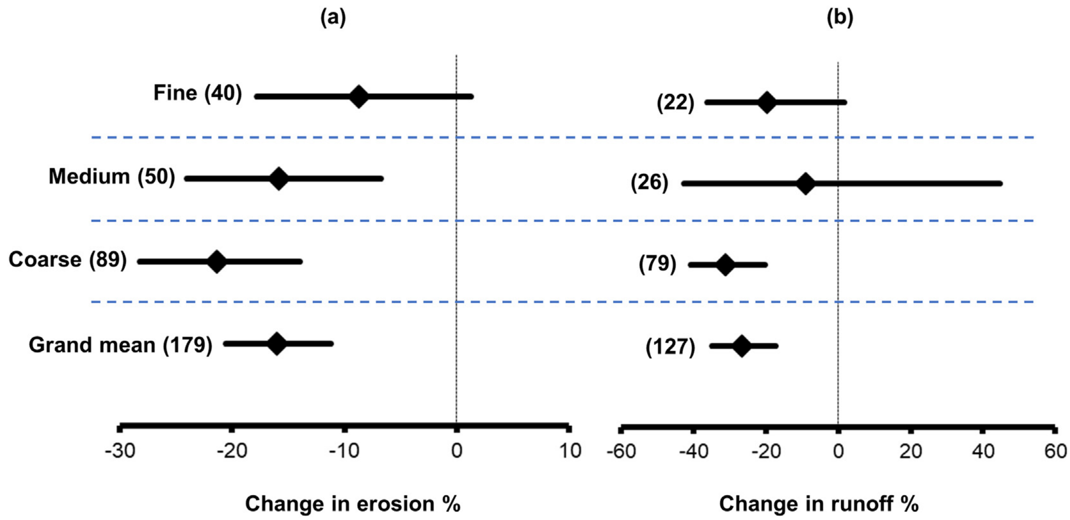

Fig. 7. The effect size of biochar application on erosion (panel a), and runoff (panel b) (%) by major soil texture category. Points (diamonds) show means, while bars represent 95 % confidence intervals. The number in parentheses is the number of pairwise comparisons on which the statistic is based. See Supplementary Tables 4 and 5 for more details on this categorisation.

et al., 2013). A nearly 20 times larger proportion of pairwise comparisons in the temperate zone used alkaline biochar (i.e. 56 against 2 in the tropics), while there was no difference in the proportion of pyrolysis temperature pairwise comparisons numbers (i.e. 55 vs. 67), which is consistent with the nutrient feedstocks used in the temperate zone having greater ash contents. Further, in both tropical and temperate zones, 73 % of the pairwise comparisons used biochar pyrolyzed at a temperature > 500 °C, and thus, pyrolysis temperature is unlikely to have caused the stronger erosion reduction in the tropics. Soil amended with biochar pyrolyzed at > 500 °C was associated with roughly double the erosion reduction as when the biochar was produced at 300–500 °C, which may indicate a hydrophobicity introduction mechanism (Zornoza et al., 2016). Mao et al. (2019) suggested the dominant factor determining the severity of biochar hydrophobicity is pyrolysis temperature.

4.2. Main causal mechanisms: vegetation cover and soil structure

Our results suggest that increased vegetation cover may be one of the main mechanisms by which biochar indirectly affects soil erosion. In general, experiments that included vegetation cover significantly reduced soil erosion twice as much as bare soil experiments (i.e. −25 % vs. −13 %). Since runoff did not differ between bare and vegetated categories, it can be speculated that biochar-stimulated plant growth reduced the mobilisation of soil particles by rain splash erosion through increased rainfall interception by plants, and/or increased soil cohesion through enhanced root growth, and/or reduced the velocity of overland flow, thus increasing soil roughness. Biochar may even better at helping soils resist erosion when raindrop impacts are low, with their energy input into soil having been moderated by the canopy. One-third of the pairwise comparisons were conducted with a vegetated cover and two-thirds were with bare soil (i.e. 57 vs. 127 out of 184). Some studies (i.e. Smetanová et al., 2013; Kumar et al., 2019; Sadeghi et al., 2020) reported a significant increase in erosion in bare soil compared to vegetation-covered soil by 117 %, 93 %, and 204 %, respectively. Since the future policy is likely to favour cover crops in the EU (Smit et al., 2019), it will become increasingly important to improve the understanding of biochar-plant cover interactions. The relative contribution of these factors requires further research, including on the interaction with root growth to find the impact on soil cohesion.

Soil structure modification is also suggested by our results as one of the mechanisms by which biochar affects soil erosion; if decreased soil bulk density was the only mechanism at work, then runoff and erosion would continue decreasing with increasing biochar concentration in the application layer. The response curve of biochar concentration on soil erosion (Fig. 4a), shows intermediate biochar concentrations (0.6–1.0 %, and 1.1–2.5 %) reduce erosion more than both the lower concentration (0–0.5 %, m/m) and higher concentrations (2.6–5.0 % and >5 %, m/m). Considering the multiple potential causal mechanisms of this dose response, it may not be a straightforward single mechanism, as suggested for some of the other factors with similarly shaped response curves (Graber et al., 2014; Jaiswal et al., 2015). More research, and more data, are required to find answers. It should also be noted that from a utilitarian perspective there may not be a C-shape, since the two higher biochar concentration categories are only used in small-scale experiments - sometimes specifically to force negative effects - but not in practice where such high application rates would be economically improbable. Since Fig. 4 shows a trend of decreasing effect sizes for higher biochar concentration categories, the existence of another mechanism that decreases infiltration, acting as a trade-off, is likely, and identifying this trade-off is paramount for policy development. Grouping all soils, biochar concentrations of 0.6–2.5 % (m/m) could be considered optimal for erosion reduction, although a wider range of concentrations may be relevant when soils are not grouped. There is no strong direct evidence suggesting a mechanism of soil surface sealing/crusting by (micro) aggregate dispersion caused by deleterious changes in ESP/SAR following the introduction of salts with biochar application. This is because data for the relevant salts - Na^+, K^+, Mg^{2+}, Ca^{2+} - were generally not reported, and even biochar ash content data – as a proxy indicator for salinity – were only reported in 12 out of 30 studies. An indirect indicator of the relevant salts can be found in biochar pH, which showed stronger erosion reduction for alkaline biochars, in both tropical and temperate zones (Hseu et al., 2014; Gholami et al., 2019). However, more data on measurements of the availability of the relevant salts are required to explore this mechanism. Biochar amendment can induce soil organic matter humification, especially in tropical soils (Amoakwah et al., 2020). This is a potentially related mechanism to soil aggregates and their water stability, which was not reported in the studies in our dataset.

4.3. Limitations of this study

Compared to studies in the temperate zone that used median biochar ash contents around 60 %, those in the tropics have generally used lower ash content biochar (6 %). In turn, the pyrolysis method showed differential effects on erosion reduction, which was significant for slow pyrolysis but not for gasification, which typically produces biochar with higher ash contents (Peng et al., 2016; Kumar et al., 2019). However, the substantially lower number of observations for these variables (i.e. pyrolysis method (Fig. S5), ash content (Fig. S7)), translates into this result not being as robust as other biochar-related parameters (e.g., pH and pyrolysis temperature, and ash content). Biochar particle size (or biochar texture categories) showed no significant effects in reducing runoff and soil erosion (Fig. S6). Coarser biochar particle size distributions (>2 mm) had no effect on erosion or runoff, but the number of pairwise comparisons was too low for a robust interpretation and more research is recommended.

The 0–0.5 % (m/m) biochar concentration category represented 54 % (i.e. 30 out of 55) of the whole pairwise comparisons in the tropical zone, while the 0.6–1.0 % (m/m) biochar concentration category represented one-third (i.e. 26 out of 86) of all observations in the temperate zone. Most studies added biochar to coarse-textured soil, with 48 out of 86 pairwise comparisons in the temperate region, and 36 out of 55 in the tropics. Recent studies (Wu et al., 2020; Du et al., 2022) with meta-analysis showed that coarse and medium-textured soils have the potential to reduce runoff and erosion compared to fine-textured soils. We can consider this as a hypothesis for the use of coarse-textured soils in biochar experiments. Biochar application rate (Fig. S1) shows a similar pattern with no effect at >50 t ha^{-1}. This pattern of biochar effects with biochar concentration has been reported for other factors as well, e.g., disease severity (Graber et al., 2014; Jaiswal et al., 2015) contaminant degradation (Qin et al., 2017), and seed germination (Li et al., 2015, 2017a,b). Tropical experiments also contrasted with temperate experiments in the biochar concentration of the topsoil application layer. The five times greater median biochar concentration resulted from a 50 % higher median application rate to a 75 % shallower topsoil depth.

Other differences in experimental set-up and approach may also contribute to explaining contrasting results between both climatic zones, at least to an extent. A greater proportion of field studies were used in the tropics compared to the temperate region, with longer durations and being subjected to natural rainfall. In the tropics, 71 % of the pairwise comparisons used natural rainfall, compared to 9 % in the temperate zone. The median study duration in the tropics was 48 weeks, as opposed to 16 weeks in the temperate region. In particular, the study duration category of 0–1 week was used in the temperate region to a greater extent (36 %), compared to the tropical region (14 %). Further, laboratory experiments are better suited to force negative effects. Identifying which biochar concentrations induce negative effects is useful to improve our understanding of the range of potential impacts and ensure a sustainable application, but it may have skewed the results of the temperate zone in the data partitioning by climatic region. The implication is that the reported overall erosion reduction in the temperate zone (9 %) may be an underestimation of the achievable erosion reduction. A future meta-analysis on an expanded dataset may find the answer to this question by partitioning the data by biochar concentration for the tropical and temperate zones separately.

Tropical experiments often included a soil vegetation cover, where only 48 % of studies used bare soil. This contrasts with the 73 % of studies that used bare soil in the temperate region (62/86). In addition, previous work (Jeffery et al., 2017) has shown that biochar improved plant growth (expressed as crop yield) three times more pronouncedly in the tropics than in temperate latitudes. This suggests that the indirect mechanism of increased soil vegetation cover may have had a significant contribution to the greater soil erosion reduction in the tropics, compared to temperate latitude. The tropics hold a substantially larger average yield gap - i.e. the difference between current farm yield and potential yield when crops are grown with optimal nutrient supply (GYGA, 2022) - than the temperate zone (Van Ittersum et al., 2013). This result is mentioned in another meta-analysis (Jeffery et al., 2017), which showed no effect of biochar on crop yield in temperate latitudes yet elicits a 25 % average increase in yield in the tropics. The proportion of nutrient feedstock used was reported just in Kumar et al. (2019) study in the tropics, and has only been reported in three studies in the temperate zone (i.e. Gholami et al., 2019; Sadeghi et al., 2016, 2020). This matter should be considered for further investigation under both climatic zones, particularly for long-term studies using different nutrient feedstock combinations.

Neither experimental duration (Fig. S9), slope angle (Fig. S10), experimental scale (Fig. S11) or rainfall type (Fig. S12) showed significant differences between categories. This is surprising considering that short-duration rainfall simulations (i.e. 2.5 times greater proportion of <1-week experimental duration in the temperate zone) may not allow the soil to "settle" after the disturbance of biochar incorporation. Depending on soil and biochar characteristics, these short-duration experiments would be expected to either, have decreased erosion or increased it (since runoff needs less energy to pick up disturbed soil particles). Yet, since long-term field studies with natural rainfall are more informative regarding real-world applications and their impacts, than short-term laboratory studies using a limited range of rainfall and vegetation development conditions, results found for the tropical zone are likely to be more relevant to inform guidelines for end-users and policy development.

4.4. Integration of predictor variables, a recommendation for future studies

Combined, these meta-analysis effect size results suggest that to optimise soil erosion mitigation biochar should be incorporated into the topsoil to 15 cm depth or less, to reach a concentration of 0.6 % to 2.5 % (m/m), which is in the range of 26–50 t ha^{-1}, in medium or coarse-textured soils, with vegetation covering the soil surface. However, the 95 % confidence intervals (CIs) are relatively large for many predictor variables (see also the Supplementary figures (Fig. S), making statistical exploration of interactions between predictor variables – such as in a mixed model – very limited with the current dataset. Further, erosion CIs for the temperate and tropical categories were similar, even though the number of observations in the temperate zone was 1.5 times higher. In turn, runoff CIs are three times greater in the tropics, which may partly be explained by 2.3 times greater number of observations in the temperate zone. Data on runoff in the subtropics were highly variable across studies, which combined with a reduced number of observations (i.e. 10) resulted in large error bars, thus suggesting that more research is required in this category before conclusions can be drawn.

If the steady increase in publications on the topic during the 2010s continues into the 2020s, a mixed model may provide more insight into interactions between predictor variables, and into causal mechanisms, to provide more accurate and specific recommendations for land users and policy developers. For example, from the current study, it cannot be determined if lower ash content biochar would maintain, or further reduce, erosion when applied to reach topsoil concentrations >2.6 %, or if in coarse-textured soils higher ash content biochar maintains or increase erosion reduction at higher biochar concentrations in the topsoil. Improved reporting of key auxiliary variables in biochar erosion/runoff experiments would facilitate meta-analytical interpretation of mechanisms and trade-offs (see Tables S1, S2, and S3).

Nevertheless, despite the limitations of the current study to explore interactions, the grand means for erosion and runoff justify prioritising research funding to be directed to expanding the number and duration of experiments, so that future meta-analyses can provide more detailed guidelines for end-users and policy developers. Against predicted global soil erosion increases of 30 % to 66 % by 2070 (Borrelli et al., 2020), a 25 % decrease in runoff and 16 % decrease in erosion (30 % in the tropics) from biochar application to soil, may provide land managers with a valuable tool - among others - to mitigate the loss of valuable topsoil and help sustain global food production. Moreover, since soil erosion is estimated to cause severe economic losses, it seems appropriate to achieve a better understanding of the causal mechanisms behind the observed erosion reduction with biochar incorporation in soils. For example, a 16 % decrease in erosion would equate to a 6.4 billion US$ saving for the USA alone, considering the estimate of Pimentel et al. (1995). The challenge is to further our understanding of the causative mechanisms and their boundary conditions for specific biochar-soil-crop-climate combinations (Verheijen et al., 2012, 2015, 2019). In general, the identification and quantification of predictor variables are limited due to the patchy reporting of these variables in the studies, thus placing further constraints on the identification of causative mechanisms.

5. Conclusions

This meta-analysis evaluated the current state of knowledge on biochar effects on runoff and soil erosion by water on 22 biochar-related, soil-related, climatic, environmental, and methodological predictor variables. Overall, results showed that biochar application to soil significantly reduced erosion by 16 % and runoff by 25 % on average. The mitigation of soil erosion in the tropics was approximately three times stronger (30 %) than in temperate latitudes (9 %). Data also suggests that vegetated soil with biochar is better at resisting low-impact raindrops that come from the canopy rather than high-impact raindrops onto bare soil, which is considered an indirect mechanism. Also, it is improved soil structure thereby decreasing soil erodibility (a direct mechanism). Future work should focus on experimental study designs that allow investigation of causative mechanisms, and mixed model meta-analyses to explore interactions. A more comprehensive and consistent reporting of auxiliary variables would greatly assist this.

CRediT authorship contribution statement

Behrouz Gholamahmadi: Conceptualization, Data curation, Investigation, Methodology, Visualization, Roles/Writing – original draft, Writing – review & editing. Frank Verheijen: Conceptualization, Data curation, Investigation, Methodology, Supervision, Roles/Writing – original draft, Writing – review & editing. Simon Jeffery: Data curation, Investigation, Methodology, Software, Writing – review & editing. Jan Jacob Keizer: Writing – review & editing. Oscar Gonzalez-Pelayo: Writing – review & editing. Ana Catarina Bastos: Writing – review & editing. Sergio Alegre Prats: Writing – review & editing.

Data availability

We have shared the dataset and software output. They are available in supplementary data.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Behrouz Gholamahmadi reports financial support was provided by Foundation for Science and Technology. Frank Verheijen reports financial support was provided by Foundation for Science and Technology. Ana Catarina Bastos reports financial support was provided by Foundation for Science and Technology. Frank Verheijen reports financial support was provided by University of Aveiro Centre for Environmental and Marine Studies. Sergio Alegre Prats reports financial support was provided by Foundation for Science and Technology. Oscar Gonzalez-Pelayo reports financial support was provided by Foundation for Science and Technology. Jan Jacob Keizer reports financial support was provided by Foundation for Science and Technology.

Acknowledgments

We acknowledge financial support to CESAM by the Portuguese Foundation for Science and Technology FCT/MCTES (UIDP/50017/2020 + UIDB/50017/2020 + LA/P/0094/2020), through national funds. We further acknowledge FCT for the funding of project SOILCOMBAT (PTDC/EAM-AMB/0474/2020) as well as of authors B. Gholamahmadi (2020.04610.BD), F. Verheijen (CEECIND/02509/2018) and S.A. Prats (CEECIND/01473/2020). A.C. Bastos is funded by national funds (OE), through FCT in the scope of the framework contract foreseen in art. 23° DL57/2016 (n. 4, 5, 6) of August 29, amended by Law 57/2017 of July 19. O. Pelayo and S. Prats were supported initially by the same funding framework and are currently funded by MED & CHANGE through FCT/MCTES (UIDB/05183/2020). The authors further acknowledge the financial support to GeoBioTec (UIDB/04035/2020) through FCT/MCTES (FEDER funds through the Operational Program Competitiveness Factors—COMPETE and national funds).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.161860.

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