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Soil application of biochar produced from biomass grown on trace element contaminated land

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ABSTRACT

Trace element (TE) contamination of soils is a worldwide problem. However, although not considered safe anymore for food production without clean-up, many of these soils may still be used to produce biomass for non-food purposes such as biochar. Exploring the suitability of such biochar for the amendment of low-fertility soil, we investigated growth and metal accumulation of ryegrass (*Lolium perenne, var. Calibra*) as well as soil microbial abundance on a non-contaminated soil after amendment with biochar from birch (*Betula pendula*) wood produced on TE contaminated soil in comparison to a treatment with birch wood biochar originating from non-contaminated soil. Biochars were produced from both feedstocks by pyrolysis at two temperatures: 450 and 700 °C. During the pyrolysis, in contrast to Cu, Fe, Mg, K, Mn and P, the elements Cd, Pb, S and Na volatilized. The root biomass of the biochar treated plants was lower than that of the non-amended plants, while that of the shoot was higher. Plant shoot K and Zn concentrations were increased significantly by up to 7- and 3.3-fold respectively. For P, Mg, Mn, Fe and Cu no significant increase in shoot concentration could be detected. Neither the TE-contaminated biochar, nor the non-contaminated biochar had adverse effect on the bacterial community of the soil.

1. Introduction

Amending soils with biochar is attracting increasing scientific attention because of its purported potential to lock away plant-sequestered carbon dioxide and to improve the quality of low-fertility soils. By incorporating biochar into soils, reduced carbon stocks could be replenished and long-term storage of carbon could be increased (Karami et al., 2011). Biochar was found to increase the cation exchange capacity of soil (Rondon et al., 2007), retain soil nutrients for plant uptake (Gaskin et al., 2010) and thereby also prevent nutrient losses with run-off and leaching (Mizuta et al., 2004), increase soil water retention capacity (Karhu et al., 2011), neutralize soil acidity (Novak et al., 2009) and improve microbial soil habitats and functions.

Biochar is not yet produced at a large scale. However, if biochar production should become used on larger scales, feedstock supply may result in similar challenges and problems as bioenergy production. Conversion of agricultural land to non-food biomass production is problematic, because it threatens food security and may lead to increased food prices (Evangelou et al., 2012a). Consequently, it is important to investigate biomass sources that are not competing with food production. An alternative could be the use of land that is not suitable for food production because of contamination, but is not so much contaminated that it requires remediation. Most of the approximately 30 million ha of land that have been contaminated worldwide by human activities with trace elements (TE) are in this category (Evangelou et al., 2012a). Landfilling of such TE-contaminated soil not only results in the loss of otherwise fertile soil, which is a precious natural resource, but is also expensive and consumes scarce disposal sites that are needed for much more hazardous wastes. Also clean-up of such soil is generally not feasible for economic and ecological reasons. Thus, keeping the contamination in place and prevent it from being dispersed into the environment and entering food chains is the only viable treatment option. This is the goal of phytostabilization. However, phytostabilization is economically not attractive if it cannot be combined with a profitable use of the land. Value may come in the form of

Abbreviations: BCL, biomass from contaminated land; TE, trace elements; TF, translocation factor.

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ecological benefits or the production of biomass for uses that are not sensitive to slightly increased TE accumulation. In a previous study for example, Evangelou et al. (2012b) showed that trees may be grown on TE contaminated land for the production of non-food biomass such as timber, biofuels or biochar.

Little is known about the fate of TE in soils that are introduced with biochars. The import of TE with applied biochars is generally not relevant compared to the contamination when biochars are used to immobilize TE in contaminated soils (Beesley et al., 2010; Hartley et al., 2009; Beesley and Marmiroli, 2011). This input may however be important when biochar originating from contaminated feedstock is used to amend uncontaminated soils. In the present study we investigated the suitability for such use of biochar produced biomass from TE contaminated land (BCL). For this purpose we compared the TE accumulation and biomass production of ryegrass (*Lolium perenne*, *var. Calibra*) grown on soil amended with biochar produced from BCL and non-contaminated birch wood at pyrolysis temperatures of 450 °C and 700 °C.

2. Materials and methods

2.1. Soil

The soil used in this study was a loamy sand (77% sand, 13% loam, 10% clay) subsoil collected at 20–40 cm depth, in a mixed deciduous-coniferous forest at Eiken, Switzerland. The soil was dried at 40 °C sieved to <2 mm and was then thoroughly mixed and characterized as followed. Soil texture was determined using the hydrometer method after wet oxidation of the organic matter by means of hydrogen peroxide (FAL, 1996a). Organic matter content was determined using the dichromate method (FAL, 1996b). The carbonate content was measured by volumetric analysis of the CO_2 that evolved after addition of 4 M HCl to the soil. Electrical conductivity was determined according to DIN ISO 11265, and soil pH was measured in 0.01 M $CaCl_2$ (FAL, 1996d). Total soil TE concentrations were determined in quadruplicates by means of X-ray fluorescence spectroscopy (Spectro X-lab 2000, Germany). Soluble soil TE were extracted with 0.1 M $NaNO_3$ (FAL, 1996c). Filtrated extracts were analysed in quadruplicates for Ca, Cd, Cu, Fe, K, Mg, Mn, Na, P, Pb, S and Zn by means of ICP-OES (Varian, Vista-MPX CCS simultaneous). For quality assurance, we analyzed two WEPAL (Wageningen Evaluating Programmes for Analytical Laboratories) referenced soils (Wageningen, Netherlands, no. 989 and 951). Recoveries were >90% for all analyzed elements. Soil properties and total and $NaNO_3$-extractable metal concentrations are given in Table 1.

Table 1
Soil properties and total and $NaNO_3$-extractable metal concentrations (mean ± standard deviation, $n = 4$).

Parameter	Mean ± standard deviation
Texture	
Clay (%)	10 ± 1
Silt (%)	13 ± 1
Sand (%)	77 ± 2
pH ($CaCl_2$)	3.9 ± 0.1
Organic matter content (%)	1.5 ± 0.4
$CaCO_3$ content (%)	0.16 ± 0.05
Max. water holding capacity (%)	40 ± 3
Electrical conductivity (mS m^{-1})	3.8 ± 0.8
$NaNO_3$ extractable TE (mg kg^{-1})	
K	6.5 ± 1.0
Mg	5.2 ± 0.6
Mn	6.0 ± 2.0
Zn	0.16 ± 0.06
Ni	b.q.
Pb	b.q.
Cd	b.q.
Cu	b.q.
Total TE (mg kg^{-1})	
K	13,380 ± 375
Mg	3210 ± 240
Mn	460 ± 20
Zn	38 ± 1
Ni	21 ± 2
Pb	17 ± 1
Cd	0.51 ± 0.38
Cu	8.2 ± 0.6

b.q.: below quantification limit.
Quantification limit for Pb 0.05 mg kg^{-1}, Ni 0.025 mg kg^{-1}, Zn 0.01 mg kg^{-1}, Cd 0.005 mg kg^{-1}.

2.2. Biochar production and characterization

The biochars were produced from birch (*Betula pendula*) wood originating from a TE contaminated site at Auby in Lille, France, and from an uncontaminated site at Dübendorf, Switzerland. The two feedstocks were first chopped into particles of approximately 1 cm^3 size, then placed in a quartz tube and pyrolized for 4 h at either 450 or 700 °C under continuous N_2 gas flow (1 L min^{-1}) in an oven (Montanaro Elektr. Heizungen & Apparate, Glattbrugg, Switzerland) according to the procedure of the international black carbon ring trial (Hammes et al., 2007). The biochars were left to cool down to ambient temperature under N_2 flow. We produced biochars at two temperatures in order to see if the TE recovery is temperature related. The mass loss was 71.3% for biochar produced at 450 °C and 73.3% for biochar produced at 700 °C.

For elemental analysis, a composite sample from each type of biochar was ground using an MM200 Mixer mill (Retsch GmbH, D-Haan). Then 0.1 g subsamples were taken from each of these samples and digested in 2 mL of HNO_3 (65%) and 2 mL of H_2O_2 (30%) for 10 min at 220 °C and 50 bar using a microwave digester (MLS-turboWave). The extracts were diluted to 25 mL with H_2O and analyzed in triplicates for Cd, Cu, Fe, K, Mg, Mn, Na, P, Pb, S and Zn by means of ICP-OES (Varian, Vista-MPX CCS).

2.3. Experimental setup

Biochar was applied to the soil, at an application rate of 16.1 g biochar per kg of soil (roughly equivalent to 20 tons per hectare), and were subsequently incubated for 2 weeks in the laboratory at 21 °C. During these 2 weeks the soil was watered 3 to 4 times a week with deionized H_2O to maintain 25% volumetric soil moisture. After the incubation, the soil was dried at 30 °C and sieved again. Subsequently the soil was distributed among the pots. The treatments were as follows: non-amended soil, with biochar produced at 450 °C (BC450), at 700 °C (BC700), with biochar produced from TE contaminated feedstock at 450 °C (BC450TE) and at 700 °C (BC700TE). Each treatment was performed in four replicates. The pot experiment was conducted in a growth chamber for 5 weeks with a light cycle of 16 h light/8 h darkness, controlled humidity (65%) and temperature (22/15 °C day/night). 400 g of air dried and sieved soil was filled in 450 mL plastic pots with 6 small holes at the bottom. In each pot, five ryegrass (*Lolium perenne*, var. Calibra) were grown. After five weeks of growth all plants were harvested, soil samples were taken and soluble soil TE were determined by 0.1 M $NaNO_3$ extraction.

2.4. Plant harvest, biomass and analysis

All plants were harvested after five weeks of growth, washed with deionized water, separated into shoots and roots and dried at