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Short Communication

Biochar and compost amendments to a coarse-textured temperate agricultural soil lead to nutrient leaching

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A B S T R A C T

Organic soil amendments benefit agricultural soils depleted in soil organic matter because they improve soil chemical and biological properties. Biochar and compost, used as organic amendments, differ in their contents of total *vs.* available nutrients and may therefore differ in their effects on soil properties. The effects of these amendments have seldom been assessed in coarse-textured temperate soils and in no-tillage agriculture. In this study, we conducted a 6-month laboratory experiment with a coarse-textured temperate soil with a history of conventional farming to determine the effects of biochar, compost, and their combination, which were spread evenly on the soil surface, on microbial activity and biomass, and nutrient release and leaching. Both biochar and compost increased microbial activity and nutrient release compared to the no-addition treatment, but compost effects were relatively short term (<two months), and biochar effects were relatively long term (>six months). Biochar and compost had additive effects on all properties when added in combination. Biochar addition to soil increased soil pH, microbial biomass, and the abundance of fungi, G^+ bacteria, and actinobacteria after 6 months of incubation compared to the compost treatment and the no-addition treatment. Although biochar was expected to reduce loss of nutrients through leaching, the short exposure time and disturbance of the soil probably hindered its capacity to adsorb nutrients and to thereby limit leaching; as a consequence, the biochar acted only as a slow-release nutrient fertilizer during the 6-month incubation.

1. Introduction

Agricultural systems worldwide are highly dependent upon external nutrient inputs (Gao et al., 2019). Although conventional farming and the use of synthetic fertilizers often result in higher crop productivity (Seufert et al., 2012), sustainable organic farming is being practiced with increased frequency to ensure both crop yield and soil quality (Ramankutty and Rhemtulla, 2012). In addition, organic soil amendments are often spread on the soil surface without additional tillage so as to slow the rate of mineralization and reduce nutrient leaching (Hansen and Djurhuus, 1997; Fraser et al., 2013). The two increasingly used organic soil amendments are biochar (Ye et al., 2016) and compost (Rigby and Cáceres, 2001). Biochar is a carbon (C)-rich, stable, solid material generated by pyrolysis, *i.e.*, thermochemical conversion of organic material in an oxygen-limited environment (Lehmann and Joseph, 2015). Compost is mainly derived from easily degradable animal manure or green waste (Rigby and Cáceres, 2001) and urban wastes such as municipal solid wastes and sewage sludge (Martinez-Blanco et al., 2013). Biochar and compost substantially differ in their contents of total *vs.* available nutrients (Al-Wabel et al., 2018), and thus may have different effects on soil properties. However, their use in no-tillage agriculture has not yet been adequately tested. In addition, much of the current research concerning the effects of organic soil amendments has focused on fine-textured tropical and subtropical soils (*e.g.*, Yamato et al., 2006; Gentile et al., 2009; Agegnehu et al., 2016), whereas the effects on coarse-textured temperate soils remain understudied.

Compost is relatively enriched in available nutrients compared to biochar because most of the available nutrients in biochar are lost during pyrolysis; on the other hand, the recalcitrant forms of nutrients that resist pyrolysis remain in biochar, resulting in a relatively high total nutrient content (Al-Wabel et al., 2018). Recalcitrant forms of nutrients in biochar may be made available during biochar decomposition by soil microorganisms. Because biochar provides sufficient substrates for microbial metabolism as well as a suitable habitat for soil microorganisms (Lehmann et al., 2011; Lehmann and Joseph, 2015), soils amended with biochar often show increases in microbial activity (Steiner et al., 2008; Zhang et al., 2018) as well as microbial biomass (Gul et al., 2015; Liu et al., 2016; Zhang et al., 2018). In addition, nutrients in biochar-

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amended soils are made available by a biochar-induced increase in soil pH (Yamato et al., 2006; Xu et al., 2014), which leads to an increase in microbial biomass and activity (Aciego Pietri and Brookes, 2008; Liu et al., 2016). Thus, although biochar contains more recalcitrant forms of nutrients than compost, the nutrients in biochar may become available over time through the accompanied changes in specific soil properties.

The content of organic matter and nutrients are generally increased by organic amendments (Abujabhah et al., 2016; Agegnehu et al., 2016; Ye et al., 2016). However, the longevity of the effect might change based on the stability of the organic amendment. Although compost provides a greater quantity of available nutrients than biochar (Al-Wabel et al., 2018), the nutrients derived from compost are expected to be released and exploited relatively quickly. On the other hand, biochar is expected to increase available nutrient contents for a longer period of time, because it contains more total nutrients than compost (Al-Wabel et al., 2018). A combination of biochar and compost may thus be an effective alternative to the repeated addition of synthetic fertilizers, *i.e.*, biochar and compost may have additive effects, with compost providing available nutrients during the short term and biochar during the long term.

Available nutrients released from organic amendments might, however, be lost from the soil through leaching. Fine-textured soils are generally better able to retain nutrients than coarse-textured soils (Raave et al., 2014; Liu et al., 2016). Organic soil amendments are, however, expected to improve nutrient retention in soil because they increase the ability of soil to adsorb and retain nutrients (Gentile et al., 2009; Laird et al., 2010). While both biochar and compost release nutrients to the soil, the surface properties of biochar enable retention of nutrients (Liang et al., 2006; Laird et al., 2010). Because nutrient leaching and surface and groundwater contamination have become major concerns throughout the world (Di and Cameron, 2002; Laird et al., 2010), it is important to assess the effects of biochar and compost on nutrient retention in the soil. In this regard, a combination of biochar and compost amendments to soil could reduce nutrient leaching, particularly from soils with a coarse texture under a temperate climate.

In this study, we conducted a 6-month laboratory incubation experiment with a coarse-textured temperate soil with a history of conventional farming to provide deeper insight into the potential impacts of the organic amendments compared to more environmentally affected field studies. Our objective was to determine the effects of biochar, compost, and their combination, when spread evenly on the soil surface, on microbial activity and biomass, and nutrient release and leaching. We tested two hypotheses: 1) compost will support microbial activity and provide available nutrients for a relatively short period, whereas biochar, because it contains more recalcitrant nutrients and supports higher microbial activity and biomass, will support microbial activity and provide available nutrients for a relatively long period; and 2) a combination of biochar and compost will reduce nutrient leaching from soils because of the surface properties of biochar.

2. Materials and methods

2.1. Collection and preparation of soil and substrates

Soil was collected from a field under conventional farming near České Budějovice (Czech Republic; 48.92°N, 14.38°E) in November 2019. Soil was collected from 0 to 10 cm depth at 20 locations in a 0.25-ha area. The collected soil was thoroughly mixed, passed through a 2-mm screen, and stored at 4 °C before being used in the experiment. Biochar and compost were commercially available substrates. Biochar was produced by combustion of maize and wheat straw at 450 °C for 19 min in a no-oxygen atmosphere. Compost was produced from heterogeneous green waste and soil by 4 months of composting in heaps, which were regularly turned around and the temperature inside the heaps was kept ~60 °C. Both substrates were passed through a 5-mm screen and stored in a dry and dark location before use.

The chemical properties of the soil and substrates are listed in Table 1. Organic matter (OM) content was determined based on loss on ignition at 450 °C for 5 h. For determination of the contents of total organic C (TOC), total N (TN), and total P (TP), air-dried samples were ball-milled and analyzed using a Flash Elemental Analyzer (Thermo Scientific) (TOC and TN) or using an ICP-OES (TP). Dissolved organic C (DOC), dissolved N (DN), and dissolved P (DP) were extracted in deionized water (dH_2O) (1:10 sample:dH_2O ratio) and analyzed using a TOC-$L_{CPH/CPN}$ analyzer (Shimadzu) (DOC and DN) and spectrophotometry according to Murphy and Riley (1962) (DP). Sample pH was assessed in a 1:10 sample:dH_2O suspension using a glass electrode. Soil texture was determined based on wet-sieving and sedimentation according to Gee and Bauder (1986). The soil was characterized as loamy sand with particle size distribution of 65 ± 1.3% for sand (2000–63 μm), 26 ± 1.2% for silt (63–2 μm), and 11 ± 0.4% for clay (<2 μm).

2.2. Microcosm experiment

An experiment was conducted using the microcosms allowing respiration measurements and the collection of leachates as described in Jílková et al. (2019). Exactly 90 g of fresh soil was packed into each microcosm chamber to 1.0 g cm^{-3} dry bulk density, resulting in a soil profile height of 3 cm. The microcosm chambers were treated by the addition of (a) 5 g of biochar, (b) 5 g of compost, (c) 2.5 g of biochar +2.5 g of compost (1:1), or (d) no addition; the substrates were spread evenly on the soil surface to mimic no-tillage agriculture. The amount of substrates added resulted in an addition of 20 t ha^{-1}, which is a common application rate for both biochar (Gao and DeLuca, 2020) and compost (Wong et al., 1999). Each treatment had four replicates, giving a total of 16 microcosms. In an additional pot experiment focused on corn (*Zea mays*) we confirmed that seed emergence and crop growth were not affected by a thin layer of organic amendments ($P > 0.05$).

Microcosms were incubated in the laboratory for 6 months (December 2019–June 2020). During the incubation, microcosms were watered with 65 mL of dH_2O every 2 weeks (corresponding to a mean annual precipitation of 676 mm, which is typical for the area), and soil leachates were collected at the bottom of each microcosm. Soil leachates on day 1, 31, 57, and 181 were stored at −20 °C until they were analyzed for DOC, DN, and DP as described earlier. Soil respiration was determined on day 2, 32, 58, and 182, which in each case was 1 day after the microcosms were watered. Gas samples were analyzed within 24 h with an HP 5890 gas chromatograph.

Microcosms were destructively harvested at the end of the experiment (day 182). Because particles of biochar and/or compost were found throughout the whole thin soil layer, the soil was homogenized and then analyzed for OM content and pH as described earlier. The soil was also analyzed for phospholipid fatty acids (PLFA) as described in the next section.

Table 1
Chemical properties of the soil and amendments (biochar and compost). Abbreviations are explained in the text. Values are means ± SEM (n = 3). Different lowercase letters in a column indicate significant differences among means based on one-way ANOVA ($P < 0.05$).

Soil or amendment	OM (g g^{-1})	TOC (mg g^{-1})	TN (mg g^{-1})	TP (mg g^{-1})	DOC (μg g^{-1})	DN (μg g^{-1})	DP (μg g^{-1})	pH
Soil	0.03 ± 0.00 a	12 ± 0 a	1.3 ± 0.1 a	424 ± 3 a	32 ± 3 a	14 ± 0 a	2 ± 0 a	6.8 ± 0.1 a
Biochar	0.69 ± 0.00 c	440 ± 19 c	17.9 ± 0.1 c	6524 ± 67 c	2544 ± 378 b	137 ± 15 b	128 ± 6 b	8.1 ± 0.1 b
Compost	0.24 ± 0.00 b	126 ± 5 b	10.9 ± 0.4 b	2709 ± 131 b	5779 ± 115 c	754 ± 11 c	117 ± 2 b	9.1 ± 0.1 c

2.3. PLFA analysis

Freeze-dried soil (1.0 g) was used for PLFA extraction and analysis to determine microbial biomass and community composition. PLFAs were extracted with a chloroform-methanol-phosphate buffer (1:2:0.8) using a procedure based on that of Bligh and Dyer (1959). Phospholipids were separated using solid-phase extraction cartridges (Supelclean™ LC-Si 500 mg, Sigma), and the samples were subjected to mild alkaline methanolysis. The free methyl esters of phospholipid fatty acids were analyzed using an Agilent 7890B series gas chromatograph coupled to a mass spectrometer.

In total, 20 PLFA compounds were consistently detected above thresholds for accurate quantification. PLFAs were assigned to indicator groups as follows: fungi 18:1ω9, 18:2ω6,9; actinobacteria 10Me-16:0, 10Me-17:0, 10Me-18:0; G^+ bacteria i15:0, a15:0, i16:0, i17:0, a17:0; and G^- bacteria 16:1ω7, 18:1ω7, cy17:0, cy19:0. Microbial biomass C (C_{mic}) was calculated as the sum of all fatty acid esters in nmol multiplied by a conversion factor of 2.4 (Bailey et al., 2002).

2.4. Statistical analysis

The effects of substrate additions on respiration and nutrient contents in leachates during the incubation were tested using repeated measures ANOVAs. The effects of substrate additions on cumulative respiration, on nutrient contents in leachates, and on soil properties at the end of the incubation were tested using one-way ANOVAs. When tests indicated significant differences, Fisher LSD post-hoc tests were used to compare means. Dependent variables were log-transformed to satisfy the assumptions of normality and homoscedasticity if needed. Statistica 13 (StatSoft Inc., USA) was used for statistical analyses.

3. Results and discussion

In agricultural soils, both biochar and compost amendments can be effective in increasing soil OM (SOM) content (Abujabhah et al., 2016; Liu et al., 2016; Al-Wabel et al., 2018). Our results support this statement as the SOM content was lower in the no-addition treatment than in the substrate-addition treatments ($F_{3,12} = 41.5$, $P < 0.001$) (Fig. 1A). However, at the same time biochar was more effective than compost after the 6-month incubation, *i.e.*, biochar increased SOM content by 129% compared to 34% for compost. This might correspond not only to the much larger OM content in biochar than in compost (Table 1), but also to the higher resistance of biochar than compost to microbial decomposition (Gul et al., 2015).

Microbial activity and nutrient contents in leachates during the 6-month incubation significantly changed with the time of incubation among treatments ($F_{9,36} = 18.0$, $P < 0.001$, Fig. 2A for microbial activity; $F_{9,36} = 23.5$, $P < 0.001$, Fig. 2B for DOC; $F_{9,36} = 10.8$, $P < 0.001$, Fig. 2C for DN; $F_{9,36} = 37.9$, $P < 0.001$, Fig. 2D for DP). In agreement with our first hypothesis, compost supported microbial activity and provided available nutrients for a shorter period than biochar. Because compost is more readily available than biochar, its support of microbial activity decreased after day 58. Biochar, on the other hand, increased microbial activity after day 58, and microbial activity was higher with biochar addition than with compost addition at the end of the incubation. A similar trend was found for the quantity of DOC and DP that leached from the microcosms, suggesting that the microbial community decomposed the biochar itself or that the biochar primed the decomposition of native SOM (Zimmermann et al., 2011). Biochar also supported microbial activity for several days or weeks at the beginning of the incubation until its stock of readily available nutrients had been depleted (Fig. 2A). A small fraction of the labile substances in biochar has been previously shown to stimulate microbial activity shortly after biochar application to soil (Cheng et al., 2006; Lehmann et al., 2011; Zimmermann et al., 2011). From the 6-month incubation, we can, however, conclude that cumulative respiration was similar among

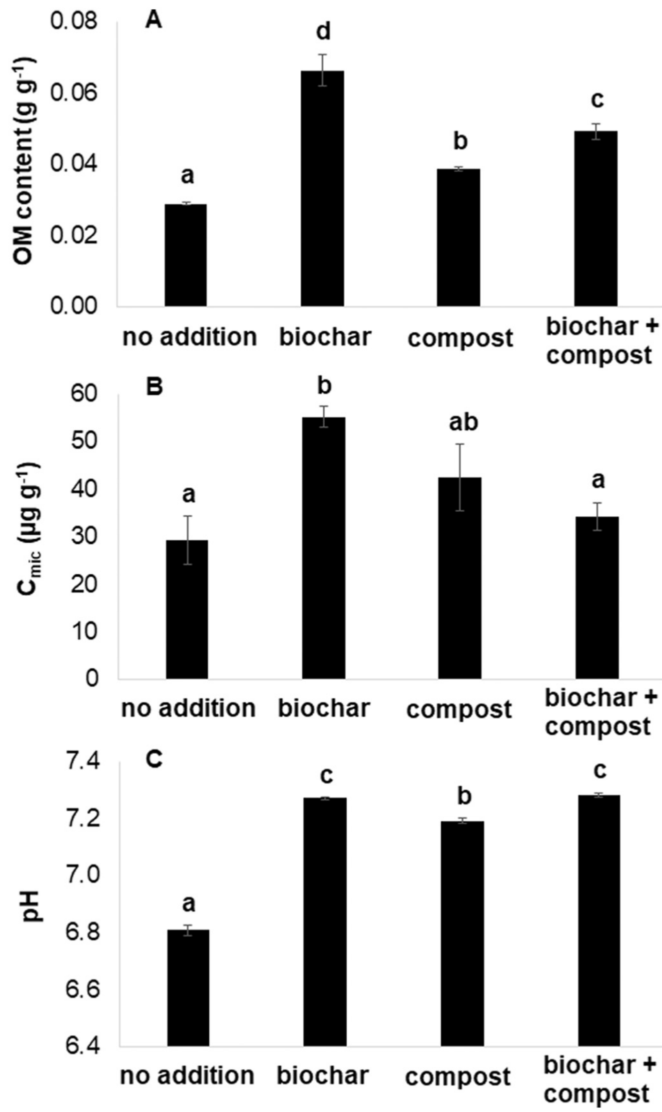

Fig. 1. Content of organic matter (OM) (A), content of microbial biomass C (C_{mic}) (B), and soil pH (C) at the end of incubation as affected by the treatments. Values are means ± SEM (n = 4). Different lowercase letters indicate significant differences among treatments.

substrate-addition treatments and was on average 50% higher in the substrate-addition treatments than in the no-addition treatment ($F_{3,12} = 29.7$, $P < 0.001$) (Fig. 2E), which is similar to the results obtained in other studies with coarse-textured soils (Liu et al., 2016; Wang et al., 2017).

The increasing microbial activity during the incubation in the biochar treatment might have several explanations. First, biochar addition to soil provides not only a metabolic substrate but also a habitat for microorganisms (Lehmann et al., 2011; Lehmann and Joseph, 2015). This effect might be relevant even when biochar was initially not mixed into the soil as biochar particles were observed throughout the whole soil layer at the end of the experiment, which means that biochar particles were partially mixed into the soil during watering events. Second, an introduction of alkaline biochar to acidic or neutral soils causes an increase in soil pH (Gul et al., 2015; Al-Wabel et al., 2018; Gao and DeLuca, 2020), which leads to an increase in microbial biomass and activity (Aciego Pietri and Brookes, 2008; Liu et al., 2016). The effect of biochar on microbial growth is generally most pronounced in soils with neutral pH (Rousk et al., 2010) and coarse texture (Liu et al., 2016). Because the soil in the current study had a nearly neutral pH (6.81 ±

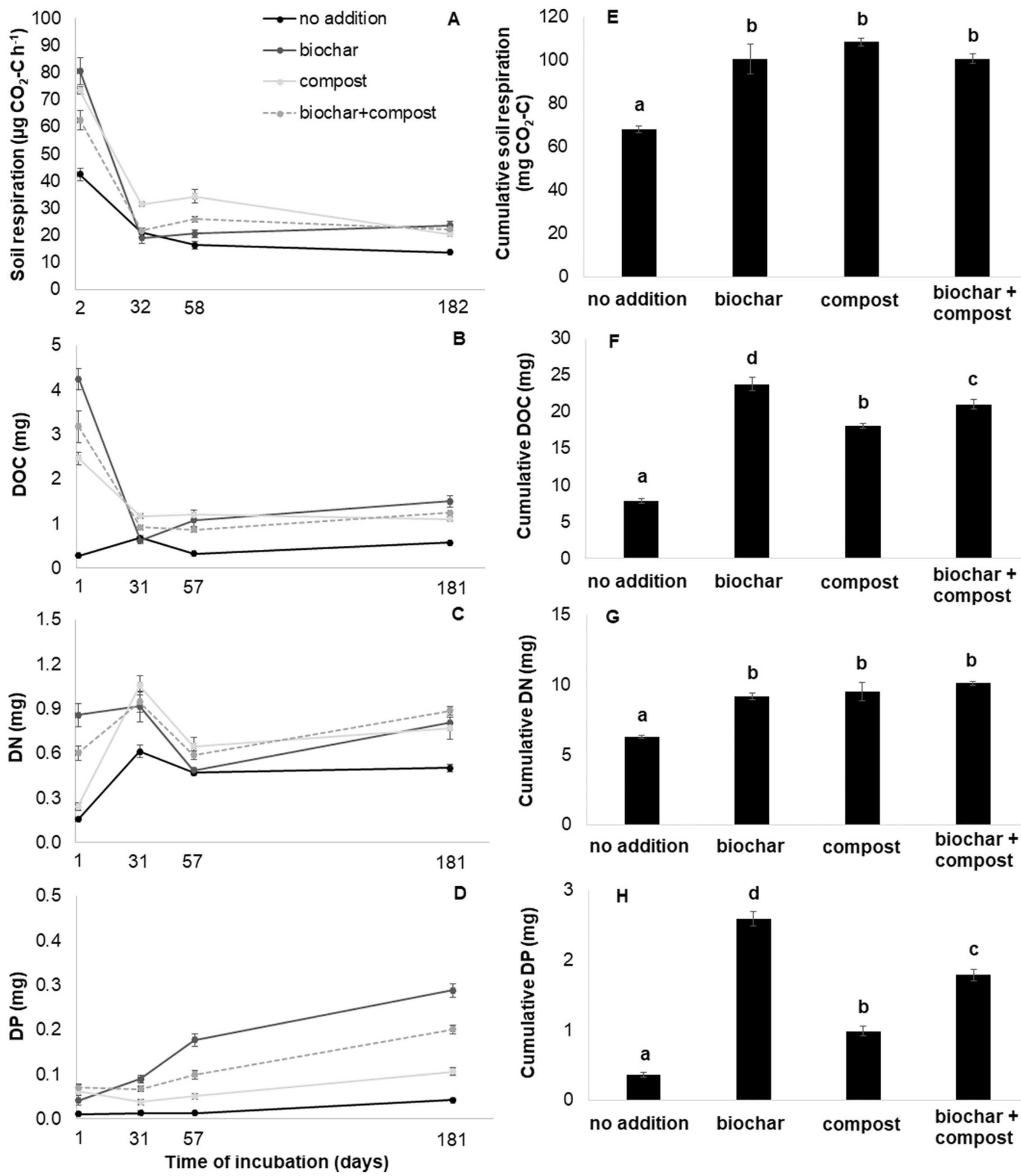

Fig. 2. Soil respiration (A,E) and the contents of dissolved organic C (DOC) (B,F), dissolved N (DN) (C,G), and dissolved P (DP) (D,H) in leachates during the incubation and cumulated at the end of incubation as affected by the treatments. Values are means ± SEM (n = 4). Different lowercase letters indicate significant differences among treatments.

0.02) and a relatively coarse texture (65% sand, 26% silt, and 11% clay), the C_{mic} content in the biochar treatment was 89% higher while that in the compost treatment was only 45% higher than in the no-addition treatment at the end of the incubation ($F_{3,12} = 5.7$, $P < 0.05$) (Fig. 1B).

A previous study indicated that the abundances of both fungi and bacteria were increased in soils amended with biochar and that both microbial groups used the C from the added biochar as a substrate (Luo et al., 2017). The results of the current study are consistent with this previous study because the abundances of fungi ($F_{3,12} = 7.2$, $P < 0.01$) as well as of G^+ bacteria ($F_{3,12} = 5.9$, $P < 0.05$) and actinobacteria ($F_{3,12} = 5.2$, $P < 0.05$) were higher in the biochar treatment than in the no-addition treatment (Fig. 3). The only exception were G^- bacteria, whose abundance was not affected by treatments ($F_{3,12} = 2.7$, $P > 0.05$) (Fig. 3). Fungi, G^+ bacteria, and actinobacteria derive greater benefit

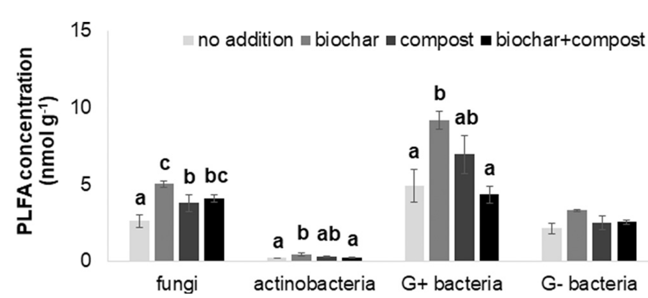

Fig. 3. PLFA concentration of fungi, actinobacteria, G^+ bacteria, and G^- bacteria in soils as affected by the treatments. Values are means ± SEM (n = 4). Different lowercase letters indicate significant differences among treatments.

from biochar than G^- bacteria because biochar commonly lacks easily available substrates, which are essential for the growth of G^- bacteria (Farrell et al., 2013; Zhang et al., 2018), and because biochar only provides less degradable substances that tend to support the growth of fungi (Luo et al., 2017), G^+ bacteria (Farrell et al., 2013), and actinobacteria (Watzinger et al., 2014). The rapid depletion of readily available compounds might also explain the generally lower abundances of fungi, G^+ bacteria, and actinobacteria in the compost treatment than in the biochar treatment and the lack of differences in the abundance of G^- bacteria among treatments. Similarly, the lower abundances of G^+ bacteria and actinobacteria in the biochar + compost treatment than in the biochar treatment (Fig. 3) suggest that the effect of biochar might have been masked by the effect of compost in that readily available compounds from compost might have supported decomposition of more recalcitrant compounds in biochar and their depletion by the end of the incubation.

Changes in microbial activity and soil pH were probably responsible for changes in nutrient release and leaching from the soil. Similar to microbial activity, nutrient leaching was highest immediately after substrate addition to the soil (Fig. 2B,C,D), and early leaching was probably related to the contents of available nutrients in the substrates (Table 1). During the incubation, however, the release of nutrients and their subsequent leaching increased in the biochar treatment, and cumulative nutrient contents leached from the soil were thus highest in this treatment ($F_{3,12} = 192.2$, $P < 0.001$, Fig. 2F for DOC; $F_{3,12} = 187.2$, $P < 0.001$, Fig. 2H for DP). The only exception was the cumulative DN content, which was similar in all three substrate-addition treatments ($F_{3,12} = 28.8$, $P < 0.001$, Fig. 2G). DN leaching in the biochar treatment, however, increased until the end of incubation (Fig. 2C). Soil pH was increased by the addition of biochar ($F_{3,12} = 369.5$, $P < 0.001$) (Fig. 1C), which probably increased nutrient availability through increased microbial activity and solubilization of nutrients (Jones and Oburger, 2011; De Oliveira Mendes et al., 2014). For all of these reasons, biochar is considered to be a slow-release P fertilizer (Sun et al., 2018).

The high level of leaching in the biochar treatment was inconsistent with our second hypothesis as we expected biochar to reduce leaching because its surfaces are known to retain nutrients (Liang et al., 2006; Laird et al., 2010). However, our results are consistent with several reports that biochar increased nutrient leaching through the soil profile (Gao and DeLuca, 2020), especially in disturbed soils (Ross and Hales, 2003); the soil in our experiment was certainly disturbed. The leaching of nutrients also depends on the length of time that biochar is on or in the soil, because biochar is more likely to reach its maximum adsorption capacity over time (Quilliam et al., 2013); perhaps the addition of biochar did not decrease leaching because the biochar in our experiment was in contact with the soil for only 6 months.

4. Conclusion

The results of the current study confirm that two organic soil amendments (*i.e.*, commercially available biochar and compost) applied in a system that mimicked no-tillage agriculture can compensate for the loss of SOM due to agricultural practices and can therefore help improve the chemical and biological properties of coarse-textured soils. Compost and biochar increased microbial activity and nutrient availability for a relatively short period in the case of compost and for a relatively long period in the case of biochar. When added in combination, the two amendments had additive effects on all properties. Improved nutrient availability, however, led to the release of nutrients and leaching. Although particles of biochar and/or compost were found throughout the whole thin soil layer at the end of the current study, biochar originally exposed on the soil surface could not fully adsorb the available nutrients. In addition, the length of exposure apparently hindered its capacity to adsorb nutrients in our experiment. As a consequence, biochar only acted as a slow-release nutrient fertilizer during the 6-month incubation. However, the conclusions of the current study are limited due to laboratory conditions and further studies need to be carried out to verify the outcomes for field conditions including plants able to take up released nutrients.

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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