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Crop-season and residual effects of sequentially applied mineral enhanced biochar and N fertiliser on crop yield, soil chemistry and microbial communities

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ABSTRACT

The use of biochar in agricultural soils has received increasing attention over the last decade and enhancing biochar through chemical modification offers a strategy to reduce the amount of biochar required for improving soil productivity. However there is limited knowledge on how mineral enhanced biochars alone, or in combination with conventional fertilisers impact on microbial processes and edaphic parameters of soil or the root, and how this influences agricultural yield in the long-term. To investigate this we assessed crop yield, edaphic parameters and microbial communities within the bulk soil and on roots at the end of the third crop-cycle from a long-term agricultural trial where pre-existing enhanced biochar applications (from previous crop-cycles) totalled between 0 and 5.5 t ha^{-1} and were then supplemented with fresh enhanced biochar (0.1 t ha^{-1}) and traditional N fertiliser (50 kg ha^{-1}) in a crossed design. We found an array of effects associated with existing and new enhanced biochar applications in conjunction with N fertiliser on plant yield, soil nutrients and microbial communities. Yield decreased up to 27% with any soil amendment and was greatest in the unamended control. Soil nitrate increased from 30.4 to 59.6 mg kg^{-1} due to N fertiliser with little effect of the enhanced biochar. Soil pH increased from 4.59 to 4.86 due to previously applied enhanced biochar and was associated with applications of at least 1 t ha^{-1}. There were differing responses in the microbial communities between bulk soil (294 taxa changes) and roots (383 taxa changes) to the fertilisation regimes, which were unrelated to the nitrate content in the soil and appeared to be driven by pH changes, especially for communities associated with plant roots. This has important implications on which soil compartments should be investigated in future studies of microbial communities. The short- and long-term effects of enhanced biochar observed here question the relevance of studies examining once-off applications of biochar and their extrapolation to real world scenarios i.e. where sequential application of biochar might occur. It is likely that responses of agricultural systems may depend on the historical use of biochar.

1. Introduction

Biochar is a carbon-rich material made from the pyrolysis of organic matter that can act as a soil conditioner (Atkinson et al., 2010; Sohi et al., 2010). The use of biochar in agricultural soils has received increased attention over the last decade in response to the need for better and more sustainable soil management (Zhang et al., 2016). The conditioning properties of biochar are thought to result in improved soil fertility, while addressing detrimental effects from conventional fertilisation practices, such as the loss of organic carbon (C) and increased acidification (Atkinson et al., 2010; Sohi et al., 2010).

Biochar can have a stable C content with a residence time in soil of up to several hundred years (Fang et al., 2015), which depends on soil type, soil temperature and biochar pyrolysis temperature (Van Zwieten et al., 2010; Kloss et al., 2012; Grunwald et al., 2017). Biochar can also cause short-term positive priming, but long-term negative priming of soil organic C (Weng et al., 2015). This has been shown to arise from decadal scale stabilisation of rhizodeposits and lower soil respiration

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(Weng et al., 2017). Indeed, a recent meta-analysis has confirmed that biochar, while generally increasing soil microbial biomass, results in lower respiration and a lower metabolic quotient (qCO_2) (Zhou et al., 2017).

While most biochar studies have focused on application doses in the range of 5 and 50 t ha^{-1}, where positive effects are often observed (Jeffery et al., 2011; Liu et al., 2013), these rates of application may not be suitable for some farming systems due to the cost of biochar production and delivery (Clare et al., 2015). A more recent strategy for biochar adoption has been the blending of biochars with conventional fertilisers to generate low-cost, high-efficiency fertiliser products. The role of biochar here is 1) to improve soil conditions (e.g. through addressing constraints, such as soil acidity, Macdonald et al., 2014; Van Zwieten et al., 2015) hence resulting in greater crop production and greater opportunity to uptake the applied fertiliser (Zheng et al., 2017); 2) to act on soil properties that may result in improved fertiliser retention, such as cation exchange capacity (Atkinson et al., 2010), resulting in lower fertiliser leaching (Singh et al., 2014), 3) to act directly on the fertiliser itself through chemical and physical processes to increase fertiliser use efficiency (Yao et al., 2015). Enhancing biochar through chemical modification offers another strategy to reduce the amount of biochar required for improvement of agricultural soils (Joseph et al., 2013; Mandal et al., 2016). Enhanced biochar are produced by adding minerals, such as clay or basalts, and nutrients (such a manure) to a biochar and then torrefying the blend to create complex organo-mineral phases on the sub-micro scale (Joseph et al., 2013; Ye et al., 2017). These enhanced biochars have been shown to increase redox activity that could stimulate beneficial microbial activities in the soil (Sun et al., 2017; Ye et al., 2017). Indeed, small applications of these mineral enhanced biochars (1–5 t ha^{-1}) have been shown to produce the same agricultural yields as chemical fertilisers, while creating shifts in the composition of the soil's microbial community (Nielsen et al., 2014).

Soil microorganisms are influenced by fertilisation practices (Traoré et al., 2016) and have direct impacts onto agricultural systems through nutrient conversion and cycling as well as interactions with plants (Böhme et al., 2005). These processes include, for example, bacterial nitrification and denitrification that determine the balance of ammonium and nitrate in the soil (Geisseler and Scow, 2014), as well as the provision of plant-growth promoting factors by rhizobacteria (Geisseler and Scow, 2014), which together influence the growth performance of plants. Most plant-microbe interactions occur on or close to the root, where exudates and microbial products are transferred, and this creates distinct microbial communities compared with parts of the soil lacking root systems (Baudoin et al., 2003; Sohi et al., 2010). However there is limited knowledge on how biochar and conventional fertilisers in combination impact onto microbial processes and edaphic parameters of the soil or on the root (Kolton et al., 2011), and how this influences agricultural yield in the longer term. Further, the effects of sequential application of biochar through crop seasons are unclear.

As part of on-going agricultural field trials examining the performance of mineral enhanced biochars across a number of corn and barley crop cycles, we examined crop yield, edaphic parameters and microbial communities within the bulk soil and those associated with plant roots. At the third crop cycle investigated here, agricultural plots with pre-existing enhanced biochar applications totalling between 0 and 5.44 t ha^{-1} were supplemented with fresh enhanced biochar (0.1 t ha^{-1}) and traditional N fertiliser (50 kg ha^{-1}) in a crossed design and with an unamended control. This design allowed us in this study to investigate the residual effects of biochar and the interaction with current fertilisation regimes, and more specifically, whether small quantities of fertiliser and enhanced biochar in addition to previous large biochar applications have observable effects on soil properties and agricultural yields.

Table 1
Chemical and physical properties of the enhanced biochar used in this study.

Variable	Limit of detection	Enhanced biochar
EC (Ds/m)	0.01	2.8
pH ($CaCl_2$)	0.04	6.8
Bray Phosphorus (mg/kg)	0.06	2300
Colwell Phosphorus (mg/kg)	2	2900
Total Nitrogen (%)	0.02	0.84
Total Carbon (%)	0.20	42
KCl extractable Ammonium-N (mg/kg)	0.3	660
KCl extractable Nitrate-N (mg/kg)	0.2	0.55
ANC (% $CaCO_3$)	0.5	14
Aluminium (%)	0.0005	0.21
Arsenic (mg/kg)	5	< 5
Boron (mg/kg)	4	15
Calcium (%)	0.0003	6.8
Cadmium (mg/kg)	0.2	< 0.2
Cobalt (mg/kg)	0.4	5.4
Chromium (mg/kg)	0.2	10
Copper (mg/kg)	0.2	30
Iron (%)	0.00003	0.7
Potassium (%)	0.0004	0.47
Magnesium (%)	0.00006	1.4
Manganese (mg/kg)	0.1	2100
Molybdenum (mg/kg)	0.3	2.4
Sodium (%)	0.0005	0.18
Nickel (mg/kg)	0.7	6.4
Phosphorus (%)	0.0003	2.6
Lead (mg/kg)	2	4.5
Sulfur (%)	0.0006	0.46
Selenium (mg/kg)	4	< 4
Zinc (mg/kg)	0.8	130

2. Methods

2.1. Experimental setup

A field trial examining the effect of biochar and N fertiliser over successive crops of barley and corn was conducted in Wollongbar, NSW, Australia, beginning in late 2010, and in this study we examine the field trial at a single time point and at the end of the third crop cycle. The experimental area is located in a subtropical zone and the soil is characterised as a highly permeable rhodic Ferralsol. The field site consisted of 30 plots (25 × 3 m) arranged in a randomised complete block design (blocks = 3). A range of biochar (0 to 5 t ha^{-1}) and N fertiliser (0 to 100 kg ha^{-1}) amounts were previously applied depending on crop type (barley or sweet corn, Supplementary Table S1). Partial examination of the field trial at the second crop cycle is given in Nielsen et al. (2014). The enhanced biochars used here were produced as described in Nielsen et al. (2014), Briefly, a wood biochar was mixed with phosphoric acid, clay, manure, rock phosphate, basalt dust, ilmenite and dolomite and torrefied for 3 h at 220 °C to given the enhanced biochar. A full chemical characterisation of the enhanced biochar is given in Table 1 based in the methds described below.

Before the beginning of the third crop cycle examined here, 0.1 t ha^{-1} of mineral enhanced biochar and 50 kg ha^{-1} N fertiliser (as urea) were added to a number of plots in a crossed design resulting in four fertilisation regimes: 1) No amendment, 2) N fertiliser only, 3) enhanced biochar only and 4) N fertiliser and enhanced biochar. The site was rotary hoed to incorporate the amendments into the 0–10 cm soil layer. Given that a gradient of previously applied mineral enhanced biochar (from 0 to 5.4 t ha^{-1}) existed in the field site (Supplementary Table 1) and that biochar has a long residence time in soil (Chia et al., 2014), the existing amount of biochar was taken into account with respect to the current fertilisation treatments. Thus, the four fertilisation regimes examined were overlaid on the gradient of previously applied biochar. This view of the treatments presented an opportunity to examine the current, shorter-term effects of the fertilisation regimes, but also the residual, longer-term effects of the biochar in the field.