



Vertical carbon and biochar transport in a sandy soil lysimeter experiment

Arthur Gross^{a,*}, Jens Kruse^b, Nina Siebers^b, Bruno Glaser^a, Snežana Maletić^c,
Marijana Kragulj Isakovski^c, Slaven Tenodi^c, Lutz Weihermüller^b

^a Soil Biogeochemistry, Martin Luther University Halle-Wittenberg, Halle (Saale), Germany

^b Institute of Bio- and Geosciences - IBG-3, Agrosphere, Forschungszentrum Jülich GmbH, Jülich, Germany

^c University of Novi Sad, Faculty of Sciences, Trg Dositeja Obradovića 3, Novi Sad, Republic of Serbia

ARTICLE INFO

Handling Editor: P. Chivenge

Keywords:

Biochar
Lysimeter experiment
Biochar dissipation
Biochar transport

ABSTRACT

Sandy soils are characterized by high water infiltration, low water and nutrient retention, and low soil organic matter (SOM). Organic soil amendments (OSA) can improve hydraulic properties and SOM levels, making them suitable for sustainable agricultural use. Additionally, biochar amendments sequester atmospheric carbon dioxide and interact with SOM, potentially enhancing its stability. This study analyzed carbon dynamics in a sandy soil following the addition of OSA, including dredged sediment (20 %) and compost (5 %), mixed with and without biochar (1 %). For this purpose, a lysimeter experiment was setup in Novi Sad, Serbia, and conducted for 441 days. Total organic carbon (TOC) stocks in the lysimeters were measured after the experiment and compared with the amounts of TOC added at the beginning. Drained water amounts were collected throughout the experiment and analyzed for truly dissolved organic carbon (DOC) and particulate organic carbon (POC) in the first six months. Black carbon was used to specifically analyze biochar in 5 cm increments of the lysimeter columns at the end of the experiment. This molecular marker revealed no significant vertical biochar transport but accumulation trends in intermediate lysimeter levels. The addition of compost exhibited the highest relative TOC loss with 24.5 %, although differences were not statistically significant. DOC leaching with increased by 0.17 % ($p < 0.05$) if compost was added purely. Mixing compost with biochar did not affect the TOC loss but significantly reduced DOC leaching. Sediment additions led to the highest relative POC loss with 0.023 % but were significantly mitigated ($p < 0.05$) by co-additions of biochar. Combining both OSA with biochar was associated with lower DOC and POC leaching than adding sediment and compost alone, while the relative TOC loss was not significantly affected. These findings suggest that biochar influences the partitioning and leaching of organic carbon in coarse-textured soil agroecosystems.

1. Introduction

Sandy soils cover 5–14 million km², representing about 10 % of the terrestrial land surface, of which only ~325,000 km² are currently used for agriculture (Bockheim, 2023). Their coarse texture is generally associated with high water infiltration and limited retention capacity, which in regions where rainfall exceeds storage potential can result in substantial water drainage. Under such conditions, water and nutrients are less available for plants, often reducing fertility and crop yields, and thereby limiting farmers' potential income. However, in arid and semi-arid regions, sandy soils can sometimes be considered advantageous, as their lower proportion of unavailable "dead water" may improve water accessibility compared to finer-textured soils (Strobbach and Kutuahiripa, 2014). Still, low biomass inputs in sandy soils located in

arid and semi-arid regions lead to limited nutrient availability and thus, limited plant growth, which eventually reduces organic matter inputs needed to sustain soil fertility (Yost and Hartemink, 2019).

Enhancing soil organic carbon (SOC) levels improves soil hydraulic properties and soil fertility (Lal, 2004). One way to increase SOC levels is the use of organic soil amendments (OSA), because of their high total organic carbon (TOC) content. Traditional forms of OSA include straw, slurry, manure, and compost, while more modern forms include biogas digestate, sewage sludge, dredged sediments, biosolids, and biochar. When added to sandy soils, OSA has been shown to improve various soil health indicators, including SOC levels (Schmidt et al., 2021). However, the coarse material in sandy soils provides limited physical means for SOC retention, because of enhanced vulnerability to oxidation, decomposition, and leaching (Yost and Hartemink, 2019; Gross et al., 2024).

* Corresponding author.

E-mail address: arthur.gross@landw.uni-halle.de (A. Gross).

<https://doi.org/10.1016/j.geoderma.2026.118074>

Received 9 December 2025; Received in revised form 22 September 2026; Accepted 27 September 2026

Available online 30 September 2026

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Open access funding enabled and organized by Projekt DEAL.

Thus, OSA might have a limited residence time in sandy soils, thus limited capacity to effectively build up SOC in the long-term.

Biochar is the product of the thermochemical conversion of biomass under limited oxygen supply, i.e., pyrolysis. During pyrolysis, the organic macromolecules of the original biomass transform into highly aromatic structures (Lehmann and Joseph, 2024). Due to its high aromaticity and thus, high environmental persistence, biochar amendments sequester atmospheric carbon dioxide (CO₂) while simultaneously improving different soil properties on longer timescales (Luo et al., 2023). Used as an OSA, biochar has proven to have many agronomic benefits such as enhanced soil hydraulic properties, higher microbial diversity and biomass, and larger SOC, all contributing to a healthier soil ecosystem (Schmidt et al., 2021), with particular relevance in sandy soils.

The surface of biochar contains oxygen-functional groups that improve nutrient retention and cation exchange and possess a high affinity for organic matter (Wiedner et al., 2015). Therefore, biochar has synergistic effects on the stabilization of non-pyrolyzed OSA (Glaser et al., 2001). However, the strength and direction of this interaction depend on biochar aging, surface oxidation, pH, ionic strength, and mineral coatings (Bolan et al., 2026). The stabilization effects of SOC through the addition of biochar mixed with non-pyrolyzed OSA or co-composted have been reported earlier (Gross et al., 2024). For example, co-composted biochar led to positive long-term impacts on soil physicochemical properties, including SOC in a loamy soil (Apostolović et al., 2024). If such SOC stabilization effects can be achieved on sandy soils, eventually leading to healthier and more productive sandy soil in the long-term, remains unknown.

Decomposition and physical fragmentation of OSA in soil may result in different carbon pathways. Part of the added organic carbon can be mineralized to CO₂, while another fraction may be transformed into truly dissolved organic carbon- in this paper operationally defined as the <1 kDa membrane-permeable fraction- or mobilized as particulate and colloid-associated organic matter. Such colloidal particles (< 1 µm) are highly reactive because of their large specific surface area and charge properties. Depending on soil texture, mineral composition, pore structure, soil water flow, pH, ionic strength, and redox conditions, particles in this size range may 1) remain mobile as carriers of organic carbon, nutrients, and pollutants, including heavy metals and cationic organic contaminants, or 2) become immobilized through aggregation, attachment to the soil matrix, or incorporation into organo-mineral associations and soil microaggregates (Krause et al., 2020; Tang et al., 2022; He et al., 2024). Their mobility is further influenced by flow velocity, pore-throat size, straining, and electrostatic interactions between particles and the surrounding matrix (Bradford et al., 2012; Wang et al., 2020). In general, organic colloids, including biochar colloids, are negatively charged under most typical soil conditions, which makes them a potential carrier for cations including heavy metals and positively charged organic pollutants such as certain pharmaceuticals and pesticides (He et al., 2024). However, mineral colloids and especially Fe oxides may differ in charge behavior and can promote microaggregation by interacting with negatively charged organic and inorganic surfaces; conversely, humic acid coatings can increase negative surface charge and favor dispersion rather than aggregation (Tang et al., 2025). Given that sandy soils contain low amounts of clay and sesquioxides, which favors low cohesion and high permeability (Missong et al., 2018), the addition of OSA increases the formation or mobilization of organic carbon colloids, while the lower abundance of reactive mineral surfaces may reduce their retention and occlusion within microaggregates. At the same time, biochar's liming capacity and its reactive surface could have an immobilizing and stabilizing effect for organic colloids as well as other nanoparticles. Unfortunately, it is still unclear how different OSA additions and their interactions influence the dynamics of leachable POC in sandy soil.

Due to its higher structural and chemical stability, biochar generally undergoes physical and chemical weathering at lower rates than non-

pyrolyzed OSA (Wang et al., 2016). Nevertheless, aging and disintegration of biochar in the soil can generate small biochar particles and colloids that may retain the high aromaticity and persistence of the parent material. While the vertical transport of larger biochar particles is mainly driven by tillage and bioturbation, transport by percolating water is largely controlled by soil physical properties and particle size of biochar (Rumpel, 2024), particularly when colloidal particles are formed (Yang et al., 2019). Their mobility may become environmentally relevant if nutrients or pollutants are sorbed to their surfaces and transported through the soil profile toward groundwater. Studies investigating nanoparticle or colloid formation following the addition of OSA to soils under field conditions are generally scarce, especially under sandy soil conditions, which are more prone to vertical particle transport. Given that OSA has beneficial effects on soil structure and hydraulics (Villagra-Mendoza and Horn, 2018; Castellini et al., 2022), it is worth investigating how the combination of different OSA, including biochar affects the vertical biochar transport in a sandy soil.

Therefore, the goal of this study was to investigate how mixing biochar with different other OSA materials affects their mobility, redistribution, and disintegration in sandy soil, and how these processes influence soil carbon dynamics. For this purpose, a lysimeter experiment was conducted. The lysimeter was filled with sandy soil and mixed with different OSA materials, including dredged sediment, compost, and biochar. The first objective was to analyze the difference in TOC in the lysimeters between the beginning and end of the experiment, to determine how much of this difference could be recovered in the drainage, and to identify influencing factors on both the TOC difference and drainage. In addition, the study aimed to measure how much of the drained TOC was particulate or truly dissolved and to analyze how different OSA treatments influenced TOC leaching. The second objective was to measure black carbon, which was used as a molecular marker for biochar, in different lysimeter depth increments to retrace the vertical biochar movement over the experimental time.

We hypothesize that i) mixing non-pyrolyzed OSA with biochar reduces OSA fragmentation and mobilization in sandy soil; ii) pure biochar exhibits greater particulate biochar transport in the soil than biochar combined with non-pyrolyzed OSA; and iii) biochar treatments result in lower overall TOC leaching than non-pyrolyzed OSA treatments, while mixtures of compost with sediment and/or biochar reduce TOC leaching compared with the individual amendments.

2. Materials and methods

2.1. Study area

The experiment was conducted at the University of Novi Sad, Faculty of Sciences (45°14'42.30" N, 19°51'13.12" E), located in the Vojvodina region of northern Serbia. This region has a continental climate with a mean annual temperature of 11.4 °C and mean annual precipitation of 647 mm (DWD 2025). The experiment ran from March 2023 to June 2024, spanning a total of 441 days. During this period, cumulative natural precipitation amounted to 790 mm (Tenodi et al., 2026). In addition, 126 irrigation events totalling 604 mm were applied to ensure sufficient drainage in all lysimeters. Irrigation was applied simultaneously across all lysimeters ensuring consistent water distribution and as a result, the total water intake, comprising of both precipitation and irrigation, was identical for all lysimeters throughout the experiment.

2.2. Soil and organic soil amendments

The main properties of the materials used to fill the lysimeters are listed in Table 1. The biochar was produced from *Miscanthus* feedstock via slow pyrolysis at 550 °C for 10 min (heating rate = 5 K min⁻¹) at RWTH Aachen University, Germany. Additionally, the biochar was dry-sieved using a 2 mm mesh, with approximately 74% of the mass >2 mm and 26% <2 mm. The largest fragments reached up to around 3 cm,

Table 1

Main properties of the different soil amendments and the sandy soil of the lysimeter experiment in Novi Sad.

Amendment /Soil properties	Biochar	Compost	Dredged sediment	Sandy soil
Feedstock/Origin	<i>Miscanthus</i>	Green waste	Sediment from Begej channel	Danube River bank
Pyrolysis temp. [°C]	550	-	-	-
Total organic carbon [g kg ⁻¹]	768.3 ± 15.2	124.5 ± 1.8	24.6 ± 0.1	4.1 ± 0.3
pH [H ₂ O]	9.5	7.5	6.7	8.5
Sand [%]	-	-	60.4 ± 6.22	96.7
Silt [%]	-	-	8.3 ± 2.9	1.3
Clay [%]	-	-	31.3 ± 6.3	2.0

while most coarse particles were roughly spherical and about 5 mm in diameter.

The compost originated from green waste collected in Novi Sad, Serbia. The dredged sediment was obtained from the Begej Channel, Serbia, and was relatively rich in clay. The sandy soil was collected near the Danube River ("Petrovaradinska Ada") in Novi Sad (45°15'39.89" N, 19°51'55.08" E).

2.3. Lysimeter experiment

Eighteen PVC lysimeters (35 cm height, 20 cm outer and 18.3 cm inner diameter) were used. Each lysimeter had a removable perforated stainless steel base (1 mm holes) and a 3 cm layer of coarse sand at the bottom to facilitate drainage and prevent soil loss. Six treatments were established using three OSA, applied alone or in combination:

- A: sandy soil + 1% (w/w) biochar (12.37 kg total mass $\pm$ 0.12 kg C)
- B: sandy soil + 20% (w/w) sediment (12.37 kg $\pm$ 0.08 kg C)
- C: sandy soil + 5% (w/w) compost (12.58 kg $\pm$ 0.13 kg C)
- D: sandy soil + 1% biochar + 20% sediment (12.30 kg $\pm$ 0.17 kg C)
- E: sandy soil + 1% biochar + 5% compost (12.57 kg $\pm$ 0.22 kg C)
- F: sandy soil + 1% biochar + 20% sediment + 5% compost (12.50 kg

$\pm$ 0.27 kg C)

All materials were oven-dried and thoroughly mixed using a construction mixer. Because the study aimed to evaluate how biochar, compost, and sediment influence each other's behaviour when applied together, total carbon inputs inevitably differed among treatments. Consequently, treatment effects should be interpreted as the combined result of amendment type, amendment interactions, and differing carbon inputs. Lysimeters were arranged in a randomized block design with three replicates per treatment (Fig. 1). Further experimental details are provided in Tenodi et al. (2026). As we assumed that DOC leaching from a soil composed of 97% sand is negligible compared to substantial amounts of OSA added, we chose to omit a bare soil control.

2.4. Soil and drainage sampling

After 441 days, soil material was removed from each lysimeter in 5 cm increments. Samples for TOC and black carbon analyses were collected in situ using a small probe before lysimeter disassembly.

Drainage water was collected at the lysimeter base through Teflon hoses into 1 L pre-cleaned glass bottles (PTFE/silicone septa, polypropylene caps). Bottles were pre-labelled and weighed (precision = 0.01 g, max = 3200 g). Drainage was sampled whenever sufficient volume had accumulated, as determined by regular inspection and weather forecasts. In total, drainage was sampled on 18 days throughout the experiment (Table S1). On thirteen days, the drainage water was analyzed for TOC leaching. On four of these, no TOC data were recorded due to insufficient drainage (04.07.23 and 31.08.2023) or technical issues and subsequent loss of sampled material (05.09.2023 and 07.05.2024). These sampling dates were excluded and accordingly, true cumulative leaching losses may be slightly higher than reported. Table S1 shows the amount of drainage water sampled on these three dates for which TOC measurements were missing.

2.5. Soil and drainage analysis

Soil total carbon (TC) and total inorganic carbon (TIC) were

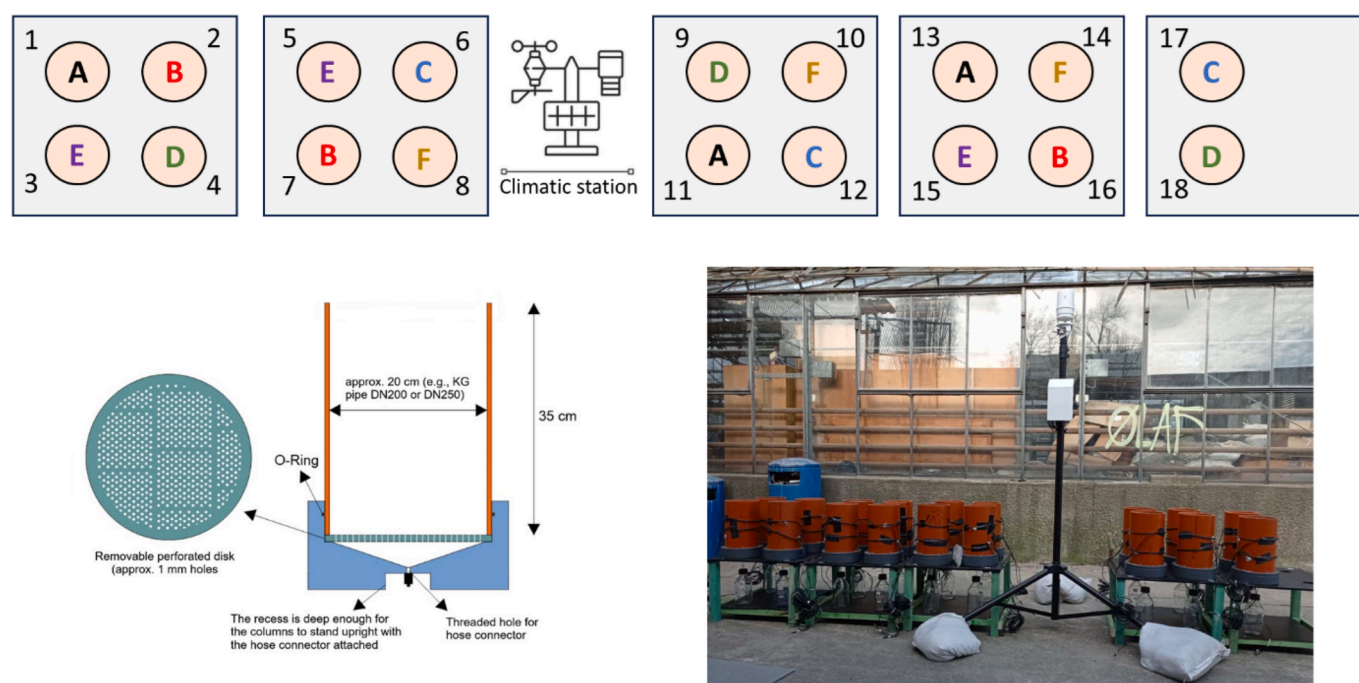


Fig. 1. Setup of the lysimeter experiment with six randomized treatments (A-F), each repeated three times (top). Construction details of each of the 18 lysimeters (bottom left). Photo showing the lysimeter experiment at University of Novi Sad, Faculty of Science (bottom right). Figure originally presented in Tenodi et al. (2026).

determined by dry combustion using a LECO RC612 carbon analyzer (LECO Corporation, St. Joseph, MI, USA). TOC was calculated as TC – TIC.

Leachate samples were analyzed by asymmetric flow field-flow fractionation (AF⁴, Postnova Analytics, Landsberg, Germany) coupled with an organic carbon detector (OCD, DOC-Labor GmbH, Germany) and an inductively coupled plasma mass spectrometer (ICP-MS; Agilent 7500, Agilent Technologies, Japan), following the methodology described by Gottselig et al. (2017) and Siebers et al. (2023). Leachate TOC was determined for the complete experiment time of 441 days, without AF⁴ size fractionation, i.e., at zero crossflow. For size-resolved analysis of the leachate in the first six months (conducted on seven sampling dates), unfiltered leachate samples were separated by AF⁴ with crossflow using a 1 kDa membrane, corresponding to an equivalent lower size limit of approximately 0.66 nm, and no upper size cut-off was applied. Thus, later-eluting particles were interpreted as a larger particle-associated fraction (>60 nm). Organic carbon in the size-separated AF⁴ fractions was quantified online by OCD and operationally defined as POC. DOC was calculated as the difference between TOC measured at zero crossflow and the sum of organic carbon quantified in the size-separated AF⁴ fractions. For element analyses, AF⁴ was coupled online to ICP-MS, and element concentrations in the size-separated fractions were determined using post-channel calibration with Rh as the internal standard. Total element concentrations were determined without AF⁴ size fractionation, i.e., at zero crossflow, and the colloidal or particle-associated element concentrations were obtained from the respective size-separated AF⁴ fractions.

The black carbon content was analyzed following the method of Glaser et al. (1998) with modifications described in Brodowski et al. (2005). After hydrolysis with 4 M trifluoroacetic acid (105 °C, 4 h) followed by a 65% HNO₃ digestion of the hydrolysis residue (170 °C, 8 h), individual benzene polycarboxylic acids (BPCA) were isolated and measured using a Shimadzu GC 2010 gas chromatograph equipped with a flame ionization detector and an HP5 column (30 m × 0.25 mm × 0.25 µm). The sum of all individual BPCA amounts was multiplied by 2.27 to convert them into black carbon (charcoal) equivalents. BPCA recovery was accepted between 70–100%. Otherwise, samples were repeated. Calibration was done using commercial BPCA compounds (apart from prehnitic acid and mellophanic acid, which are commercially not available) and two internal standards (phthalic acid and bisphenylen-2,2-dicarboxylic acid). Blank correction was not necessary. Black carbon was determined for all treatments, including the non-biochar compost and sediment treatment. This non-biochar black carbon was subtracted from the total black carbon determined in the biochar + compost, biochar + sediment, and biochar + compost + sediment treatments to ensure that black carbon only represents biochar particles in the lysimeter columns. Black carbon data from all treatments can be obtained from the referenced raw data Zenodo file.

Bulk density was determined from the known filling volume and total mass of each lysimeter. Soil water retention characteristics were measured with the HYPROP® system (Meter Group, Munich, Germany) using the evaporation method (Schindler et al., 2010) in combination with the WP4® Dewpoint Potentiometer (Decagon Devices, WA, USA). Cylinders (250 cm³) were packed to the same bulk density as in the lysimeters. The unimodal (Van Genuchten, 1980) and dual-porosity (Durner, 1994) models were fitted to the retention data using HYPROP-Fit software (Meter Group, Munich, Germany). As the Durner model provided the best fit, it was used for all subsequent analyses. Volumetric water contents at pF 1.8 (field capacity) and pF 4.2 (permanent wilting point) were calculated from the fitted parameters.

2.6. Statistical analysis

Linear mixed-effects models were used to test lysimeter treatment effects on relative TOC stock changes, drained TOC fractions, total drainage element amounts, and black carbon distribution with depth

measured during and after the experiment. The block structure of the experiment was included as a random effect. In addition, differences in the bulk density, pF 1.8, and pF 4.2 between treatments simulated before the experiment based on the Durner model were tested. Therefore, the simulation ID (1–5) was included as a random effect to account for variability introduced by repeated hydraulic parameter simulations. The lme4 package (Bates et al., 2015) was used and the statistical analysis was carried out in R. Model residuals were evaluated using diagnostic plots and were tested for normality (Shapiro-Wilk test) and homoscedasticity (Levene's test). Significant effects were assessed using least-squares means (emmeans package; Lenth et al. (2023)).

3. Results

3.1. TOC recovery and drainage in the lysimeters

The amounts of TOC added at the beginning of the experiment varied among treatments, and so did the TOC stocks measured at the end (Fig. 2). Among the single added OSA, compost addition introduced the highest amount of TOC (130 g TOC lysimeter⁻¹). The TOC added with biochar was similar (120 g TOC lysimeter⁻¹). The sediment treatment exhibited the lowest TOC stock loss, with 2.6 g TOC lysimeter⁻¹ corresponding to a relative loss of 3.2%. However, due to relatively large standard errors, no significant differences in relative TOC losses were

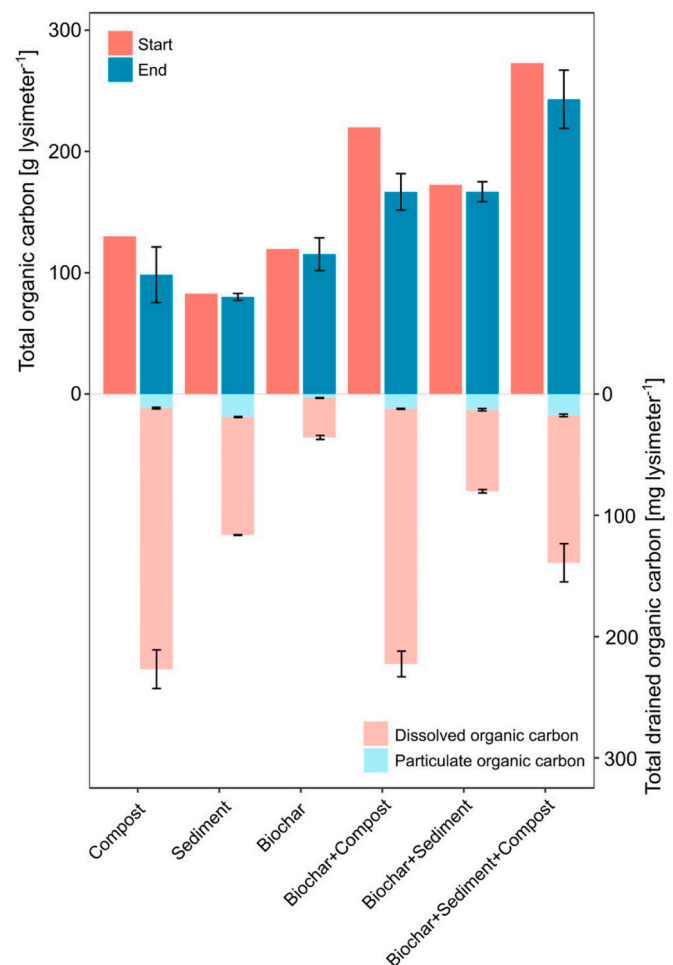


Fig. 2. Comparison between the total organic carbon (TOC) stock present in the lysimeters at the start and the end of the experiment in the different treatments. Amount of truly dissolved organic carbon (DOC) and particulate organic carbon (POC) leached from the lysimeters over the first six months experiment time in the different treatments. Bars represent the mean of three replicates; error bars represent standard errors.

observed between treatments (Table 2). TOC amounts recovered in the leachates differed over time of the experiment (Fig. 3). TOC was mainly composed of DOC and both fractions followed a very similar pattern. POC and DOC were determined at seven sampling dates, of which t4 partly provided insufficient drainage amounts for organic carbon detection. The compost containing treatments exhibit strong variation in TOC and DOC, especially at sampling dates with large drainage amounts as consequence of large rainfall events exceeding 20 mm (Tenodi et al., 2026), which included t2 with ~ 65 mm day⁻¹ of precipitation and t7 with ~ 36 mm day⁻¹. The large drainage peak at t9 was not due to heavy rainfall but a series of constant days of precipitation with >10 mm day⁻¹. All single treatments showed measurable DOC and POC drainage at the first seven sampling dates covering six experiment months, but to varying degrees (Fig. 3). The compost treatment had the highest cumulative leaching losses, with 215.9 ± 15.9 mg TOC lysimeter⁻¹ as DOC and 11.4 ± 0.7 mg TOC lysimeter⁻¹ as POC. The sediment treatment leached less DOC (92.8 ± 5.1 mg TOC lysimeter⁻¹) but more POC (17.6 ± 1.1 mg TOC lysimeter⁻¹) than compost. While relative DOC losses were higher for compost than sediment, the relative POC loss was significantly higher in the sediment treatment. Notably, the sediment treatment revealed pronounced POC leaching on the first sampling date (Fig. 3), responsible for 91% of the cumulative leaching loss. Of the single amendments, biochar exhibited the lowest TOC losses overall, both absolute (32.8 ± 1.6 mg TOC lysimeter⁻¹ DOC and 3 ± 0.28 mg TOC lysimeter⁻¹ POC) and relative.

The TOC stock losses of the mixed OSA treatments varied substantially between the biochar + compost treatment (53.2 g TOC lysimeter⁻¹) and the biochar + sediment treatment (5.8 g TOC lysimeter⁻¹) throughout the experiment time. Considering the relative TOC loss, however, no significant differences were observed (Table 2). The biochar co-addition to compost significantly reduced the relative DOC leaching (Table S2) and POC leaching decreased noticeably in the biochar + sediment treatment (12.9 ± 0.9 mg TOC lysimeter⁻¹) compared to sediment alone (17.6 ± 1.1 mg TOC lysimeter⁻¹), corresponding to a reduced relative POC loss when biochar was added (Table S2). However, similar to the single sediment treatment, the biochar + sediment and biochar + sediment + compost treatment revealed pronounced POC leaching on the first sampling date (Fig. 3), responsible for 91% and 84% of the cumulative leaching loss, respectively.

The combined amendment of compost, sediment, and biochar yielded the highest recovered TOC stock after 441 days (243 ± 23.9 g TOC lysimeter⁻¹). The relative TOC loss was lower than that of the biochar + compost or biochar + sediment mixtures, although differences were not statistically significant (Table 2). Total DOC leaching in the first six months amounted to 121.7 ± 15.8 mg DOC lysimeter⁻¹, corresponding to a relative DOC loss which was significantly lower than that of the compost, sediment, and biochar + compost treatments.

3.2. Treatment effects on soil hydraulic factors

Mixing the amendments with the sandy soil resulted in differences in soil hydraulic properties, which are shown in Table 3. Bulk density,

pF1.8 and pF4.2 were estimated based on Durner model simulations. The highest estimated bulk density was found in the compost treatment. Besides the pure addition of biochar, all other OSA combination revealed significantly lower bulk densities. The water content at pF1.8 (field capacity) was lower in the pure biochar, pure compost, and the combined treatment while the treatments containing sediment exhibited significantly higher water contents at pF1.8. The water content results at pF4.2 exhibited a similar picture. Mixing biochar, sediment, and compost led to significantly higher contents at pF1.8 and pF4.2 than in all other treatments. The highest drainage amount recovered over the experiment runtime was found in the compost treatment. All the treatments containing sludge exhibited significantly lower drainage amounts than the remaining ones.

3.3. Black carbon stocks in different lysimeters depths

Black carbon stocks at the end of the experiment varied among biochar-containing treatments and with depth (Fig. 4). The combined biochar + sediment + compost treatment exhibited the highest stocks, followed by biochar + sediment, which contained more black carbon than biochar alone or biochar + compost.

The vertical redistribution of black carbon resulted in comparable trends, with accumulation at 20–25 cm depth in the biochar, biochar + sediment, and biochar + sediment + compost treatments. All biochar containing treatments also suggested depletion of black carbon in the uppermost (0–5 cm) layer. However, high variability between replicates limited the ability to draw statistically robust conclusions regarding the observed patterns.

4. Discussion

Influence of different OSA on the total TOC loss and leached TOC, DOC and POC

The TOC stock differences during the experiment varied among treatments and so did the amounts of leached TOC. The observed trends nevertheless provide insights into amendment-specific processes, which are discussed as potential explanations supported by the literature rather than as demonstrated treatment effects, given the missing statistical significance. The pure biochar treatment exhibited the lowest relative and absolute stock change (n.s.), indicating a trend towards lower TOC loss. The very low leaching losses compared to other OSA can be explained by the polyaromatic backbone of biochar. However, it is also known that biochar contains some labile carbon, mostly in aliphatic form, which could have been dissolved (Rudra et al., 2024) and leached out of the lysimeters, and therefore, can explain the leaching losses in that treatment, which mainly occurred during the initial experiment phase (Fig. 3). Some leaching amounts in the pure biochar treatment might also be related to the TOC natively present in the sandy soil (Table 1). The largest relative and absolute TOC stock difference and leached amount was found in the compost treatment, added as a single amendment or mixed with biochar. This observation did not translate into a significant difference. However, the DOC amount in this treatment was significantly higher than in any other OSA and over time, both TOC and DOC leaching followed the total drainage pattern very well (Fig. 3). Combining both observations suggests a trend towards compost amendments showing the lowest stability of all OSA under study. Moreover, biochar could not mitigate the compost-driven TOC dissipation as both treatments were at a similarly high level; however, the DOC leaching was reduced (Table S2). In general, compost is a humified material and contains a high proportion of soluble organic acids (Campitelli and Ceppi, 2008), which can explain the high amount of DOC found in that treatment. Moreover, organic macromolecules such as lignin and (hemi)celluloses may have been destabilized during the composting process, meaning that the resulting compost contains less stable carbon compounds (Tuomela et al., 2000). When added to sandy

Table 2

Relative loss of total organic carbon (TOC) in the lysimeters between the start and the end of the experiment. Presented are the means of three replicates $\pm$ standard errors. Different letters indicate significant differences between treatments at $p < 0.05$, based on linear mixed-effect models and least square means post-hoc tests.

Treatment	Relative TOC loss [%]		
Biochar	3.6	$\pm$	11.3 a
Sediment	3.2	$\pm$	3.5 a
Compost	24.5	$\pm$	17.6 a
Biochar+Sediment	3.4	$\pm$	4.8 a
Biochar+Compost	24.2	$\pm$	6.9 a
Biochar+Sediment+Compost	10.9	$\pm$	8.8 a

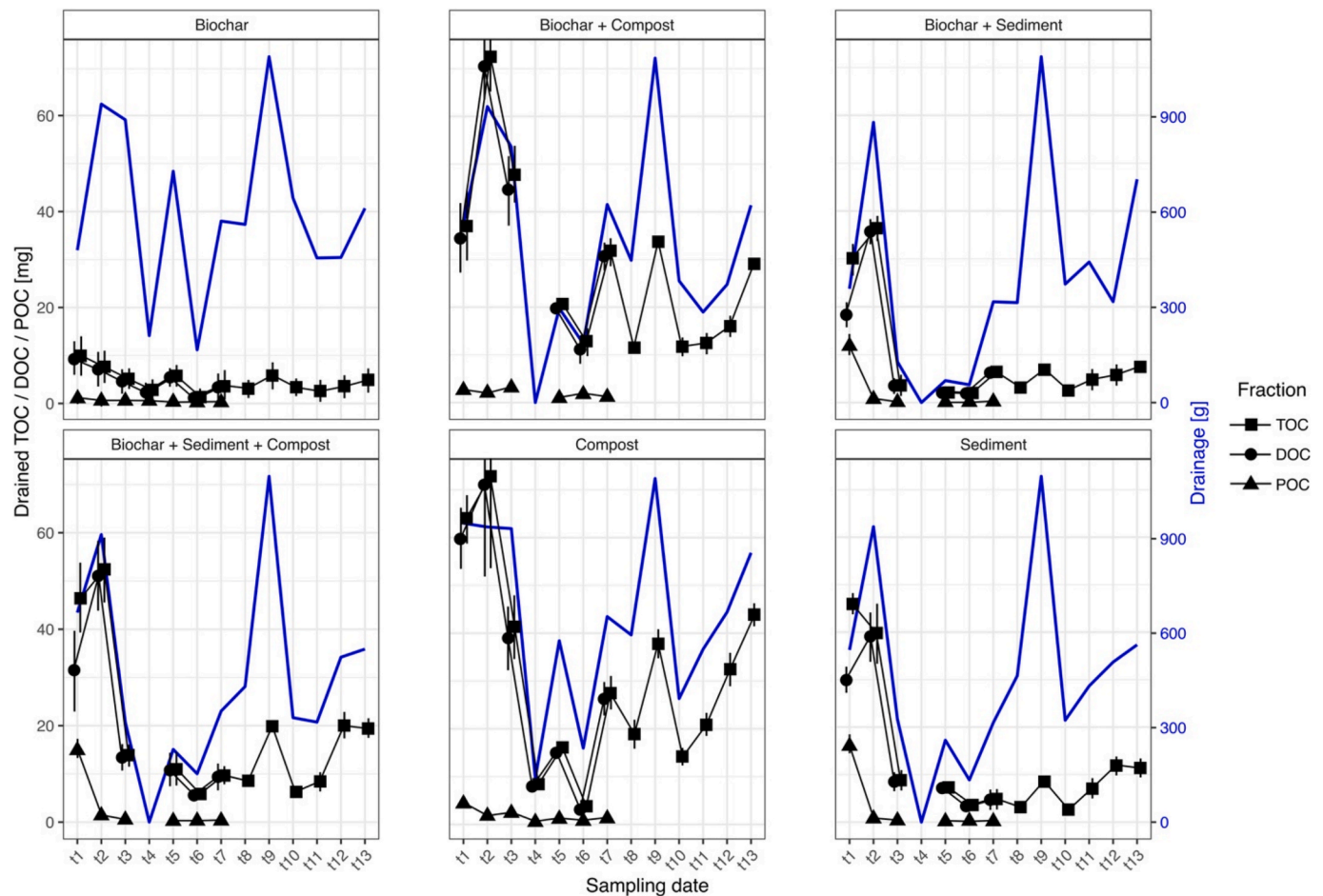


Fig. 3. Drained total organic carbon (TOC) (black squares), truly dissolved organic carbon (DOC) (black dots), particulate organic carbon (POC) (black triangles) and total drainage (blue line) leached from the lysimeters in the different treatments at different sampling dates. Bars represent the mean of three replicates; error bars represent standard errors.

Table 3
Bulk density, pF1.8, pF4.2 and the drainage amount in the different treatments. Presented are the means of three replicates $\pm$ standard errors. Different letters indicate significant differences between treatments at $p < 0.05$, based on linear mixed-effect models and least square means post-hoc tests.

Treatment	Bulk density [g cm ⁻³]			pF1.8 [cm ³ cm ⁻³]			pF4.2 [cm ³ cm ⁻³]			Drainage [g]			
Biochar	1.42	±	0.015	ab	0.14	± 0.019	a	0.11	± 0.013	a	9165.9	± 187.7	a
Sediment	1.36	±	0.007	b	0.21	± 0.008	d	0.16	± 0.006	b	6632.7	± 456.3	b
Compost	1.46	±	0.029	a	0.11	± 0.008	a	0.08	± 0.008	a	9877.3	± 622.3	c
Biochar + Sediment	1.35	±	0.011	bc	0.22	± 0.010	b	0.18	± 0.012	b	5630.1	± 239.9	b
Biochar + Compost	1.37	±	0.032	b	0.12	± 0.012	a	0.08	± 0.007	a	7673.7	± 137.4	a
Biochar + Compost + Sediment	1.28	±	0.019	c	0.26	± 0.023	c	0.21	± 0.023	c	6686.6	± 715.2	b

soil, these less stable compounds may have contributed to fast oxidation and turnover and the large TOC losses observed (Aranyos et al., 2016). In contrast, long-term annual amendment of compost for 18 years to a SOC-depleted Cambisol in North-East China was found to significantly enhance SOC storage (Chen et al., 2024). However, the duration of the increase was limited to nine years until the SOC reached a steady state, pointing to fast mineralization as well.

The addition of dredged sediment resulted in a flatter TOC leaching curve (Fig. 3) over the course of the experiment and a lower TOC stock difference (Table 2); however, this difference was not statistically significant. Given the considerably lower TOC difference, this suggests that the TOC added via sediment was more stable than compost over 441 days, even in a sandy soil. Dredged sediments, compared to compost, generally contain organic residues often bound to fine mineral particles such as clay (Table 1). On the one hand, these clay particles might have stabilized TOC already, and therefore, either mineralization or drainage

is reduced. On the other hand, the sediment treatment exhibits more drainage of POC, potentially through increased leaching of clay colloids (Fig. 2). However, under the neutral-alkaline experiment conditions (Table 1), direct clay colloid leaching is unlikely. Moreover, the pronounced POC leaching observable on the first sampling date in the sediment-containing treatments (Fig. 3) was not connected with higher particulate Si and Al exports (Fig. S1 and S2), which could further indicate loss of clay particles. Particulate Fe slightly followed a similar pattern as POC (Fig. S3) but was not as clearly linked to the initial POC flush as particulate P (Fig. S4). This suggests an early co-mobilization of C, P and Fe-containing colloids rather than a clay-mineral-driven flush. Enhanced particulate P mobilization typically occurs during and after heavy rainfalls, particularly following dry soil conditions (Lucas et al., 2023), similar to the initial lysimeter settings prior to the first flush.

Co-adding biochar could not prevent the initial POC flush but reduced the amount of DOC and POC drainage significantly (Table S2),

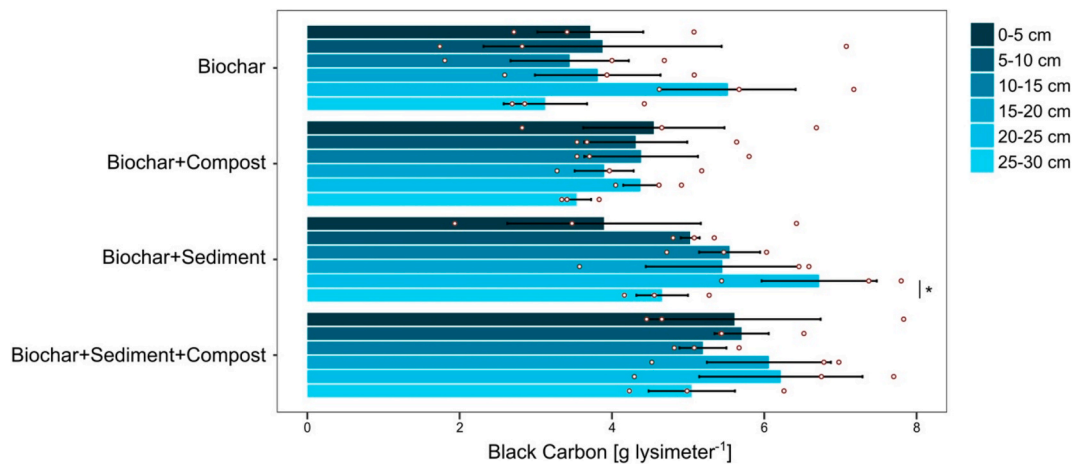


Fig. 4. Black carbon stocks measured at the end of the experiment in different lysimeter depth increments. Bars represent the mean content of three replicates, error bars represent the standard errors. Red dots represent individual data points. Asterisks indicate significant differences among depth increments within one treatment at $p < 0.05$, based on linear mixed-effect models and least square means post-hoc tests.

which could be explained by an interaction of sediment with the biochar particle surface. Clear evidence for such an interaction would necessitate a thorough investigation of the involved mechanisms, e.g., by characterizing the mineral surface or by providing spectroscopic evidence of organo-mineral associations. However, based on the findings of previous studies, it is well known that the functional groups present at the biochar surfaces have a strong affinity for organic matter (Hagemann et al., 2017; Gross et al., 2025). Moreover, in previous studies, biochar was found to enhance TOC stability in the presence of fine material (Blanco-Canqui et al., 2020; Gross et al., 2024). Fe, Mn, and Al often present in dredged sediments (Darmody et al., 2004; Ferrans et al., 2022) can oxidize and become electrostatically attracted to the negative bonding sites of biochar, while biochar bonding sites might already be occupied by cations, and therefore, can also attract negatively charged organic compounds (Joseph et al., 2010; Lehmann and Joseph, 2024). In addition, biochar did not effectively reduce the absolute DOC leaching in the compost amendment (Fig. 3), but in relative terms (Table S2). This could be related to the reduced contact time of DOC with the soil matrix in this mixture because of faster drainage due to the structural forming by the coarser compost fragments in the already coarse sandy soil. Therefore, the beneficial properties of the biochar particle surfaces in retaining TOC in sandy soil environments is limited (Yang et al., 2022). Mixing biochar with compost and sediment did result in a significant reduction of POC and DOC leaching, and may reflect interactions among the amendments, differences in carbon inputs, and changes in soil hydraulic conditions. However, since compost was not mixed with sediment in the absence of biochar, it is difficult to isolate whether the response in the three OSA mix treatment really indicates an interaction among the three OSA, an effect of sediment plus compost, or simply the higher total OSA and carbon input. The fine material (especially the clay fraction) available in the sediment, in theory, could potentially contribute to stabilizing the DOC fraction present in compost, which could not be stabilized by biochar amendment alone. This is a likely explanation because the sediment introduced fine material into the sandy soil and altered the coarse texture. It has already been shown that even slight shifts in the soil texture can impact the soil hydraulic conditions substantially (Tenodi et al., 2026), and thus, likely also DOC leaching. The biochar, in turn, was associated with reduced POC leaching from the sediment treatment. In general, the three-amendment treatment showed comparatively low carbon leaching relative to its TOC input, which may reflect synergistic amendment interactions. However, other factors may also play a role, such as residence time of water in the system, and the contact time between DOC and reactive surfaces, which cannot be isolated with the present experiment design and require

further investigations.

Hydraulic properties explaining the total TOC losses and leaching

Differences in soil carbon leaching behaviour are linked to soil physical and hydraulic properties, as changes in soil hydraulic properties will change the water fluxes, such as drainage and evaporation, as shown by Tenodi et al. (2026). As retention and hydraulic conductivity characteristics are not easy to interpret with respect to carbon leaching, we used basic information, such as water contents at pF1.8 and pF4.2, as explanatory variables for the carbon losses. Additionally, bulk density was used as it is directly connected to total porosity. Differences in bulk density are directly caused by the soil amendments, and the lowest bulk density was found in the three-amendment-mix treatment. This observation is in line with findings of Villagra-Mendoza and Horn (2018) for biochar and Rivier et al. (2022) and Castellini et al. (2022) for compost. A lower bulk density, and therefore, higher total porosity might favour faster deep percolation (Canet-Martí et al., 2023), and consequently larger drainage because a higher volume of larger pores is present, with likely also larger pore throats reducing straining of colloids. Unfortunately, the drainage rates were amongst the lowest for the three amendment mixtures, which was caused by higher evaporation losses (see Tenodi et al., 2026). Therefore, not the total water loss by drainage, but the larger pore throats seem to favour leaching losses via POC in this amendment. On the other hand, the pure biochar treatment exhibited a similarly high bulk density as the compost treatment, which had the highest bulk density of 1.47 g cm^{-3} amongst all treatments. For both treatments, the relative TOC and DOC losses were also highest, likely caused by the highest drainage rates observed. For POC the relative losses for the biochar treatment were smallest, likely due to the high chemical stability of the aromatic backbone of biochar, and potentially due to straining of the biochar colloids in the smaller pores and pore throats.

The water contents at pF1.8 and pF4.2 were positively affected by the presence of dredged sediment. At pF1.8, larger pores have been formed by adding the sediment, and at pF4.2, the finer sediment can hold more water due to its larger surface. In addition, all sediment-based mixtures showed the lowest drainage rates as evaporation losses were highest (see Tenodi et al., 2026). This can also explain the lower relative TOC losses as less drainage occurred. In both sediment-containing mixtures, the vertical black carbon redistribution was most pronounced (Fig. 4), which is at first glance counter-intuitive as less water moved downwards and as the pores are in general smaller, favouring straining of colloids. One possible explanation can be that the movement

was mainly caused during heavy rainfall or irrigation events as during such events, the pore water velocities will be larger in such mixtures, causing more stress on the colloids in the pore system, and therefore, higher leaching losses occur (Tang and Raoof, 2024). Such erosion events are especially severe, if they occur after periods of drought, e.g., Masroor et al. (2022) demonstrated a significant correlation between drought indices and soil loss. The organic carbon leaching time series in Fig. 3 clearly shows that most POC (84–91%) left the lysimeters during the initial flush of the dry mixtures. Rapid flooding of dry soils can promote aggregate slaking and the mobilization of fine particles (Le Bissonnais, 1996), which could explain the initial POC flush leaching observed after drought. Although the experiment soil was sandy, the addition of the clay-rich dredged sediment likely promoted the formation of aggregates that became susceptible to slaking, enhancing the mobilization of POC. Notably, the initial flush resulted in higher POC leaching than after the heavy rainfall events at t2 and t7, suggesting lower fine particle mobilization under moist soil conditions than for dry soil. Consistent with this observation, Khan et al. (2022) found significantly greater P losses when drought-affected soils were flooded compared with soils maintained at field capacity, which they attributed to the breakdown of organic matter due to soil drying. This finding could further explain that the particulate P leaching time series closely followed a similar pattern as POC (Fig. S4).

Leaching could not fully explain the total TOC stock difference

Generally, the TOC amounts leached (in the range of mg) were ~1000 times lower than the observed TOC differences (in the range of g), meaning that there is a large amount of TOC dissipation not recovered. As the mass balance has to be closed, the observed losses are likely due to the organic matter into gaseous CO₂.

Whitman et al. (2024), amongst many others, reported that the mineralization rates were especially high following the fresh addition of OSA. Due to a lack of fine materials in sandy soils and a lack of physical protection of TOC through interaction with clay minerals, oxides, and soil aggregates, mineralization can be more pronounced, as the TOC is exposed to microbial decomposition (Yang et al., 2022). Moreover, sandy soils offer more pore space, enabling better gas exchange rates for oxygen and CO₂. Given that the supply of oxygen in soils is one limiting factor for mineralization, larger pore space enables higher mineralization rates (Mendoza et al., 2025). However, in the lysimeter systems used in this study, no direct information is available on mineralization. Only an experiment with CO₂ flux measurement, ideally combined with the use of isotopically labelled amendments and isotope measurements of the gaseous flux, will reveal the specific mechanisms involved, including possible positive and negative priming due to the presence of biochar (Whitman et al., 2024).

Besides the mineralization to CO₂, non-gaseous pathways such as dissolved inorganic carbon (DIC) export could explain unaccounted carbon dissipation but do not explain differences in the TOC stocks. Under the alkaline conditions of this experiment, DIC leaching can be substantial (Kindler et al., 2011), however, the total inorganic carbon contents between the experiment start and end did not differ (data not shown).

Analytical limitations of the AF⁴-OCD approach may also have contributed to the apparent imbalance. Although TOC was determined at zero crossflow and should therefore include both DOC and POC passing through the AF⁴ channel, incomplete recovery of larger or hydrophobic particles due to sedimentation before injection, adhesion to tubing or channel surfaces, or incomplete transport through the analytical system cannot be fully excluded (Meyn and Hallé, 2017). However, this should be interpreted as a methodological uncertainty rather than as direct evidence for a major unmeasured carbon pool.

Limitations of the experiment itself as well as during the sampling introduces uncertainty into the mass balance. For example, POC and DOC leaching has only been determined in the initial third of the

experiment time, leaving a large period of the experiment unexplained. Moreover, TOC leaching data from four drainage samples could not be recorded due to insufficient drainage or technical issues. These dates were subsequently eliminated from the cumulative TOC leaching calculation, resulting in lower cumulative leaching losses than actually have occurred. Although the lysimeters were carefully filled with the sandy soil and OSA mixture, spatial heterogeneity inside the lysimeters at the experiment beginning and through the experiment runtime, and the influence of water entering the system might also have led to uncertainty in the mass balance. Even though each lysimeter was repeated three times to control for uncertainty, the partly large standard errors especially in the relative TOC difference results limited drawing definitive conclusions. This spatial heterogeneity was also visible in the black carbon distribution in the lysimeter columns, exhibiting large data variability.

Biochar particle movement within the lysimeters

Although the OSA were homogeneously mixed with soil at the beginning of the experiment, the initial vertical distribution of biochar within the lysimeters was not measured directly. Therefore, the interpretation of the final black carbon depth profiles and redistribution patterns depends on the assumption of a relatively homogeneous initial mixture and should be considered with some caution.

Nevertheless, a trend towards higher black carbon stocks in the intermediate depth layers and lower stocks in the top- and the bottom-most layer were observable (Fig. 4), suggesting vertical redistribution within the lysimeter profile during the experiment. Comparing the pure addition of biochar and the mixture of biochar and sediment revealed slightly different trends of redistribution compared to the biochar mix with compost and the mixture of all three OSA. The co-addition of dredged sediment to biochar seemingly increased the biochar accumulation trend in the mid- to bottom section, which corresponds with the observation of higher POC leaching in the sediment-containing treatments (Table 2). Though the co-addition of biochar reduced the leached amounts, it was still at a high level compared to the other treatments (Fig. 2). However, biochar-derived POC in drainage water was not measured specifically, and therefore, biochar transport and POC leaching cannot be directly linked. Consequently, the observed depth redistribution should not be interpreted as direct evidence of biochar export from the lysimeters.

Adding compost to this mixture resulted in a more even redistribution of black carbon in the lysimeter profile. This could be related to the effects of compost on the soil pore space and soil hydraulic properties. It is known that the addition of compost enhances the aggregate formation in soils (Ngo et al., 2016), which, if present, could also affect biochar particle translocation. Castellini et al. (2022) reported a larger water retention after biochar amendment if the amendment was combined with compost. Similar effects were observed in the lysimeter experiment performed here and reported by Tenodi et al. (2026), though the largest effects on water retention were observed if all three OSA were combined. Looking at the black carbon biomarker distribution, the combination of all three OSA resulted in a comparatively even redistribution within the lysimeters, with less pronounced evidence of vertical redistribution than in the pure biochar and biochar + sediment treatments.

The pure biochar treatment revealed a similar trend as the biochar + sediment treatment with a pronounced accumulation of black carbon in the 20–25 cm depth increment (Fig. 4), indicating a more pronounced trend towards vertical redistribution of black carbon within the sandy soil profile. Fresh biochar particle surfaces that have not yet reacted with the mineral soil matrix are generally considered more prone to fragmentation and vertical movement in soils (Czimczik and Masiello, 2007), which could explain the observed trend. With increasing residence time in soil, biochar particles may undergo physical disintegration, leading to a breakdown of larger particles into smaller ones (Lehmann et al., 2024). These smaller and lighter particles may be more

mobile in sandy soils than coarse particles. Notably, no statistically significant accumulation in the bottom layers was observed in any of the treatments. Instead, only trends towards redistribution into the intermediate-depth increments were observed. These patterns provide limited evidence for pronounced redistribution to the deepest layers. The absence of initial depth-distribution data and biochar-specific measurements in drainage prevents conclusions about biochar fragmentation or overall stability.

5. Conclusion

This study had the objective to analyze TOC and biochar transport dynamics of different OSA treatments in a sandy soil lysimeter experiment over 441 days. We hypothesized that mixing non-pyrolyzed OSA with biochar reduces their fragmentation and mobilization, eventually leading to lower TOC stock differences in the lysimeter. This hypothesis must be rejected since we could not observe significant differences between the different OSA mixtures with or without biochar. Furthermore, we hypothesized that pure biochar exhibits greater particulate biochar transport in the soil than biochar combined with non-pyrolyzed OSA, which can only partly be accepted. The pure biochar treatment and the biochar + sediment treatment were the two treatments suggesting enhanced black carbon movement into deeper lysimeter depth increments. A clear redistribution of black carbon into the deepest depth increment could not be observed for any treatment. Thus, the results indicate predominantly intermediate-depth redistribution, although the lack of initial depth-distribution measurements, biochar-specific drainage data, and the large variability between replicates prevent firm conclusions about biochar stability and black carbon transport patterns. Lastly, it was hypothesized that biochar treatments result in lower overall TOC leaching, and that mixing compost with sediment and/or biochar reduces the TOC leaching compared with the individual amendments. Biochar addition was associated with reduced particulate carbon leaching in the sediment treatment, whereas its effect on DOC leaching was more pronounced in the compost treatment. The three-amendment treatment showed reduced DOC and POC leaching relative to adding OSA individually. This pattern may reflect interactions among the amendments, however, a specific synergistic effect among biochar, compost, and sediment cannot be isolated because a sediment + compost treatment without biochar was not included. Thus, the hypothesis can again only partly be accepted. This finding suggests that carbon leaching is not merely a function of carbon quantity but is influenced by the type of TOC present in each OSA. Moreover, adding non-pyrolyzed OSA to a sandy soil was associated with enhanced DOC leaching in the case of compost or enhanced POC leaching in the case of sediment. Combining these two OSA with biochar was found to effectively mitigate POC and DOC leaching during the first six experiment months in which these fractions were measured. The TOC amounts leached were ~1000 times lower than the observed TOC differences across the treatments, suggesting that other factors, such as TOC mineralization to CO₂ might explain the unexplained fraction in the carbon balance. Measuring the CO₂ mineralization rates was not part of the initial experiment layout, meaning that the actual amounts of carbon released into the atmosphere could not be quantified. Additionally, it remained unsolved how these individual OSA influence the SOC priming of the sandy soil. These research questions should be considered in future studies.

CRediT authorship contribution statement

Arthur Gross: Writing – original draft, Visualization, Investigation, Formal analysis. **Jens Kruse:** Writing – review & editing, Supervision, Investigation, Formal analysis, Conceptualization. **Nina Siebers:** Writing – review & editing, Investigation, Formal analysis, Funding acquisition. **Bruno Glaser:** Validation, Writing – review & editing, Supervision, Conceptualization, Funding acquisition. **Snežana Maletić:**

Writing – review & editing, Funding acquisition, Formal analysis, Conceptualization. **Marijana Kragulj Isakovski:** Formal analysis, Conceptualization. **Slaven Tenodi:** Writing – review & editing, Formal analysis, Conceptualization. **Lutz Weihermüller:** Writing – review & editing, Supervision, Conceptualization.

Funding

Funded by the European Union (GA No. 101059546-TwinSubDyn.) and the Bioeconomy Science center (BioSC) (Boost Fund 2.0 NewBIAS).

Declaration of competing interest

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

Acknowledgements

We acknowledge Alexandra Axt from RWTH Aachen University for preparing the biochar used in the lysimeter experiment. The authors gratefully acknowledge the financial support of the Bioeconomy Science Center (BioSC). This work was funded by the Ministry of Culture and Science of the German State of North Rhine-Westphalia (MKW NRW) as part of the BOOST FUND 2.0 project NewBIAS, and by the European Union as part of the TwinSubDyn project (GA No. 101059546). Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.geoderma.2026.118074>.

Data availability

Raw data are available at Zenodo (<https://doi.org/10.5281/zenodo.17358265>).

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