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Research paper

Long-term presence of charcoal increases maize yield in Belgium due to increased soil water availability

Bart Kerré*, Bernd Willaert, Yannah Cornelis, Erik Smolders

Division of Soil and Water Management, KU Leuven, Kasteelpark Arenberg 20, 3001, Heverlee, Belgium

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ABSTRACT

The short-term benefits of biochar application on crop yield await confirmation with long-term effects when initial liming or nutritional benefits are attenuated. In this study, we determined the above-ground silage maize yield in soils under historical charcoal kilns (black spots, > 150 years enrichment) and adjacent soils in southern Belgium in three consecutive years (2014–2016). Maize yield in these well fertilized arable soils was, on average, 23% higher ($P < 0.05$) in black spots than in the adjacent soils and the charcoal-C concentration was, on average, 2.2 g 100 g^{-1} soil (63% of total SOC) in the black spots. The factor yield increase decreased with average rainfall during the growing season ($P < 0.05$). Water retention curves of both soil types revealed 11% higher ($P < 0.05$) available water content, determined between pF 1.8 and pF 4.2, in soils under black spots. The $\delta^{13}C$ analysis of maize leaves at final harvest determined in one season indicated lower water stress for plants grown on black spots. Nutrient concentrations in maize leaves were unaffected by charcoal even though significant positive effects of charcoal on soil CEC and concentrations of available Ca and Mg were detected. This study shows, for the first time, that historical charcoal amendment can increase maize yield in fertile, temperate soils considerably. These effects are most likely related to soil physical effects, rather than to nutritional effects.

1. Introduction

Adding biochar to soil is frequently considered as a strategy for soil carbon (C) sequestration while improving soil properties and soil fertility. The discovery of charcoal-rich tropical soils (*terra preta*), displaying surprisingly high organic carbon (OC) and nutrient levels, has boosted the scientific interest in using charred biomass as a soil amendment (Glaser et al., 2002). Positive effects of biochar on soil quality are generally attributed to its capacity to enhance nutrient availability, increase pH and improve water holding capacity of the soil (Liang et al., 2006; Major et al., 2010; Jeffery et al., 2011; Liu et al., 2012). Higher nutrient availability due to biochar can result from the mere addition of nutrients and from the increase in cation exchange capacity (CEC) of the soil (Glaser et al., 2002). The combination of biochar ageing (i.e. surface oxidation over time) and its high intrinsic specific surface area can increase the negative charge density and, hence, the CEC of the soil (Liang et al., 2006; Cheng et al., 2014). An increase in soil pH the first months following biochar addition results from the concurrent addition of ashes containing alkaline oxides of K, Ca and Mg that will (temporarily) lime the soil (Glaser et al., 2002). The water holding capacity of a soil can improve as a result of increased soil aggregation and soil porosity following biochar addition (Lorenz and Lal, 2014; Omondi et al., 2016).

Improved soil fertility has concurrent impact on crop yields. Recent meta-analyses showed that positive effects on crop yield following biochar addition are most pronounced in tropical soils (Jeffery et al., 2011; Liu et al., 2013). Tropical soils are highly weathered, i.e. having low soil pH and low OC content. The capacity of biochar to change CEC, pH and water retention is, therefore, high in these soils. In a Colombian oxisol, Major et al. (2010) found higher maize yield up to several years after biochar amendment, related to soil pH increase and higher nutrient availability. In Kenya, biochar addition doubled maize yield, however, this could not be fully explained by above-mentioned biochar properties (Kimetu et al., 2008). Biochar increased maize and peanut production in Indonesia, related to increase in soil pH and nutrient availability (Yamato et al., 2006). A higher soil pH will not only affect nutrient availability, but additionally can reduce Al toxicity to crops in highly weathered soils (Lorenz and Lal, 2014). Studies dealing with the effect of biochar in temperate soils are much more scarce. Borchard et al. (2014b) found no effect on maize yield over a three year period when biochar was applied to soils from Germany. In addition, only marginal changes in soil pH and nutrient concentrations were observed. Glaser et al. (2015) found increased maize yield and nutrient uptake when biochar was applied in addition to fertilizer. Another study

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* Corresponding author.
E-mail address: bart.kerre@kuleuven.be (B. Kerré).

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reported a positive effect on grass biomass the third year after biochar application in a field trial in Wales, along with a slight pH effect (Jones et al., 2012).

The above-mentioned studies are based on observations over a period of maximally a few years. Taking into account biochar's well-known persistency in soil, long-term studies with aged biochar are of primary importance to justify its use (Jeffery et al., 2011; Borchard et al., 2014b; Hardy et al., 2016a). The effect of biochar on soil liming may attenuate with time due to depletion of the alkaline metal oxides originally present in the ashes, and due to biochar ageing creating carboxylic functional groups. Similarly, other plant nutrients may be depleted after a certain time, despite an ongoing increase in CEC (Cheng et al., 2006; Jones et al., 2012; Hardy et al., 2016a). Long-term (> 10 years) biochar studies are scarce due to evident practical constraints. The soils under former charcoal kilns are of particular interest to assess the long-term effect of biochar on soil characteristics and plant response (Oguntunde et al., 2008; Borchard et al., 2014a; Criscuoli et al., 2016; Hardy et al., 2016a; Hardy et al., 2016b). Charcoal was produced in several areas, mainly for melting (in Europe) and cooking purposes (in Africa and Central Amazonia). These soils are highly enriched in charcoal and can contain up to 70 ton charcoal-C per hectare (Borchard et al., 2014a).

The aim of this study was to investigate the effect of aged biochar on maize yield in temperate agricultural soils, in relation to biochar-induced changes in soil properties. Therefore, we selected a number of abandoned charcoal kilns in southern Belgium, being in use during 18th-19th century. Those kilns can nowadays be identified as black spots (ca. 10 m diameter) on bare soil due to the presence of charcoal residues (Hernandez-Soriano et al., 2016; Kerré et al., 2016). Comparison of soil parameters of interest between such black spots and corresponding adjacent soils, located on the same field, allows investigating effects that are solely related to charcoal presence. Maize yield was estimated in black spots and adjacent soils in three consecutive years (2014–2016) and relevant soil characteristics were determined. We hypothesized that charcoal effects on yield, if any, are related to soil physical and/or nutritional effects. The selected arable fields are well-managed (fertilization, tillage,…) and are located in a fertile area ideally suited for agriculture with average silage maize yields of more than 15 ton d.m. ha^{-1}.

2. Materials and methods

2.1. Study area

The former charcoal kilns are located in southern Belgium (Wallonia), in the province of Hainaut. Those kilns served for charcoal production for steel-making and smelting until 1860, as comprehensively described elsewhere (Hardy et al., 2016a). Those kilns can nowadays be identified as black spots (ca. 10–20 m diameter) on bare soil due to the presence of charcoal relics (Hernandez-Soriano et al., 2016; Kerré et al., 2016). For the current study, we selected multiple pairs of sites, i.e. black spots and corresponding adjacent soils, distributed over four different arable fields. Each pair of soil type (black spot and corresponding adjacent soil) is located in close proximity on the same field. The average charcoal-C concentration in the black spots was 2.2 g 100 g^{-1} soil, whereas the average charcoal-C concentration of the adjacent soils was 0.8 g 100 g^{-1}, as determined by Differential Scanning Calorimetry (DSC) (Kerré et al., 2016).

2.2. Soil sampling and chemical analysis

In January 2014, composite soil samples (8 subsamples, 0–23 cm) were taken from those sites, as described in detail elsewhere (Kerré et al., 2016): for the black spots, the subsamples were taken over the entire extent of the spot, whereas for the adjacent soil, the subsamples were taken identically next to the black spot. Soil samples were air-dried, sieved (< 2 mm) and stored until analyses. Soil texture (sand/silt/clay) was determined by laser diffraction particle size (Beckman Coulter LS13 320). Soil pH was measured in 0.01 M $CaCl_2$ with a 1:5 soil:solution ratio. Cation exchange capacity (CEC) was measured using a hexaminecobalt solution as extractant (ISO 23470:2007). Organic C (%OC) was determined with a Flash EA 1112 HT after grinding the soil to a powder with a ball mill and acidifying with HCl. Total soil element (metals and phosphorus (P)) concentrations were measured with Inductively Coupled Plasma Mass Spectrometry (ICP-MS, Agilent 7700x, Agilent Technologies) after soil digestion with *Aqua Regia*. Nitrate (NO_3-N) was determined colorimetrically using a Skalar autoanalyzer after soil extraction with 1 M KCl in a 1:10 soil:solution ratio. Available Ca, Mg, K and P were extracted with ammonium lactate 0.1 M/acetic acid 0.4 M solution at pH 3.75 with a 1:20 soil:solution mass ratio, and measured by ICP optical emission spectroscopy (ICP-OES, Thermo Scientific, ICAP 7000 series).

2.3. Water retention curve (pF curve)

In March 2016, undisturbed soil samples (Kopecky rings, 100 cm^3) were taken from four black spots and four corresponding adjacent soils at one field, with 3 replicates per site (i.e. 24 rings). The field was at that time used as a pasture, however it is normally used for maize cultivation. Grass biomass was carefully removed before soil sampling. In the laboratory, the soil samples were saturated with water, covered at the top and placed in a water-saturated sand bath. Over a period of six weeks, different suction pressures were applied (pF 0, 0.5, 1, 1.5, 1.8 and 2) and the soil cores were weighted after reaching equilibrium. Afterwards, the soil samples were placed in a pressure membrane apparatus to apply suction pressures pF 2.3, 2.8, 3.4 and 4.2. In this study, available water content (AWC) for the crops is defined as the difference in soil water content between field capacity (pF 1.8, i.e. ca. −6 kPa soil water potential) and the permanent wilting point (pF 4.2, i.e. ca. −1500 kPa soil water potential).

2.4. Maize sampling and analysis

Maize (*Zea mays* L.) biomass was sampled in three consecutive years (2014–2016), close to harvest (end of September). All aboveground biomass, except the bottom 10 cm of the stalk, of 20 randomly selected maize plants was harvested on each site. For the black spots, the 20 plants were picked over the entire extent of the black spot. For the adjacent sites, the 20 plants were picked in the same way over an area of equal extent next to the corresponding black spot.

In 2014, maize biomass was determined at six pairs of sites, i.e. three different fields with, on each field, two black spots and two corresponding adjacent soils. The wet weight was recorded on each site and subsamples consisting of two whole maize plants per site were taken to determine the dry weight (oven-drying at 70 °C for about 48 h). In 2015 and 2016, maize biomass sampling was limited to one field but with four pairs of sites: two black spots and two corresponding adjacent soils that were identical as in 2014, and an additional two black spots and two corresponding adjacent soils. In those years, only two sets of subsamples were taken: eight whole maize plants per soil type (black spot or adjacent soil), collected from the different sites. All plant dry yield were converted to area based yield (ton ha^{-1}) taking into account the plant density which did not vary over years and fields.

The dried maize leaves from the harvest of 2014 were homogenized by grinding and plant nutrient (all 13 mineral nutrients except N and Cl) concentrations were measured with ICP-MS after plant digestion with HNO_3. Additionally, the%C, %N and δ^{13}C of the leaf samples were determined with a Flash EA 1112 HT coupled to a Delta-V Advantage isotope ratio mass spectrometry (IRMS). Differences in δ^{13}C of plant samples reflect differences in water use efficiency and, hence, can be used to detect water stress during growth (Dercon et al., 2006). Additionally, the factor maize yield increase, i.e. the yield increase