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Soil amendment with biochar increases the competitive ability of legumes via increased potassium availability

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ABSTRACT

Soil amendment with biochar is currently proposed as a management strategy to improve soil quality and enhance plant productivity. Relatively little is known about how biochar affects plant competition, although it has been suggested that it can increase the competitive ability of legumes. This study tested the impact of a biochar on the competitive ability of legumes through alterations to soil pH and/or nutrient availability. Biochar was produced from aboveground plant biomass from a species-rich semi-natural grassland pyrolysed at 400 °C. In a greenhouse experiment, a legume (red clover, *Trifolium pratense* L.); a grass (red fescue, *Festuca rubra* L.); and a forb (plantain, *Plantago lanceolata* L.) were grown in (1) monocultures, (2) in a mixed culture of red fescue and red clover, and (3) in a mixture of all three species. Soil treatments included fertilisation with nitrogen (N), potassium (K), phosphorus (P), or micronutrient fertiliser in the presence or absence of biochar; a pH-adjusted control soil; and a control (i.e. with no amendment). The competitive ability of red clover was quantified as the proportion of aboveground biomass of this species within the mixtures. Both biochar amendment and K fertilisation significantly ($P < 0.001$) increased red clover biomass, and increased the competitive ability of red clover when grown with red fescue and plantain. Application of N fertiliser, irrespective of biochar amendment, resulted in significantly ($P < 0.001$) greater red fescue and plantain biomass and eliminated the competitive advantage of red clover. The biochar-mediated pH increase did not affect red clover biomass or its competitive ability. We conclude that biochar has a beneficial effect on red clover under N limiting conditions due to an increase in K availability. Our results suggest a potential role for biochar to maintain the proportion of forage legumes in agricultural pastures or semi-natural grasslands.

1. Introduction

Biochar is generally defined as biomass which is carbonised through heating in a low to zero oxygen environment and which is produced with the intention of application to soil (Lehmann and Joseph, 2009; Verheijen et al., 2010; Sohi, 2012; Jeffery et al., 2013). Biochar has been promoted as improving soil quality and fertility. Application of biochar may increase crop production through several proposed mechanisms: providing a liming effect (Jeffery et al., 2011), increasing soil water-holding capacity (Karhu et al., 2011), enhancing water and nutrient uptake (Hunt et al., 2010) and delaying or reducing N leaching (Lehmann et al., 2003).

Next to recalcitrant carbon, macro and micro nutrients are the main components of most biochars (Lehmann et al., 2011), although, the amount and availability of nutrients varies based on the feedstock and pyrolysis conditions used. By providing additional nutrients to the soil, and consequently influencing plant nutrient uptake, biochar application may alter the competitive ability of particular plant species. In particular, leguminous species have been shown to benefit from biochar amendment (Rondon et al., 2007). For example, the addition of biochar, identical to the one used in the present study, to a species-rich grassland in the Netherlands resulted in a nearly threefold increase in the proportion and biomass of legumes (mainly red clover, *Trifolium pratense*) after one growing season (van de Voorde et al., in press).

Several mechanisms have been proposed to explain the enhanced competitive ability of legumes in the presence of biochar (Lehmann and Rondon, 2006). For example, N immobilisation by

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the microbial community has been found after charcoal addition to a Ferralsol (Lehmann et al., 2003). Besides a reduction in available N, biochar-mediated increases in soil pH (Jeffery et al., 2011) could benefit legumes by stimulating biological nitrogen fixation (BNF) (Rondon et al., 2007) and thereby enhancing the competitive ability of leguminous plants, particularly under N limiting conditions. Biochar addition may also increase the content of soil P, K, magnesium (Mg) and other nutrients, which in turn may also increase BNF (Rondon et al., 2007). It has been shown that, under K-limiting conditions, legume nodulation can be suppressed (Sangakkara et al., 1996). Since grasses have a greater root mass density, they are effective competitors for K; potentially causing the proportion of legumes in a grass-legume mixed culture to decrease under K-limiting conditions (Mengel and Kirkby, 2001).

While these mechanisms have all been observed or proposed in separate studies, a coherent assessment of them within a single experiment is currently lacking. We hypothesised that the competitive advantage of legumes grown in sandy soils amended with carbonised material produced from a mixture of grassland species occurs due to (1) increased macronutrient availability from the biochar, (2) increased micronutrient availability from the biochar, and (3) a biochar-induced pH increase in the soil. We tested the hypothesised mechanisms for mixed and monocultures of red clover (*T. pratense* L.), red fescue (*Festuca rubra* L.) and plantain (*Plantago lanceolata* L.) simultaneously in a greenhouse pot experiment.

2. Materials and methods

To test our hypotheses, we conducted a greenhouse pot experiment, composed of two sub-experiments. In Sub-experiment I we tested whether the performance of red clover, red fescue and plantain (in monocultures and a mixed culture of red clover + red fescue) was due to a pH or a nutrient effect. In Sub-experiment II, we tested the effects of micronutrients, as well as specific macronutrients, on the competitive ability of red clover in a three-species mixture (red clover + red fescue + plantain). The experiment was set up in a randomised block design and the sub-experiments were conducted simultaneously.

2.1. Soil and biochar characteristics

Soil was collected from a species-rich grassland, near Ede, the Netherlands (latitude +52°3′34.03″, longitude +5°45′2.81″). This area is of glacial origin (Saalien ice age). The soil is classified as a Podzol (FAO, 2007), with a coarse sand cover; the top 20 cm, the A horizon, texturally consist of 93.9% sand, 5.3% silt, and 3.4% clay, with an organic C content of 2.8%, which is described in detail in van der Putten et al. (2000) and see details, “Field 12” in van de Voorde et al. (2011). Soil was collected during Spring 2012 from the top 20 cm of the soil profile, air dried for 6 days (d), sieved to 8 mm and mixed. Biochar was produced from aboveground plant biomass collected from the same species-rich semi-natural grassland (van de Voorde et al., in press). The grassland was dominated (>65%) by *Lolium perenne*, *Bromus hordeaceus*, *Jacobaea vulgaris*, and *Holcus lanatus* (van de Voorde et al., 2011). As in van de Voorde et al. (in press), the natural grassland was mown in October 2010, and the dried cuttings were pyrolysed for 5 min at 400 °C at Biogreen, ETIA, France using a Biogreen 130 pyrolyser with a continuous flow of 10 kg per hour. Mineral N, available K and P–PO_4 in biochar were photometrically determined in a 1:10 (w/v) 0.01 M $CaCl_2$ extract (Houba et al.), and were found to be: 0.8 mg kg^{-1} (SE 0.03), 1620.8 mg kg^{-1} (SE 24.4) and 1.9 mg kg^{-1}(SE 0.02), respectively (van de Voorde et al., in press). Selected biochar characteristics are presented in Table 1. A pyrolysis GC/MS characterisation revealed that this biochar was devoid of fingerprints for labile C (e.g., levoglucosan; data not shown).

Table 1
Chemical characteristics of the biochar used in the present study. Biochar was produced at 400 °C through slow pyrolysis from combined various grassland species.

	Mean ± SE
Volatile matter content[a]	32.10 ± 1.89%
Ash[a]	25.22 ± 5.01%
N[b]	1.91 ± 0.09%
C[b]	59.02 ± 0.78%
H[b]	3.81 ± 0.06%
S	0.00 ± 0.0%
Atomic H/C	0.77 ± 0.03
pH[c]	7.41 ± 0.01
$CaCO_3$ equivalent value	8.68%

[a] Ash and volatile organic matter content were determined according to ASTM D 1762-84 (2007).
[b] Carbon (C), hydrogen (H) and nitrogen (N) were determined using a Thermo Scientific FLASH 2000 Organic Elemental Analyzer.
[c] pH was measured in a 1:10 (w/v) biochar:water suspension using a pHM 92 meter (Radiometer Copenhagen, DK).

2.2. Experimental setup

Sub-experiment I consisted of five soil treatments: a control treatment (C) with no amendment, a biochar amendment treatment (B) to test the effect of biochar addition on plant growth, and 3 additional treatments to test the effects of macronutrients and of pH (Hypotheses 1 + 3): a pH treatment (liming: L), fertilisation with macronutrients (F), and biochar and macronutrients (F + B). It included four plant treatments: red clover, red fescue, plantain monocultures and a red clover + red fescue mixture.

Sub-experiment II included the same soil treatments as Sub-experiment I. Seven additional soil treatments tested the effect of specific nutrients on plant growth: addition of N (N), P (P), K (K), or micronutrient fertiliser (Mic), as well as those treatments in combination with biochar (N + B, P + B, Mic + B respectively). Sub-experiment II consisted of only one plant treatment: a mixture of all three species.

Application rates were: Biochar (10 t ha^{-1}), lime (43 kg $CaMg(CO_3)_2$ ha^{-1}), N (calcium ammonium nitrate (CAN) 50 kg N ha^{-1}), P (triple super phosphate (TSP) 30 kg P ha^{-1}), K (patentkali, 50 kg K ha^{-1}), micronutrients (applied in a solution consisting of H_3BO_3 (794 g B ha^{-1}), $MnSO_4$ (803 g Mn ha^{-1}), $CuSO_4$ (32 g Cu ha^{-1}), $ZnSO_4$ (80 g Zn ha^{-1}), and $(NH_4)_6Mo_7O_{24}$ (17 g Mo ha^{-1})). The rate of lime that was needed to increase the soil pH to the same level as was induced by addition of 10 t ha^{-1} of biochar, was determined using a soil titration with $CaMg(CO_3)_2$ in a pilot experiment.

For both sub-experiments, Mitscherlich pots (diameter 19 cm, height: 22 cm) were filled with 7.0 kg dry weight (dw) equivalent of soil. Each pot contained three layers of soil (expressed in kg dw): a bottom layer of 4.5 kg untreated soil, a middle layer of 1.5 kg to which the treatments were applied, and an untreated top layer of 1.0 kg of soil. The upper two layers made up the top 10 cm of the pot. Fertilisers were added only to the middle layer to prevent seedling damage. Biochar or lime were added to the two uppermost layers of soil. The monoculture pots were sown on day 0 with 1.50 g red clover, 3.00 g red fescue or 0.75 g plantain. The two species mixed culture received 0.75 g red clover and 1.50 g red fescue, and the three species mixture 0.50 g red clover, 1.00 g red fescue, and 0.25 g plantain. Seeds were ordered from a commercial organic seed supplier (De Bolderik, Wervershoof, the Netherlands). Under these conditions, an application rate of 10 t ha^{-1} biochar corresponds with 12.6 g kg $soil^{-1}$.