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A single high compost application accelerates organic matter restoration in marginal soil and enhances C and nutrient retention

Rüdiger Reichel [a,*,1], Zhijie Li [a,b], Xinyue Cao [a], Kerui Zhao [a,l], Manuel Endenich [c], Amit Kumar [d,e], Vicky M. Temperton [d], Julien Roy [f,g,h], Matthias C. Rillig [f], Sergey Blagodatsky [i,j], Michael Bonkowski [i], Stefanie Schulz [k], Michael Schloter [k], Thomas Pütz [a], Nicolas Brüggemann [a,m]

[a] Forschungszentrum Jülich GmbH, Institute of Bio, and Geosciences, Agrosphere (IBG-3), Jülich, 52428, Germany
[b] Environment and Plant Protection Institute, Chinese Academy of Tropical Agricultural Science, Haikou, 571101, China
[c] Department of Reclamation, RWE Power AG, Jüchen, 41363, Germany
[d] Institute of Ecology, Leuphana University Lüneburg, Lüneburg, 21335, Germany
[e] Department of Biology, College of Science, United Arab Emirates University, Al Ain, 15551, United Arab Emirates
[f] Institute for Biology, Ecology of Plants, Freie Universität Berlin & Berlin-Brandenburg Institute of Advanced Biodiversity Research, Berlin, 14195, Germany
[g] GECO, CIRAD, University Montpellier, Montpellier, 34398, France
[h] CIRAD, UPR GECO, Le Lamentin, Martinique, 97285, France
[i] Terrestrial Ecology, Institute of Zoology, University of Cologne, Köln, 50674, Germany
[j] Karlsruhe Institute of Technology, Institute of Meteorology and Climate Research — Atmospheric Environmental Research, Garmisch-Partenkirchen, 82467, Germany
[k] Helmholtz Zentrum München GmbH, Research Unit for Comparative Microbiome Analysis, Neuherberg, 85764, Germany
[l] School of Forest Sciences, University of Eastern Finland, Joensuu, 80100, Finland
[m] Institute of Crop Science and Resource Conservation (INRES), Soil Science and Soil Ecology, University of Bonn, Bonn, 53115, Germany

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ABSTRACT

Current German regulations on compost application rates may constrain organic C restoration and agricultural productivity in C-poor marginal soils. The objective of our study was to determine whether applying municipal organic waste compost to reclaimed soil with 0.45% organic C (dry matter), at rates higher than currently allowed, could be used to accelerate organic C enrichment without substantial C, N, and P losses over a full crop rotation. In an outdoor lysimeter experiment conducted from September 2019 to March 2023 on marginal silty loam soil under a winter wheat–winter barley–spring field pea rotation, compost was applied at either a regular rate of 4000 g m^{-2} (40 Mg ha^{-1}) or a high rate of 8000 g m^{-2} (80 Mg ha^{-1}) and compared with mineral-fertilized controls. We assessed crop performance, soil C and nutrient status, greenhouse gas emissions, water and nitrate leaching, and diverse microbial indicators. The regular compost application increased the soil C level by 40% and enhanced mean crop biomass by 13% compared to the control. The high compost application rate doubled the soil C content and led to the lowest inter-replicate variability in grain yield over the three-year study period. There was no obvious decline in soil organic C levels over the crop rotation. Both regular and high compost application rates reduced water leaching by about 43% and did not significantly increase nitrate leaching or nitrous oxide emissions. Compost application increased mean annual cumulative carbon dioxide emissions by about 17%, while the high compost rate showed no clear additional effect. High compost application altered microbial indicators associated with nutrient cycling and reduced the relative abundance of fungal taxa assigned as plant pathogens in the year following application. Overall, the higher compost application combined with adjusted mineral fertilization enhanced C and nutrient retention without clear increases in nutrient losses over the three-year crop rotation, supporting its potential use for organic C restoration while emphasizing the need for long-term, multi-site studies with environmental monitoring to provide a basis for revising current regulations.

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* Correspondence to: Wilhelm-Johnen-Straße, Jülich 52428, Germany
E-mail address: ru.reichel@fz-juelich.de (R. Reichel).
[1] ORCID: 0000-0002-4950-5494

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1. Introduction

A sufficient supply of water and nutrients is essential for maintaining stable crop yields. Their availability to plants is governed by interactions among agricultural management, topographic and climatic conditions, and soil properties such as texture, pH, soil organic carbon (C) and nitrogen (N) contents (Blume et al., 2016; Oldfield et al., 2019; Schjønning et al., 2018; Teng et al., 2024). Beyond its role in supporting nutrient availability and soil water dynamics, soil organic matter (SOM) also reduces the risk of erosion and compaction by improving soil structure, enhancing water infiltration and retention, promoting gas exchange, suppressing soil-borne pathogens, and functioning as a C sink (Feeney et al., 2024; Tejada and Gonzalez, 2003).

Agricultural surface horizons affected by cultivation (Ap horizons) in Europe have average total organic C (TOC) and total N (TN) contents of ~1.8% and ~0.18% of dry matter (dm), respectively, with a mean C:N ratio of 10:1 (Matschullat et al., 2018). Soil microbial biomass represents only a small fraction of about 4% of SOM but controls the retention and release of elements such as C, N, and P and thus the persistence of SOM (Brookes et al., 2008; Joergensen et al., 1990; Zhao et al., 2025a, Zhao et al., 2025b). On average, bacteria have a C:N ratio of 4:1, whereas fungi have a mean C:N ratio of 10:1 (Gupta and Tiedje, 2024). Microbial biomass in agricultural soils is composed of bacteria and fungi in variable proportion and, depending on management and organic matter inputs, has C:N ratios between 6.7 and 12.4 (Cleveland and Liptzin, 2007; Zhu et al., 2021). Globally, soil TOC pools are declining due to intensive soil management and increasingly adverse effects of climatic change on crop production (Amelung et al., 2020; Ni et al., 2024). Given the importance of different SOM components for overall soil functionality, strategies are needed both to prevent further SOM losses and to restore depleted SOM stocks.

Because restoration of SOM levels requires external organic matter inputs, compost application is widely recognized as an effective strategy to increase TOC and SOM stocks. For example, municipal organic waste compost containing 15.4% TOC in dm and a C:N ratio of 14 (Tognetti et al., 2007) has been shown to contribute substantially to the SOM pool and to function as a long-term source of C and nutrients with a stoichiometry close to that required for microbial biomass maintenance (Spohn, 2016). Through supporting microbial growth and stabilization processes, appropriate compost inputs may reduce long-term nutrient losses from SOM mineralization, including nitrate (NO_3^-) leaching and emissions of nitrous oxide (N_2O) and carbon dioxide (CO_2) (Jain and Kalamdhad, 2020). However, the agronomic benefits of municipal organic waste compost need to be balanced against the potential accumulation of contaminants such as heavy metals, microplastics, and persistent organic pollutants (Röhler et al., 2021; Steiner et al., 2023), particularly under repeated or high-rate applications.

Recent evidence suggests that the effectiveness of organic amendments depends critically on whether soils exceed a minimum TOC threshold required for sustained C accrual (Ling et al., 2025). In marginal soils below this threshold, microbial C use efficiency (CUE) declines sharply, and respiration losses relative to microbial biomass formation increase exponentially with decreasing TOC (Clayton et al., 2021), thereby limiting net C retention potentials (Poeplau et al., 2019). Consequently, small incremental compost additions may be insufficient to shift degraded reclamation soils into a regime of positive C balance. This suggests that the response to compost addition may depend not only on the amount of C supplied, but also on whether the added C is sufficient to alleviate microbial C limitation and increase the capacity of the soil–plant–microbial system to retain additional C and nutrients.

Currently, the German Fertilizer Ordinance (DüV, 2017) restricts compost application rates in agricultural soils to minimize NO_3^- and phosphate (PO_4^-) losses (DüV, 2017). At this time, reclamation soils in Germany may receive a maximum of approximately 4000 g m^{-2} (40 Mg ha^{-1}) fresh compost within three years (Dumbeck, 2023), corresponding to an increase of only about 0.2% TOC. At such application rates and frequencies, restoring pre-mining SOM levels of approximately 1.3% TOC may take up to a century (Leal et al., 2025; Zhao et al., 2022). Given that about 57,277 km^2 of land worldwide are affected by mining (Baier et al., 2022), the number of marginal soils with critically low TOC levels is expected to increase. Accelerating the restoration of SOM-derived ecosystem services in these soils remains challenging, as current compost-application limits may be too restrictive to overcome TOC thresholds necessary for efficient C retention and sustained SOM rebuilding (Amelung et al., 2020).

However, alleviating C limitation alone may not maximize C retention if microbial growth, element retention, and cycling subsequently become constrained by other nutrients, particularly N or P (Cleveland and Liptzin, 2007; Manzoni et al., 2010). Stoichiometric imbalances, such as P limitation after soil reclamation, can additionally affect the efficiency of C and nutrient retention (Mooshammer et al., 2012). Phosphorus acts as an important driver of C and N use efficiency because it is an essential component of plant and microbial phospholipids, energy-rich compounds such as ATP, and DNA and RNA, and is therefore required for biomass growth and microbial processes (Widdig et al., 2020). Thus, P addition may also enhance nutrient losses by N_2O emissions (Müller et al., 2015). The extent to which P availability controls stabilization of compost-derived organic matter in marginal soil under field conditions remains not fully resolved. Accordingly, insufficient P availability could constrain microbial processing and retention of compost-derived C and N, whereas excessive mineral P supply may alter stoichiometric balances and increase nutrient loss pathways.

Higher compost inputs may accelerate SOM restoration, but may simultaneously increase respiratory C losses, N_2O emissions, nutrient leaching, or P accumulation if the capacity of the soil–plant–microbial system to retain the additional C, N, and P inputs does not increase accordingly. Conversely, enhanced retention of these elements could allow the benefits of accelerated SOM restoration to outweigh the associated environmental risks.

Assessing this requires experimental systems that capture realistic soil–plant–microbial interactions while allowing the relevant retention and loss pathways to be quantified. Field experiments best capture treatment effects under realistic soil–plant–microbial interactions but can be limited in quantifying nutrient balances, leaching losses, and gaseous emissions (Johnston and Poulton, 2018; Pütz et al., 2018). Laboratory incubation experiments offer high control over experimental conditions but cannot reproduce natural plant growth, soil structure, hydrological dynamics, or weather variability (Pütz et al., 2018). Lysimeters bridge this methodological gap by enabling the quantification of element inputs and outputs for a well-defined soil area and volume while maintaining controlled yet realistic soil-plant-water-atmosphere interactions (Pütz et al., 2018).

Therefore, our objective was to assess how municipal organic waste compost (hereafter compost) and varying levels of mineral P input affect C, N, and P retention and loss pathways within the soil–plant–microbial continuum of a C-limited reclaimed soil under near-natural conditions. We specifically tested whether compost inputs exceeding the rates currently allowed under the German Fertilizer Ordinance (DüV, 2017) can accelerate soil C restoration and improve crop performance, while quantifying the associated trade-offs in gaseous emissions, nutrient leaching, and soil nutrient accumulation. We further examined microbial and stoichiometric indicators to explore potential mechanisms associated with the observed changes in C, N, and P cycling and retention. For this, we quantified C, N, and P fluxes across soil, plant, water, and atmospheric compartments using lysimeters (Pütz et al., 2018) in a four-year outdoor experiment with reclamation soil from open-cast lignite mining, covering a complete crop rotation under natural conditions.

1.1. We formulated the following hypotheses

I. Compost application improves resource availability in the reclaimed soil and thereby enhances plant performance, with the strongest response at high application rates.

II. High compost input enhances C and nutrient retention, resulting in a greater proportion of added C, N, and P remaining in the soil–plant–microorganism system rather than being lost through gaseous emissions or leaching.

III: With increasing mineral P supply, the stoichiometric balance of the compost-amended marginal soil should shift toward more typical P levels, alleviating P limitation and thereby increasing nutrient mobilization and losses.

2. Material and methods

2.1. Experimental design

Meteorological data from the Forschungszentrum Jülich station were used to characterize site conditions, with detailed annual and seasonal patterns provided in the supplementary material. Conditions varied among years, with 2021 being cooler and wetter than 2020 and 2022 (Table S1).

In the four years before collection of the lysimeter soils, the mining company RWE Power AG (Essen, Germany) had deposited a mixture of former agricultural Haplic Luvisol soil and the underlying SOM- and nutrient-poor loess material, thereby creating an artificial marginal soil of 2 m depth before cultivating alfalfa for three years. In May 2019, stainless-steel lysimeter frames, measuring 0.5–1.0 m^2 and 1.15 m depth were placed onto the reclamation soil at the Inden lignite mine near Jülich (50.882784°N, 6.366538°E, Germany) to cut out intact soil monoliths by an excavator (Fig. S1). The lysimeters were transported in the stainless-steel frames to the nearby Forschungszentrum Jülich campus (Germany, 50.90875° N, 6.403657° E), where the experiment was conducted (Fig. S2). Further details on the lysimeters can be found in Führ et al. (1998).

A completely randomized experiment was conducted with the following treatments (n = replicates): **P1**, soil with regular P fertilization (n = 4); **P2**, soil with twice the regular P fertilization (n = 5); **CP1**, soil with regular compost + regular P fertilization (n = 4); **CP2**, soil with regular compost + twice the regular P fertilization (n = 5); and **CCP1**, soil with double the regular compost rate + regular P fertilization (n = 3). Compost was incorporated into the Ap horizon (0–25 cm) at 0 g m^{-2} (control), 4000 g m^{-2} fresh mass (fm; maximum permitted), or 8000 g m^{-2} fm (double rate). Mineral P was applied at an area-typical rate (4.5 g m^{-2} in 2020 and 6.0 g m^{-2} in 2021; P1, CP1, CCP1) or at twice that rate (9.0 g m^{-2} in 2020 and 12.0 g m^{-2} in 2021; P2, CP2) to evaluate effects on nutrient leaching and gas emissions.

Remaining alfalfa residues after biomass removal were accounted for as an N-fertilizer equivalent of 2.0 g N m^{-2} in 2020 (winter wheat). All lysimeters additionally received 16.1 g N m^{-2} in 2020 (winter wheat) and 19.5 g N m^{-2} in 2021 (winter barley) of mineral fertilizer, while no additional mineral N or P was applied in other years. All lysimeters were managed according to area-typical agronomic recommendations (Table S2). Detailed information on the type and timing of soil management, mineral fertilizer types and rates, plant protection measures, and sampling dates is provided in Table S2.

2.2. Initial soil parameters

The reclaimed soil had a loamy silt texture with 12.5% clay, 82.7% silt, and 4.8% sand and had received a mineral fertilization equivalent to 3.0 g N m^{-2}, 1.3 g P m^{-2}, and 2.5 g K m^{-2} three years before sampling of the soil, without any plant protection. The initial topsoil TOC content of the reclaimed soil (~0.45% dm) was substantially below the mean reported for European agricultural Ap horizons (~1.8%; Matschullat et al., 2018) and the 1.07–1.46% organic C range reported for adjacent original agricultural Luvisols from the same mining area (Reichel et al., 2024; Leal et al., 2025). Together with the pronounced microbial C limitation reported for comparable reclaimed soils (Clayton et al., 2021), we classify the experimental soil as C and nutrient limited.

The initial soil properties of the profile (0–0.3, 0.3–0.6, and 0.6–1.1 m, respectively) next to the sampled lysimeters can be found in Table 1.

2.3. Municipal organic waste compost

Mature, fine-grained (particle size of 0–10 mm) municipal organic waste compost, made of 95% organic household waste and 5% organic garden and park waste, was obtained from GABCO Kompostierung GmbH (Würselen, Germany). The compost had a TOC content of 21.8% of dm and a C:N ratio of 11. Based on the dm content of 72.8%, the typical compost application rate of 4000 g fresh matter m^{-2} supplied 634 g organic C m^{-2}, while the high application rate of 8000 g fresh matter m^{-2} supplied 1267 g organic C m^{-2}. Compost quality was assured by a certificate of the German Institute for Quality Assurance (RAL Deutsches Institut für Gütesicherung und Kennzeichnung e.V., Bonn, Germany), allowing maximal up to 0.5% foreign matter with particles > 2 mm and maximal 0.1% of non-degradable synthetic materials such as plastic (Braun et al., 2021). The reported electrical conductivity (EC) was 10.2 mS cm^{-1}, and the average heavy metal concentrations were: Pb 15.5, Cd 0.3, Cr 7.0, Cu 13.9, Ni 4.8, Hg 0.03, and Zn 81.4 mg kg^{-1} dm. Details about the compost can be found in Table 2.

Table 1
Initial soil characteristics of different soil layers of the reclamation soil used in the lysimeters. The table shows physical properties (top to bottom: bulk density, texture, pH, gravimetric water content), plant-accessible elements (NH_4^+, ammonium; NO_3^-, nitrate; SO_4^{2-}, sulfate; P_2O_5, phosphate; K_2O, potassium; Mg, magnesium), and total element contents in the top layer (TOC, organic carbon; TN, nitrogen; TOC-to-TN (C:N) mass ratio; TP, phosphorus; TOC-to-TP (C:P) mass ratio; TN-to-TP (N:P) mass ratio; TK, potassium; TS, sulfur; TMg, magnesium; TCa, calcium; TMn, manganese; TFe, iron; TIC, inorganic carbonate).

Soil properties				
Soil layer		0–30 cm	30–60 cm	60–110 cm
Physical properties				
Bulk density	g m^{-3}	1506 × 10^3	1546 × 10^3	1537 × 10^3
Texture	-	Silty loam	Silty loam	Silty loam
pH	in 0.01 M CaCl	7.5 ± 0.1	7.6 ± 0.1	7.7 ± 0.1
H_2O	% dry soil	15.6 ± 0.8	15.9 ± 0.6	16.5 ± 0.9
Accessible compounds				
NH_4^+	g N m^{-2}	0.1 ± 0.0	0.1 ± 0.0	0.2 ± 0.1
NO_3^-	g N m^{-2}	0.2 ± 0.2	0.1 ± 0.1	0.1 ± 0.1
SO_4^{2-}	g S m^{-2}	0.2 ± 0.1	0.5 ± 0.4	1.8 ± 2.1
P_2O_5 (P_{CAL})	g P m^{-2}	7.5 ± 3.6	7.1 ± 3.1	11.4 ± 5.4
K_2O (K_{CAL})	g K m^{-2}	13.1 ± 6.0	14.4 ± 5.3	19.9 ± 4.1
Mg	g Mg m^{-2}	35.8 ± 2.3	39.1 ± 4.2	65.3 ± 5.3
Total compounds				
TOC	g C m^{-2}	1573 ± 611	1244 ± 405	1672 ± 512
TN	g N m^{-2}	237 ± 63	191 ± 39	327 ± 36
C:N	mass ratio	7 ± 1	7 ± 2	5 ± 1
TP	g P m^{-2}	161 ± 5		
TK	g K m^{-2}	1960 ± 510		
TS	g S m^{-2}	105 ± 65		
TMg	g Mg m^{-2}	2650 ± 215		
TCa	g Ca K m^{-2}	13510 ± 1980		
TMn	g Mn m^{-2}	177 ± 2		
TFe	g Fe m^{-2}	7490 ± 74		
TIC	g TIC m^{-2}	4967 ± 414		

Table 2
Compost properties: bulk density, pH, particle size, dry matter (dm) content, total organic carbon (TOC), total nitrogen (TN), TOC:TN (C:N) ratio, dissolvable nitrogen (DN), total phosphate (P_2O_5), potassium oxide (K_2O), and magnesium oxide (MgO). Proportions and amounts applied with compost at the typical (4000 g m^{-2}) and high rate (8000 g m^{-2}) are expressed on basis of fresh matter (fm) and dm.

Properties	Basis	Value	Unit
Bulk density		585,000	g m^{-3} dm
pH	H_2O	9.1	pH
Particle size	fm	0–10	mm
Dry matter content (dm)	fm	72.8	% dm
Total organic carbon (TOC)		21.8	% dm
	4000 g fm m^{-2}	634	g m^{-2} dm
	8000 g fm m^{-2}	1267	g m^{-2} dm
Total nitrogen (TN)		2.0	% dm
	4000 g fm m^{-2}	58	g N m^{-2} dm
	8000 g fm m^{-2}	115	g N m^{-2} dm
C:N ratio (TOC:TN)	dm	11.0	mass ratio
Dissolvable nitrogen (DN)		0.1	% dm
	4000 g fm m^{-2}	2.2	g N m^{-2} dm
	8000 g fm m^{-2}	4.5	g N m^{-2} dm
Total phosphate (P_2O_5)		1.0	% dm
	4000 g fm m^{-2}	12.6	g P m^{-2} dm
	8000 g fm m^{-2}	25.2	g P m^{-2} dm
Potassium oxide (K_2O)		1.7	% dm
	4000 g fm m^{-2}	41.5	g K m^{-2} dm
	8000 g fm m^{-2}	83.1	g K m^{-2} dm
Magnesium oxide (MgO)		0.8	% dm
	4000 g fm m^{-2}	14.8	g Mg m^{-2}
	8000 g fm m^{-2}	29.5	g Mg m^{-2}
Water soluble sulfate (SO_4^{2-})		0.1	% dm
	4000 g fm m^{-2}	1.4	g S m^{-2}
	8000 g fm m^{-2}	2.9	g S m^{-2}

2.4. Samplings and analyses

Methods are briefly described here, with full details in the Supplementary Material. **Crop performance.** Aboveground biomass of wheat (2020), barley (2021) and field pea (2022) were harvested by cutting stems 1 cm above the soil. After drying to constant mass, the material was separated into straw and seeds and threshed (Haldrup LT-20, Inotec Engineering GmbH, Germany). Subsamples of wheat and barley straw and grain were milled (M 20 Universal Mill, IKA-Werke GmbH & CO. KG, Staufen, Germany) and analyzed for total C and N by combustion (EA, Vario EL Cube, Elementar Analysensysteme GmbH, Germany). Total P was determined after microwave digestion (MARS 5, CEM GmbH, Germany) and measurement by ICP-OES (iCAP 7600, Thermo Fisher Scientific, Germany). Wheat and barley C, N and P values matched published ranges (Döhler, 2009); field pea element concentrations were derived from this reference data.

Soil sampling and composition. Soil samples were taken several times a year after harvest and during the growing season (Table S2). Per sampling, 9 soil cores were obtained from randomly selected spots between the plants of each lysimeter by drilling in 5-cm steps until reaching a soil depth of 25 cm (~15 g fresh soil per core), using a custom-made stainless-steel soil auger tool with an inner diameter of 0.8 cm to minimize disturbances. When soil resistance in summer was too high and for the sampling of deeper soil layers (August 30, 2022) to assess potential N and P accumulation (Table S3) within the soil profile (0–25, 30–55, and 60–85 cm), we used a Pürckhauer soil auger with 1.8 cm inner-diameter (ecoTech Umwelt-Messsysteme GmbH, Bonn, Germany) at five randomly selected spots per lysimeter to obtain 80 g fresh soil per layer. All soil cores of a lysimeter were pooled, crushed, freed of visible plant residues, and mixed before sieving to 2 mm to obtain a homogenous sample. This composite sample was then split into three portions and stored at 4°C, −20°C, or air-dried depending on the subsequent analyses (see below).

Mineral N and dissolved organic carbon (DOC) were extracted from soil stored at 4 °C using 0.01 M $CaCl_2$, filtered (0.45 μm), and analyzed by ion chromatography (NO_3^-), continuous flow analysis (NH_4^+), and TOC analysis (DOC) as described before. TOC and TN were determined by elemental analysis of ball-milled, freeze-dried soil after carbonate removal by HCl fumigation. Total P, K, and S were quantified by ICP-OES following microwave digestion of 50 mg air-dried soil, as described in the Supplementary Material.

Leachate. The leachate was collected in stainless-steel pans below each lysimeter and pumped into mobile stainless-steel containers when the pan water level exceeded 5 cm. Thus, leachate collection was volume-triggered rather than based on discrete samplings. Containers were weighed empty and full using a platform scale (ICS439, Mettler-Toledo, Switzerland). Aliquots were collected in wide-neck PP screw-cap bottles (Bürkle GmbH, Germany). Samples were filtered (0.45 μm, Macherey-Nagel, Germany) and analyzed for DOC and dissolved N (TOC analyzer, VcPH + TNM-1 + ASIV, Shimadzu, Japan). Further aliquots were analyzed for NH_4^+ (CFA Analyzer, FLOWSYS 3-Kanal, Alliance Instruments, Salzburg, Austria), for NO_3^- (IC Dionex DX-500, Thermo Fisher Scientific, Waltham, MA, USA), and for dissolved P (iCAP 7600 ICP-OES, Thermo Fisher Scientific, Oberhausen, Germany).

Greenhouse gas emissions. Greenhouse gas emissions were measured once every two weeks during the post-harvest period, once per week during the growing season, and three times per week following fertilization events, with detailed measurement dates provided in Table S2. The increased measurement frequency following fertilization was intended to better capture short-term emission pulses. Nevertheless, because chamber measurements were discrete in time, short-lived peaks between measurement dates cannot be excluded. We used three permanently installed PVC soil chambers per lysimeter inserted 15 cm deep, with fertilizer applied proportionally inside the chambers. CO_2 and N_2O fluxes were measured by connecting the three chambers per lysimeter to one virtual dynamic chamber, which was connected in closed-loop mode to an FTIR analyzer (DX4015, Gasmet Technologies Oy, Helsinki, Finland). The FTIR analyzer recorded concentrations every 20 s over 6 min (18 points). Greenhouse gas fluxes were calculated from the linear change in headspace concentration over time, chamber volume, surface area, temperature correction, and molar mass, and considered non-zero when the concentration–time relationship met $R^2 > 0.81$. Cumulative emissions were obtained by trapezoidal integration between sampling dates.

Microbial biomass. Microbial biomass C (C_{mic}) and N (N_{mic}) were determined by chloroform fumigation–extraction from soils stored at −20 °C (Joergensen, 1996; Reichel, et al., 2017). After 24 h fumigation in a desiccator with ethanol-free chloroform, 0.01 mol $CaCl_2$ soil extracts were centrifuged, filtered (0.45 μm), and analyzed for DOC and dissolved N using the TOC analyzer as described before. C_{mic} and N_{mic} were calculated based on the differences between fumigated and control samples, using correction factors of 0.45 and 0.40 for extractable C and N, respectively (Reichel et al., 2017).

Microbial genes. The abundance and diversity of soil bacteria and fungi were assessed using quantitative PCR (qPCR) and DNA metabarcoding based on 16S rRNA genes and internal transcribed spacers (ITS), respectively (Smith and Osborn, 2009). DNA was extracted from 0.3 g of frozen soil (-20°C) using the NucleoSpin Soil Kit (Macherey-Nagel GmbH & Co. KG, Germany) according to the instructions of the manufacturer (lysis buffer SL1, 30 s at 5.5 m s^{-1} bead beating). Blank extractions served as negative controls to check for possible contamination. DNA extracts were stored at –20 °C.

Bacteria. Further microorganisms which catalyze key processes in the N and P cycles were quantified using the same method (Bergkemper et al., 2016; Kurth et al., 2021; Thaqi et al., 2025). Here, we used the *amoA* gene, encoding ammonia monooxygenase, as a marker for ammonia-oxidizing archaea and bacteria, the nitrite reductase genes *nirK* and *nirS* as markers for nitrite-reducing/denitrifying microorganisms, the nitrous oxide reductase gene *nosZ* as marker for microorganisms capable of N_2O reduction, as well as the glucose dehydrogenase gene *gcd* and the alkaline phosphatase gene *phoD* to characterize microorganisms involved in inorganic P solubilization (via organic acid production) and organic P mineralization, respectively.

Fungi. The same DNA extracts were also used for fungal analyses. In the first cropping year after compost application, fungal community composition and the relative abundance of saprotrophs, plant pathogens, and arbuscular mycorrhizal fungi were assessed using ITS2 Illumina metabarcoding. The ITS2 region was PCR-amplified (fITS7/ITS4), followed by a second PCR for dual-indexing. Amplicons were purified, pooled equimolarly, and sequenced on an Illumina MiSeq platform (2 × 300 bp). Sequence data were processed to generate denoised, chimera-free, non-singleton amplicon sequence variants (ASVs), taxonomically assigned against a fungal reference database (retaining only ASVs classified as fungi), and functional guilds were inferred using a fungal guild assignment database. Further methodological details are provided in the Supplementary Material.

2.5. Statistical analyses

All data in this paper are reported per unit area (m^2) for consistency, except for the fungal metabarcoding data. Data on a mass basis were converted using the following information: 1 m^2 area, 0.25 m soil depth, and 1400×10^3 g m^{-3} bulk density = 3.5×10^5 g dm m^{-2}. For example, an increase in TOC of 35 g m^{-2} corresponds to an increase of 0.01% (w/w, dm), 0.1 g kg^{-1} (dm), 350 kg ha^{-1}, and 0.35 t ha^{-1}.

Prior to statistical analysis, data collected across sampling dates within each year were aggregated to annual values. Crop, soil, and microbial variables were expressed as annual means, whereas gas emissions and leachate variables were expressed as annual cumulative values. This aggregation was used to assess treatment effects at the annual rather than seasonal scale. Analyses of microbial indicators, including key taxa driving N and P turnover and fungal plant pathogens, were restricted to the year following compost application. The dataset and R script templates used for the linear mixed-effects analyses are provided as Supplementary Material.

Statistical data processing, testing, and visualization were performed in R (version 4.5.0, The R Foundation for Statistical Computing Platform) via RStudio (2025.05.0, Posit, Boston, USA). For repeated measurements across years, response variables were analyzed using linear mixed-effects models fitted with the *lme* function from the R package *nlme*. Treatment and year were included as fixed effects, and experimental unit identity was included as a random intercept. Treatment replication ranged from three to five independent lysimeters, with three experimental units representing the lower end of this range, which need to be accounted when interpreting the results. Year-specific residual variances were modeled using a *varIdent* variance structure. Final models were fitted using restricted maximum likelihood, whereas fixed effects and the treatment × year interaction were tested by likelihood-ratio tests based on maximum likelihood. Estimated marginal means and pre-defined planned contrasts were calculated using the R package *emmeans*. Planned contrasts tested the effects of doubling mineral P input (P2 vs. P1), compost application compared with mineral P only (CP1 vs. P1), additional mineral P at the regular compost rate (CP2 vs. CP1), a high compost application rate (CCP1 vs. CP1), and the overall effect of compost-amended treatments compared with non-compost treatments (CP1 +CP2 +CCP1 vs. P1 + P2). P-values from planned contrasts across multiple years were adjusted using the Holm method. For single-time measurements, analogous models were fitted without year as a fixed effect or year-specific residual variance structures, and Holm adjustment was not applied. Visual inspection of the residual and Q–Q plots indicated deviations from the normality assumption. These deviations were accepted, as linear mixed-effects models are thought to be robust to violations of the normality assumption. Levene's tests indicated heterogeneity of variance, but the models were considered appropriate, as the fitted variance structures accounted for it.

Distance-based redundancy analysis (RDA) was performed using the following R library packages: dplyr, vegan, FSA ggplot2, ggrepel, haven, multcompView, officer, readxl, rvg, svglite, tidyr, and tidyverse. The RDA was based on a Euclidean distance matrix calculated from z-standardized variables. Year was accounted for as a conditioning factor: distance ~ treatment + condition (Year). Significance of the treatment term was verified by permutation tests (999 permutations). Centroids (mean scores) along both ordination axes were calculated for each Treatment × Year group and plotted. To aid interpretation, environmental vectors were fitted onto the constrained ordination (999 permutations). Correlation analyses were used to test the significance of the pairwise relationships between vectors vs. scores and vectors vs. vectors ($p < 0.05$).

3. Results

3.1. Crop properties

Overall response to treatment was found for the mean annual crop biomass C and grain yield (Fig. 1 A, S4A). All response variables showed an overall significant response to the year and to interactions between treatment and year (Table S4, S5).

A comparison of the contrasts revealed that compost significantly increased the mean annual crop biomass C and grain yield throughout the main cropping years. The regular compost application (CP1) significantly increased the crop biomass C by 13% or 52.0 g C m^{-2} compared to the P1 treatment without compost. No significant difference was found between CP1 and P1 for grain yield, but a large effect size suggests a potentially relevant effect. Although the high compost application rate (CCP1) did not further increase the mean annual crop biomass C compared to CP1, it showed the lowest inter-replicate grain yield variability compared to other treatments across the years (Fig. 1B). Compost application had no treatment effects on the grain-to-biomass ratio, crop biomass C:N, and C:P (Fig. S4B-D). Adding twice the amount of mineral P (P1 vs. P2 and CP1 vs. CP2) to soil with or without compost did not significantly affect the crop response variables (Tables S4, S5).

3.2. Soil properties

After three years of permanent alfalfa cultivation, the reclaimed soil showed a weakly developed Ah–Cv profile.

3.2.1. Total and dissolved organic C

Significant effects of both treatment and year were observed, but not the interaction between treatment and year on mean annual TOC contents (Fig. 1C, Table S4). Overall, compost application significantly increased the mean annual TOC by about 46% or 789.5 g C m^{-2} compared to P1 and P2. The application of the regular compost rate significantly increased the mean annual TOC by 40% or 669.6 g C m^{-2} (CP1 vs. P1). High compost rates increased the mean annual TOC content by an additional 30% to 1498.5 g C m^{-2}, which equates to a TOC increase by ~0.43%, approaching a TOC level of 0.9% dm (CCP1 vs. CP1). Adding twice the regular amount of mineral P was not significant, but effect sizes indicate without compost a small positive (6% or 95.3 g C m^{-2}, P1-P2) and with compost a moderately negative effect on TOC contents (-9% or −206.2 g C m^{-2}).

There were significant effects of treatment, year and the treatment × year interaction on DOC (Fig. 2A, Table S6). Overall, compost

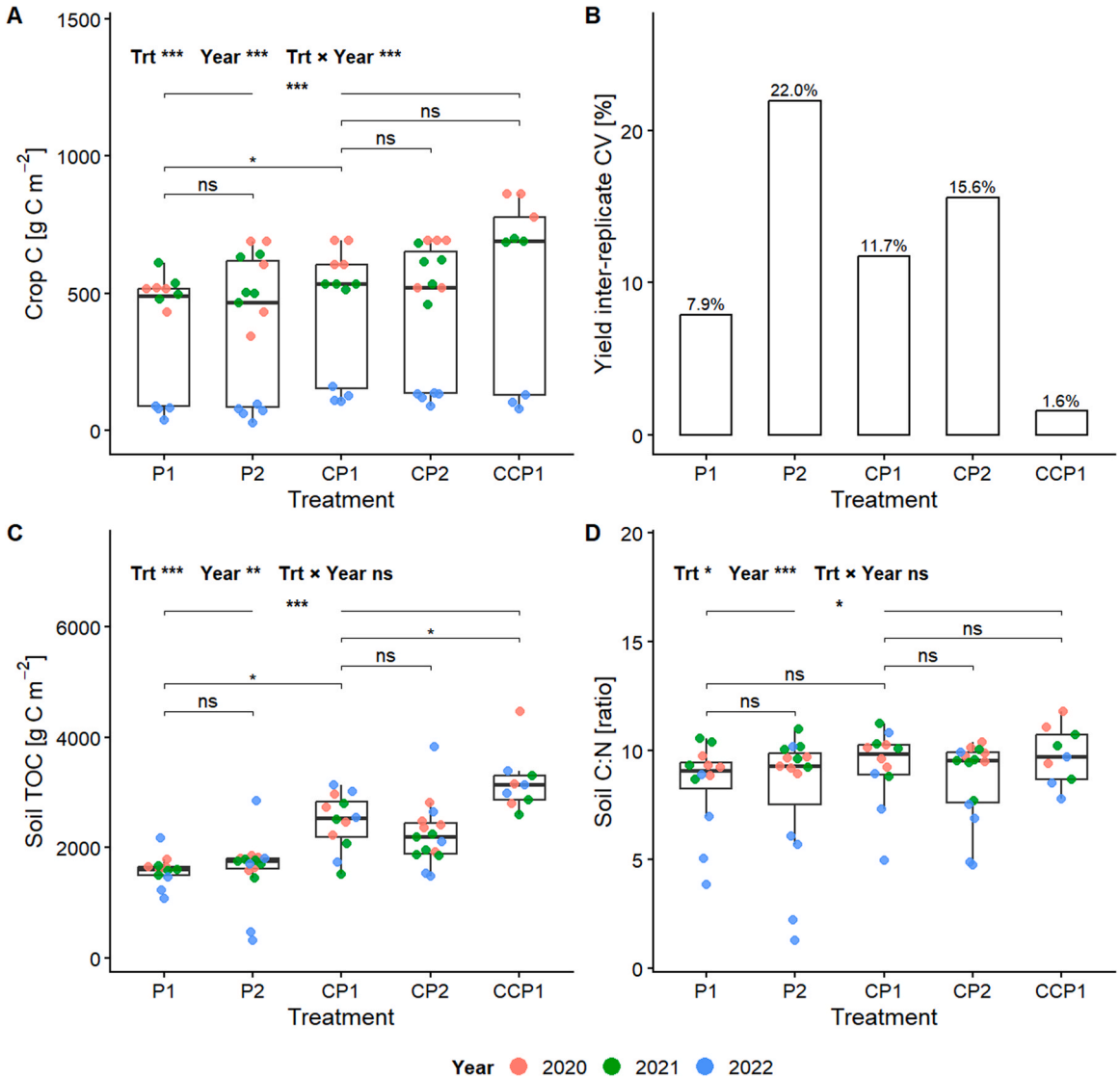

Fig. 1. Treatment and year effects on mean annual crop biomass C (A), inter-replicate yield variability (B), total organic carbon (TOC; C), and soil C:N ratio (D). Boxplots show the variables across the five treatments: P1, P2, CP1, CP2, and CCP1. Panel B shows the yield variability between replicates (Yield inter-replicate CV), expressed as the coefficient of variation relative to the mean yield. Individual points in panels A, C, and D represent observed replicate values and are colored by year (2020, 2021, 2022). Boxes indicate the interquartile range, horizontal lines the median, and whiskers the data range excluding outliers. Overall treatment, year, and treatment × year effects shown above the panels were tested using likelihood-ratio tests from linear mixed-effects models. Horizontal brackets indicate predefined Holm-adjusted treatment contrasts: P2 − P1, CP1 − P1, CP2 − CP1, CCP1 − CP1, and P1 + P2 versus CP1 + CP2 + CCP1. Significance levels are indicated as $P < 0.05$ (*), $P < 0.01$ (**), $P < 0.001$ (***), and non-significant effects as ns.

application had a large effect on DOC, increasing mean annual DOC content by approximately 32% or 0.9 g C m^{-2} compared to P1 and P2. Although the tested contrasts were not statistically significant, effect size estimates suggested moderate positive effects of regular compost application and additional small positive effects of high compost application rates on mean annual DOC availability. Mineral P addition in treatments with and without compost (P2 and CP2) had no significant effect on DOC, but effect size estimates indicated a potential small positive response. Subsoil sampling after field pea in 2022 showed no difference in DOC contents between the treatments at different soil depths (Table S3).

3.2.2. Total N and mineral N

Both treatment and year, but not the interaction between treatment and year, had significant effects on mean annual TN contents (Table S7). In total, compost had a large and significant effect on the mean annual TN compared to P1 and P2 (Table S7). The regular compost application rate significantly increased the TN by 38% or about 75.5 g N m^{-2} (CP1 vs. P1). The high compost application rate further increased the mean annual TN by an additional 25% or 69.5 g N m^{-2} (CCP1 vs. CP1). Doubling the mineral P application rate, both without and with compost (P1-P2 and CP1-CP2), had no significant effect on TN. However, the medium effect size observed for CP1 vs. CP2 may indicate a negative effect of additional P fertilization on compost TN stabilization.

NO_3^- was not different to mineral N (N_{min}). Treatment and year had significant effects on NO_3^-, but not the interaction between treatment and year (Fig. 2B, Table S6). Generally, compost application had no significant effect on NO_3^- content, but the effect size indicates the potential for an increase of up to 17% or 0.2 g N m^{-2}. Regular (CP1) and high compost application (CCP1), as well as additional mineral P fertilization (P2 and CP2), had no clear effect on NO_3^-. Subsoil sampling revealed no accumulation of N_{min} in the deeper soil layers (Table S3).

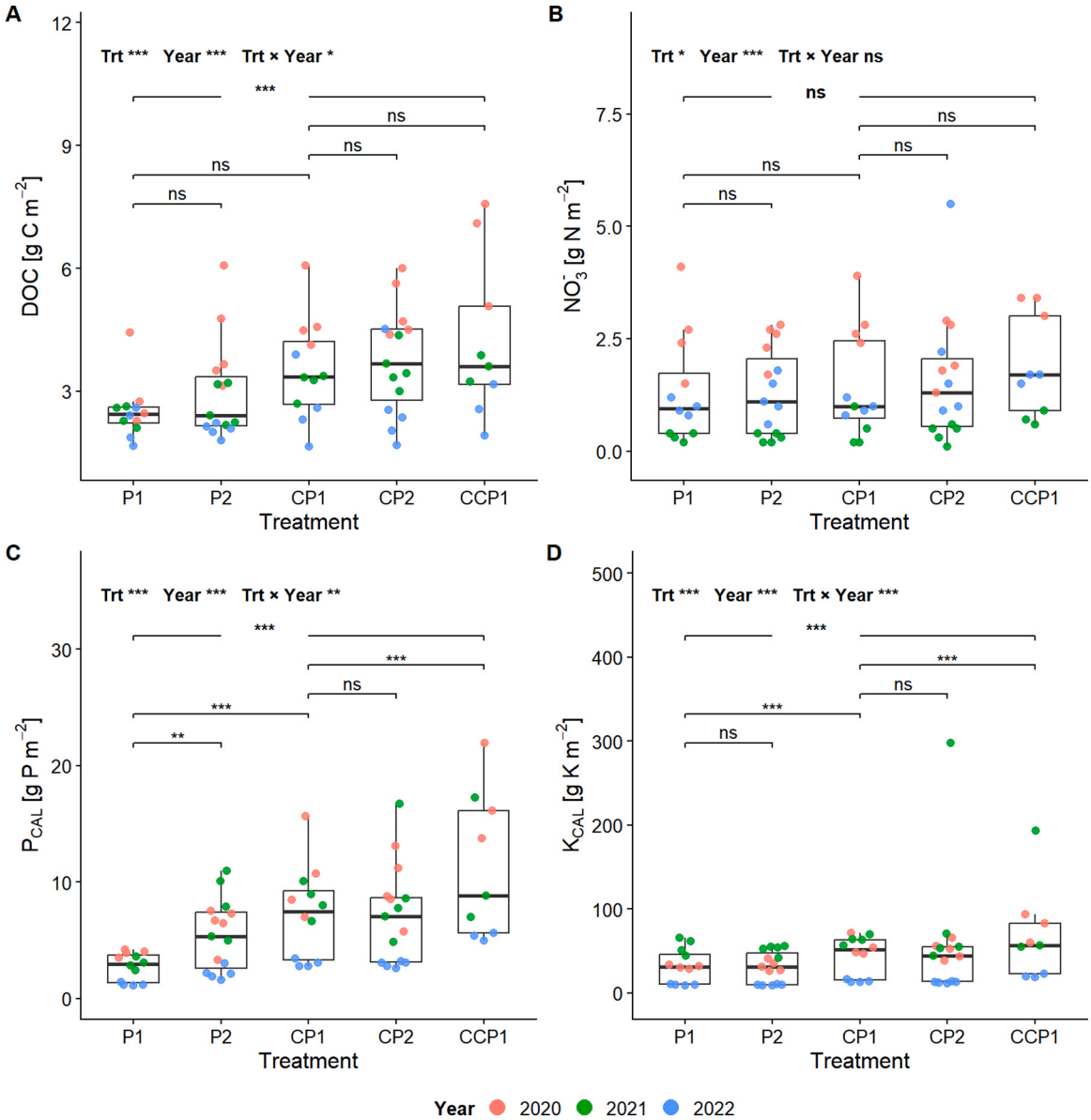

Fig. 2. Treatment and year effects on mean annual soil dissolved organic carbon and available nutrients. Boxplots show dissolved organic carbon (DOC; A), nitrate nitrogen (NO_3^-; B), calcium-acetate-lactate-extractable phosphorus (P_{CAL}; C), and calcium-acetate-lactate-extractable potassium (K_{CAL}; D) across the five treatments P1, P2, CP1, CP2, and CCP1. Individual points represent observed replicate values and are colored by year (2020, 2021, 2022). Boxes indicate the interquartile range, horizontal lines the median, and whiskers the data range excluding outliers. Overall treatment, year, and treatment × year effects shown above each panel were tested using likelihood-ratio tests from linear mixed-effects models. Horizontal brackets indicate predefined Holm-adjusted treatment contrasts: P2 − P1, CP1 − P1, CP2 − CP1, CCP1 − CP1, and P1 + P2 versus CP1 + CP2 + CCP1. Significance levels are indicated as $P < 0.05$ (*), $P < 0.01$ (**), $P < 0.001$ (***), and non-significant effects as ns.

3.2.3. *Total and plant available P*

Significant effects of treatment and the treatment × year interaction on mean annual TP contents were observed (Table S7). Generally, compost application had a large and significant positive effect on TP content, increasing it by approximately 9% or 6.4 g P m^{-2}. Despite larger effect sizes, the contrasts comparing regular compost application (CP1 vs. P1) and high compost application rates (CCP1 vs. CP1) showed no statistically significant effects on mean annual TP contents. Doubling the mineral P application rate (P1 vs. P2 and CP1 vs. CP2) had no significant effect on TP contents.

Overall, there were highly significant effects of treatment, year and the treatment × year interaction on plant-available P (P_{CAL}; Fig. 2C, Table S6). Compost generally had a significant, positive medium-sized effect on P_{CAL}, increasing it by about 39% (Table S6). Compost application at the regular rate significantly raised mean annual P_{CAL} by about 37% or 1.8 g P m^{-2} (CP1 vs. P1), while the higher compost rate resulted in an additional significant increase of 34% or 2.3 g P m^{-2} in this marginal reclamation soil (CCP1 vs. CP1; Table S6). Also, the mineral P application (P1 vs. P2) significantly increased mean annual P_{CAL} by approximately 19% (0.9 g P m^{-2}), whereas no such effect was observed for the contrast among CP1 vs. CP2. Subsoil analyses showed no accumulation of leachable P and thus no differences among the treatments (Table S3).

3.2.4. *Total and plant available K*

Mean annual total K responded significantly only to year (Fig. S5, Table S7). Treatment contrasts revealed no significant differences in the mean annual total K. Mean annual K_{CAL} showed significant effects of both year and the treatment × year interaction (Fig. 2D, Table S6). Mean annual K_{CAL} increased by about 10% (4.3 g K m^{-2}) under regular

compost application (CP1 vs. P1) and by a further 13% (6.1 g K m^{-2}) under high compost application (CCP1 vs. CP1). Doubling the mineral P application rate had no clear effect on the mean annual total K and K_{CAL}.

3.2.5. Soil element stoichiometry and other properties

Significant effects of both treatment and year on the mean annual soil C:N ratio were observed, whereas their interaction was not significant (Fig. 1D, Table S4). Compost significantly increased the mean annual soil C:N ratio by approximately 8% or 0.7 units, corresponding to a large effect size. This was also reflected in the effect sizes for soils with regular and high application rates, although the corresponding contrasts (CP1 vs. P1 and CCP1 vs. CP1) were not statistically significant. The

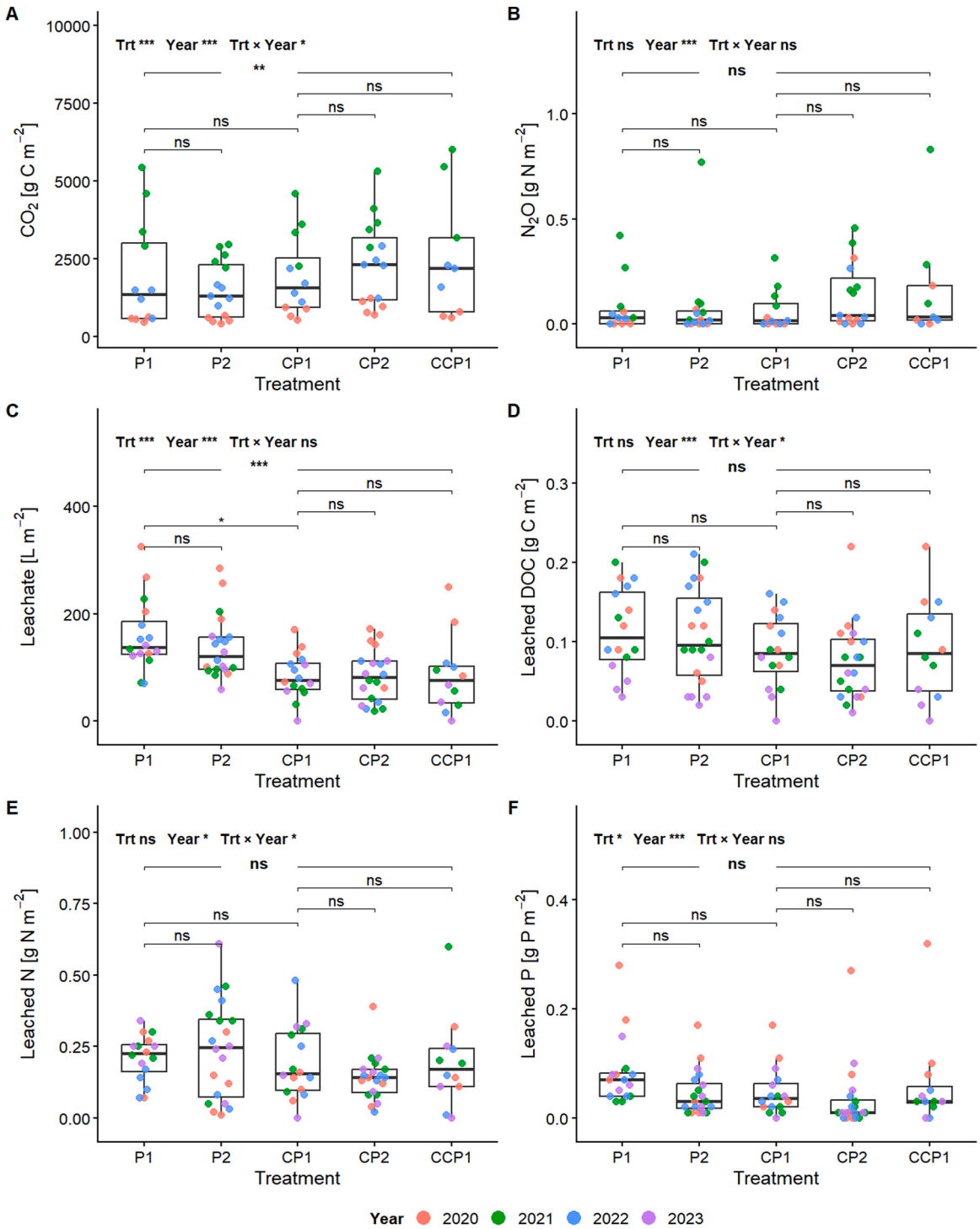

Fig. 3. Treatment and year effects on mean annual cumulative greenhouse gas and leaching losses. Boxplots show CO_2 emissions (A), N_2O emissions (B), leachate volume (C), leached DOC (D), leached N (E), and leached P (F) across the five treatments P1, P2, CP1, CP2, and CCP1. Individual points represent observed replicate values and are colored by year (2020, 2021, 2022, and, for leaching variables, 2023). Boxes indicate the interquartile range, horizontal lines the median, and whiskers the data range excluding outliers. Overall treatment, year, and treatment × year effects shown above each panel were tested using likelihood-ratio tests from linear mixed-effects models. Horizontal brackets indicate predefined Holm-adjusted treatment contrasts: P2 − P1, CP1 − P1, CP2 − CP1, CCP1 − CP1, and P1 + P2 versus CP1 + CP2 + CCP1. Significance levels are indicated as $P < 0.05$ (*), $P < 0.01$ (**), $P < 0.001$ (***), and non-significant effects as ns.

application of the double amount of mineral P had no significant effect on the C:N ratio.

Overall, the mean annual soil C:P ratio was significantly affected by both treatment and year, while their interaction was not significant (Fig. S5C, Table S7). Generally, compost significantly increased the mean annual soil C:P ratio by up to 35%, increasing the C:P ratio by 2.7 units (CP1 vs. P1) and 3.7 units (CCP1 vs. CP1), respectively.

The mean annual soil pH and gravimetric H_2O content were only significantly affected by the year (Fig. S5A, B, Table S7). Effect size estimates indicated that the high compost application resulted in a non-significant but large negative effect on soil pH($CaCl_2$) and a medium positive effect on gravimetric H_2O content relative to the control, respectively. Mean total S and plant-available S_{min} showed significant responses only to year, while none of the tested treatment contrasts had a significant effect (Fig. S5D, F, Table S7).

3.3. Greenhouse gas emissions

The treatment, year, and the treatment × year interaction significantly affected mean annual cumulative CO_2 emissions (Fig. 3A, Table S8). Compost application increased the mean annual cumulative CO_2 emission by about 17% or 305.4 g C m^{-2}. However, regular and high compost application rates, when individually compared with their respective controls, did not significantly increase the mean annual cumulative CO_2 emission. Nevertheless, effect size estimates indicated a larger positive effect on CO_2 emissions following regular compost application (CP1 vs. P1) and in combination with the high mineral P application (CP2 vs. CP1). The comparison between the high and regular compost applications (CCP1 vs. CP1) showed no statistically detectable additional increase in the mean annual cumulative CO_2 emission. Depending on the meteorological conditions, CO_2 emissions increased by an average factor of 5.5 in 2021 compared to 2020 and declined again in 2022 (Fig. 3A).

The mean annual cumulative N_2O emissions responded significantly only to the factor year (Fig. 3B, Table S8). Compost applications did not increased mean annual cumulative N_2O emissions compared with their respective controls (CP1 vs. P1 and CCP1 vs. CP1). Nevertheless, the large effect size observed for the contrast CP2 vs. CP1 suggests that a high mineral P application rate in compost-amended soil may increase mean annual cumulative N_2O emissions.

3.4. Leachate properties

The mean annual cumulative leachate volume was significantly affected by both treatment and year, whereas the treatment × year interaction was not significant (Fig. 3C, Table S8). Compost application, irrespective of the application rate, had a large effect on reducing mean annual cumulative leachate volume by approximately 43% (64 L m^{-2}). The high mineral P fertilization (P2 vs. P1 and CP2 vs. CP1) did not affect the amount of leachate water.

Mean annual cumulative DOC leaching was significantly affected year and the treatment × year interaction (Fig. 3D, Table S8). Generally, compost application, independent of application rate, reduced DOC content in the leachate by up to 24% (0.03 g C m^{-2}), corresponding to a medium effect size. No significant changes in the mean annual cumulative DOC leaching were observed following additional mineral P fertilization (P2 vs. P1 and CP2 vs. CP1)

The mean annual cumulative N leaching was significantly affected by year and the treatment × year interaction (Fig. 3E, Table S8). In general, compost application tended to reduce mean annual cumulative N leaching by approximately 24% (0.05 g N m^{-2}). Although this effect was not statistically significant, the estimated effect size suggested a response of up to medium strength. Additional mineral P fertilization (P2 vs. P1 and CP2 vs. CP1) did not result in significant changes in mean annual cumulative N leaching.

Mean annual cumulative P leaching showed significant responses to both treatment and year (Fig. 3F, Table S8). Compost application showed a small effect in reducing mean annual cumulative P leaching by about 31% or 0.02 g P m^{-2}, even though statistical significance was not reached at the individual treatment level. The high mineral P fertilization (P2 vs. P1 and CP2 vs. CP1) had no significant effect on P leaching.

3.5. Microbial responses

Means of the microbial biomass (C_{mic}), C_{mic}:N_{mic} ratio, bacterial 16S rRNA gene copy number, and the bacterial:fungal gene copy number ratio responded significantly to the factor year (Fig. S6A-D, Table S9). Only the C_{mic}:N_{mic} ratio showed a significant treatment × year interaction. C_{mic} indicated no responses, whereas bacterial 16S rRNA gene copy numbers showed a small, non-significant response to both compost application (CP1 vs. P1) and high mineral P fertilization (P2 vs. P1). The C_{mic}:N_{mic} ratio showed high variability and was not significantly affected by compost or high mineral P application, although mean values and effect size estimates indicated a declining trend with increasing rates of both mineral P and compost. This was consistent with shifts in the bacteria:fungi gene copy number ratio. Plotting the C_{mic}:N_{mic} ratio against the soil C:N ratio for each lysimeter replicate and year, revealed a significant negative relationship (Pearson $r = -0.67$, $R^2 = 0.45$, $p < 0.01$; Fig. S8).

N cycling microorganisms responded to the compost and P treatments in the year after compost application as indicated by the effect size estimates (Fig. S7A-B, S9A-C, Table S10, S11). The abundance of ammonia-oxidizing bacteria (AOB) was significantly higher at high compost application rate (CCP1 vs. CP1). Abundances of nitrite-reducing microorganisms, represented by the *nirS* and *nirK* genes, were significantly increased in the year after compost application compared with the corresponding control (Fig. S7B, S9B). Microorganisms capable of reducing N_2O, as indicated by the *nosZ* gene abundance tended to increase following high compost application (CCP1 vs. CP1; Fig. S9C). Doubling mineral P inputs did not cause clear significant changes in the abundance of microbial groups associated with N transformation.

Microbial groups involved in P transformation showed no statistically significant responses to compost or mineral P treatments in the year after compost application (Fig. S7C, S9D, Tables S10, S11). The abundance of the *gcd* gene, associated with microbial potential for inorganic P solubilization, tended to be higher in compost-amended treatments, with a large effect size despite the lack of statistical significance. The abundance of microorganisms involved in the mineralization of organically bound P, represented by the *phoD* gene, was not affected by compost application or high mineral P fertilization.

High compost addition significantly reduced the relative abundance of fungal plant pathogens by 32% in the year following application (CCP1 vs. CP1; Fig. S7D; Table S10). A similar reduction was observed in soil without compost after high mineral P fertilization (P2 vs. P1). The high compost rates tended to increase the proportion of fungal saprotrophs, as indicated by large effect sizes, but this effect was not significant (Fig. S9E, Table S11). Arbuscular mycorrhizal fungi showed no consistent response to compost and high mineral P addition (Fig. S9F, Table S11), although compost seems to stabilize the abundance at the P1 level.

3.6. Multivariate soil-plant-microbial responses

The experimental year explained 43.3% of the total variance of measured parameters (Fig. S10). After accounting for the year, RDA1 explained 77.3% of the constrained variance (16.9% of the total variance), while RDA2 explained 13.1% of the constrained variance (2.9% of the total variance). Together, they accounted for 90.4% of the constrained variance (19.8% of the total variance). CCP1, located in the positive quadrant of RDA1, shows higher scores compared to CP1 and CP2 and was further separated by negative scores along RDA2. P1 and

P2 were in the negative RDA1 and RDA2 quadrant, separate from all the other treatments. CP1 was variable along RDA2, while CP2 had positive scores across all years, separate from CCP1.

Environmental vectors that had a predominantly positive relationship with RDA1 with significant impact on the separation of the treatments (P1, P2 < CP1, CP2 < CCP1) were: total soil elements (TOC, TN and TP), total element stoichiometry (C:N, C:P and N:P), and available elements (DOC, P_{CAL} and K_{CAL}). Although plant (grain, C, N and P content) and GHG parameters (CO_2 and N_2O) were correlated with these vectors, they had no further significant contribution on the treatment score separation. In contrast, the extractable C:P was predominantly negatively related to the RDA1.

A predominant negative relationship with the RDA2, as well as a significant contribution to the separation of CP1 and CP2 vs. CCP1 scores, was indicated for the following response variables: plant C:N ratio, leached N, leached P, and fungal abundance (FunITS).

The leachate volume, leached DOC content, and C_{mic}:N_{mic} ratio were negatively related along RDA1 and RDA2, significantly contributing to the separation of P1, P2 vs. CP1, CP2 vs. CCP1 scores. The abundance of bacteria (RDA1/2: positive/negative) and the bacteria-to-fungi ratio (RDA1/2: positive/positive) also contributed to the separation of these treatments.

4. Discussion

German agricultural regulations govern compost application rates to agricultural soils to prevent nutrient losses (DüV, 2017), thereby restricting SOM enrichment in marginal soils. Reclamation soils have a high potential for sustained organic C retention and would benefit most from restoring SOM-derived soil functions that also support a climate change-resilient agricultural production. This study evaluated, under realistic weather and typical climate-change anomalies (Fig. S3), how compost applications above current regulatory limits affect crop performance, C retention, and nutrient losses under regular mineral fertilization with typical and double P amount.

4.1. Reclamation soil characteristics and nutrient dynamics

After three years of alfalfa cultivation, the reclaimed soil developed into a Calcaric Regosol with a weakly developed Ah-Cv profile, morphologically still clearly distinct from the Luvisol profile of the undisturbed cropland before mining (Pihlap et al., 2019). Reclamation processes can substantially alter soil structure, increasing susceptibility to erosion and compaction when inadequately managed (Dickmann, 2011; Dumbeck, 2023). The mixing of loess-containing subsoil with topsoil reduces SOM content $\leq$ 0.5% dm, below levels typical of most EU agricultural soils (Leal et al., 2025; Matschullat et al., 2018), resulting in impaired soil functioning. However, there is evidence that appropriate management can restore key soil functions and microfaunal communities within several years, although the original state may not be fully restored (Schmid et al., 2020; Roy et al., 2023; Reichel et al., 2024).

The high carbonate content of loess, combined with dilution by subsoil, limits nutrient availability in these freshly recultivated soils. While Ca^{2+} and Mg^{2+} availability increased, P solubility decreased under the alkaline conditions, resulting in plant-available P and K levels below agricultural optimal ranges (Barrow and Hartemink, 2023; Penn and Camberato, 2019). The N_{min} content (0.3 g N m^{-2}) was well below typical post-harvest levels for German agricultural soils (BMEL, 2023), and also SO_4^{2-} availability initially was low for optimal crop production (Dick et al., 2008; Döhler, 2009; Kolbe, 2024).

Despite variation in N supply by compost and mineral fertilization across treatments (18.5–24.3 g N m^{-2}), efficiency of the use of N remained high across treatments (low residual NO_3^-, Fig. 2B). Even the treatment with a high compost application did not exceed the optimal P range for plant growth, likely due to plant uptake and precipitation as hydroxyapatite (Penn and Camberato, 2019). Plant-available K remained within optimal ranges in nearly all treatments (Fig. 2D), with no evidence of antagonistic effects on Ca^{2+} or Mg^{2+} uptake (Khan et al., 2014) in the high compost treatment. Mineral S levels were maintained at adequate concentrations for crop production during the experiment (Fig. S5D; Dick et al., 2008; Kolbe, 2024). The use of plant growth regulators as routinely applied in agriculture for wheat and barley production could have attenuated some compost-related effects on plants. Nevertheless, the effects of compost addition on performance were evident (Fig. 1 A, S4A).

Given the adequate fertilizer supply across most treatments, the observed differences may reflect factors beyond nutrient availability alone, including improved soil-plant-microbial interactions.

4.2. Compost-mediated benefits for crop performance

The application of compost improved crop performance and, at the higher application rate, was associated with lower inter-replicate yield variability (Fig. 1A, B), which could not be explained by soil nutrient concentrations alone. In structurally weak reclamation soils, compost probably enhanced root access and uptake of water and nutrient resources, thereby reducing potential loss pathways (Fig. 3C-F). These findings align with reports of improved crop performance after high compost application (Drury et al., 2014; Escobedo-Monge et al., 2020). This could be related to an improved soil porosity and water retention in compost-amended soil (Giusquiani et al., 1995; Cao et al., 2018), which may have contributed to the reduced inter-replicate variability in yield observed in the high-compost treatment (Fig. 1B).

The high compost application rate also shifted soil microbiota composition in ways that may have supported plant performance: in the year following compost application, the abundances of several microbial genes involved in N cycling increased, whereas P-cycling genes showed only numerical responses and the relative abundance of fungal plant pathogens decreased (Fig. S7, S9A–D). Shifts in microbial functional indicators may reflect changes in nutrient availability following compost application (García-Ruiz et al., 2009; Singh et al., 2022; Yang et al., 2024). High compost application rates have been shown to suppress pathogens, thereby reducing disease pressure and increasing yields (Tilston et al., 2005). Although high compost application increased the abundance of microbial functional genes associated with potential N-cycling functions in the year following application (Fig. S7A-B, S9A-C), no statistically detectable increase in mineral N was observed (Fig. 2B), while measured N losses via N_2O emissions (Fig. 3B) and leaching remained low (Fig. 3E; Eriksen et al., 1999; Hargreaves et al., 2008). Together, these effects may have contributed to the lower inter-replicate yield variability observed in the high-compost treatment (Fig. 1B).

These results support Hypothesis I, indicating that high compost application was associated with enhanced crop C and nutrient retention.

4.3. Mechanisms regulating C and nutrient retention in compost-amended soil

The total organic C levels also after high compost application were maintained throughout the crop rotation despite mineral fertilization (Fig. 1C). Compost application increased mean annual cumulative CO_2 emissions by approximately 17%, while N_2O emissions showed no clear increase (Fig. 3A, B), despite higher availability of DOC (Fig. 2A) and compost-derived organic matter (Fig. 1C, D). Other studies similarly report stable organic C and N levels years after compost application (Ludwig et al., 2005; Hepperly et al., 2009), although a tendency towards greater losses was observed in the high mineral P treatment over the three-year period (CP2; Fig. 2C). Marginal soils typically have soil C levels below those that can be maintained even under conventional agricultural management (Reichel et al., 2024; Leal et al., 2025), indicating substantial potential for longer-term C retention (Georgiou et al., 2025; Poeplau et al., 2024). The lack of accelerated compost

mineralization at high application rates, contrary to German regulatory assumptions (DüV, 2017), may be consistent with microbial dynamics affecting CUE. Clayton et al. (2021) demonstrated that increasing TOC of these marginal reclamation soils shifted microbial biomass from C limitation to combined C:N co-limitation, accompanied by an exponential decline in biomass-specific CO_2 respiration and a concomitant sharp increase in microbial CUE. The response follows a non-linear trajectory and approaches a plateau at approximately 1% TOC, suggesting a critical threshold beyond which enhanced microbial CUE promotes sustained TOC accrual rather than respiratory C losses (Clayton et al., 2021). Mechanistically, this threshold behavior may be linked to mineral surface interactions. Zhao et al. (2025b) suggest that mineral surfaces in this reclaimed soil may retain microbial-derived compounds, particularly peptides derived from microbial enzymes. Such mineral–organic matter associations involving compost-derived compounds or products of microbial (compost) transformation may promote the stabilization of C and nutrients, thereby reducing their mobility and potential loss pathways (Turner et al., 2007; Hicks et al., 2021; Mainka et al., 2022).

In marginal reclamation soils, mineral surfaces may immobilize microbial compounds such as extracellular enzymes, potentially increasing microbial investment in resource acquisition and metabolic turnover. This may reduce microbial C and nutrient use efficiencies until increasing organic matter inputs progressively occupy available mineral surfaces. This mechanism could also help explain the higher biomass-specific respiration rates observed in these soils at TOC levels below 1% (Clayton et al., 2021). Reaching this threshold may enhance microbial nutrient-use efficiency, thereby reducing competition with plants for nutrients and improving plant performance, which in turn may increase also the stabilization of root-derived C inputs (Fig. 1C; Ludwig et al., 2005). Consistent with this, the multivariate analysis indicated that high compost application was associated with greater C and nutrient retention and lower losses (Fig. S10).

Furthermore, the observed trend toward a narrower C_{mic}:N_{mic} ratio (Fig. S8) may indicate shifts in microbial biomass stoichiometry that could have contributed to greater nutrient retention (Fig. 3).

In summary, the observed responses largely support Hypothesis II, as high compost application increased C and nutrient retention in the soil–plant-microbial system without corresponding increases in the measured gaseous or leaching losses. In contrast, Hypothesis III was not statistically supported, as increasing mineral P supply did not significantly reduce C or N retention or enhance nutrient loss pathways, although effect-size estimates suggested a tendency toward greater losses at higher P supply.

4.4. Policy implications and limitations

The outlined findings indicate that current compost-application limits may be too restrictive for the restoration of comparable marginal soils. As described above, the marginal soil effectively retained C and nutrients supplied through a single high compost application and co-applied mineral fertilizers. Importantly, this study does not provide a basis for continued high-rate compost applications once soil organic C has reached the level that can be maintained under a given agricultural management system. Over time, repeated high compost applications may lead to the accumulation of nutrients and contaminants beyond the retention, recycling, and degradation capacity of the soil–plant–microbial system.

Municipal organic waste composts may also contain trace metals and organic micropollutants. While compost quality regulations routinely set threshold values for selected heavy metals and physical impurities, monitoring requirements and regulatory standards for emerging contaminants such as PFAS and microplastics remain limited or are not systematically established (Röhler et al., 2021; Steiner et al., 2023). Consequently, compliance with conventional compost quality standards does not necessarily exclude the long-term accumulation of contaminants. Nevertheless, targeted single applications at high rates to marginal soils such as the soil studied here may provide substantial benefits by restoring key soil functions, including production, habitat provision, filtration, buffering, and the storage and regulation of water, nutrients, and C. These potential benefits should, however, be weighed against the risks outlined above, particularly when waste-derived composts are applied at high rates.

Under the current restrictive German regulations on compost application, equilibrium SOM levels in comparable marginal soils may only be reached after several decades (Leal et al., 2025). Although lysimeter experiments cannot capture full field complexity, our results indicate that high compost application rates can accelerate SOM restoration in marginal soil and enhance C and nutrient retention. The transferability and practical implementation of these benefits depend on site-specific conditions, such as initial SOM, soil texture and hydrology, compost characteristics, availability, and transport costs (Diacono and Montemurro, 2010; Wortman et al., 2017).

Nonetheless, for marginal soils, the current German limit of 510 kg total N ha^{-1} over three years (DüV, 2017) may unnecessarily delay SOM restoration and the recovery of key soil functions. Future regulation should therefore distinguish targeted single high-rate compost applications for soil restoration from repeated high-rate applications, while accounting for site-specific TOC targets and cumulative nutrient and contaminant inputs.

5. Conclusions

Current German regulations on compost application rates may constrain the rate of restoring strongly C-depleted marginal reclamation soils toward typical agricultural TOC levels. In the present study, compost application at rates exceeding the German regulatory limit of 510 kg total N ha^{-1} over three years was associated with enhanced C and nutrient retention, without clear increases in measured nutrient losses over the study period. Taken together, these findings support considering targeted single high-rate compost applications as a potential strategy to accelerate SOM restoration in comparable marginal reclamation soils. Practical initiatives (Dunst and Bühler, 2010) further indicate that such high compost applications may also be applicable to other agricultural soils under appropriate soil and site conditions. Further long-term, multi-site studies across different soil types and management systems, coupled with environmental risk monitoring should help define appropriate soil C targets achievable through a single high compost application and provide a basis for revising current regulations.

CRediT authorship contribution statement

Rüdiger Reichel: Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **Zhijie Li:** Writing – review & editing, Investigation. **Xinyue Cao:** Investigation. **Kerui Zhao:** Investigation. **Manuel Endenich:** Resources. **Amit Kumar:** Writing – review & editing, Investigation. **Vicky M. Temperton:** Writing – review & editing, Funding acquisition. **Julien Roy:** Writing – review & editing, Investigation. **Matthias C. Rillig:** Writing – review & editing, Funding acquisition. **Sergey Blagodatsky:** Writing – review & editing, Investigation. **Michael Bonkowski:** Writing – review & editing, Funding acquisition. **Stefanie Schulz:** Investigation. **Michael Schloter:** Writing – review & editing, Funding acquisition. **Thomas Pütz:** Resources. **Nicolas Brüggemann:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT by

OpenAI and DeepL by DeepL SE to correct text, review R code, and support the preparation of Fig. S3 in the appendix. No output was copied directly into the manuscript; the authors critically reviewed and revised all suggestions and take responsibility for the published article.

Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2026.110776.

Data availability

Data will be made available on request.

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