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Fading positive effect of biochar on crop yield and soil acidity during five growth seasons in an Indonesian Ultisol

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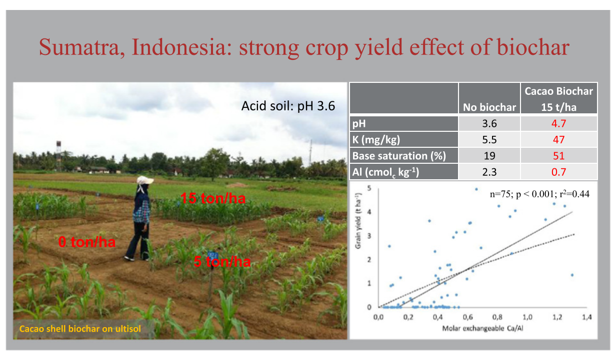
HIGHLIGHTS

- Two biochars at 3 dosages over 5 seasons were studied in Indonesia.
- Cacao shell biochar showed a strong positive effect on maize crop yield.
- The effect was cause by alleviation of soil acidity.
- After 3 to 5 seasons reapplication of the biochar was necessary.

GRAPHICAL ABSTRACT



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ABSTRACT

Low fertility limits crop production on acidic soils dominating much of the humid tropics.
Biochar may be used as a soil enhancer, but little consensus exists on its effect on crop yield. Here we use a controlled, replicated and long-term field study in Sumatra, Indonesia, to investigate the longevity and mechanism of the effects of two contrasting biochars (produced from rice husk and cacao shell, and applied at dosages of 5 and 15 t ha^{-1}) on maize production in a highly acidic Ultisol (pH$_{KCl}$ 3.6).
Compared to rice husk biochar, cacao shell biochar exhibited a higher pH (9.8 vs. 8.4), CEC (197 vs. 20 cmol$_c$ kg^{-1}) and acid neutralizing capacity (217 vs. 45 cmol$_c$ kg^{-1}) and thus had a greater liming potential. Crop yield effects of cacao shell biochar (15 t ha^{-1}) were also much stronger than those of rice husk biochar, and could be related to more favorable Ca/Al ratios in response to cacao shell biochar (1.0 to 1.5) compared to rice husk biochar (0.3 to 0.6) and nonamended plots (0.15 to 0.6).
The maize yield obtained with the cacao shell biochar peaked in season 2, continued to have a good effect in seasons 3–4, and faded in season 5. The yield effect of the rice husk biochar was less pronounced and already faded from season 2 onwards.
Crop yields were correlated with the pH-related parameters Ca/Al ratio, base saturation and exchangeable K. The positive effects of cocoa shell biochar on crop yield in this Ultisol were at least in part related to alleviation of soil acidity. The fading effectiveness after multiple growth seasons, possibly due to leaching of the biochar-associated alkalinity, indicates that 15 t ha^{-1} of cocoa shell biochar needs to be applied approximately every third season in order to maintain positive effects on yield.

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1. Introduction

Biochar amendment to soils offers a method to sequester carbon in soil with the co-benefits of waste management, pollutant immobilization, fertility increase and/or N_2O emission reductions of degraded soils (Jeffery et al., 2015; Lehmann, 2007). The mechanism behind this fertility increase can be improved water retention (Bruun et al., 2014), improved soil structure (Bruun et al., 2014; Obia et al., 2017; Obia et al., 2016), improved nutrient retention (Biederman and Harpole, 2013; Hale et al., 2013; Laird et al., 2010; Martinsen et al., 2014), increased robustness towards pests (Harel et al., 2012; Mehari et al., 2015), improved nutrient transport by mycorrhizae (Warnock et al., 2007), alleviation of soil acidity (Biederman and Harpole, 2013; Jeffery et al., 2017; Martinsen et al., 2015; Yamato et al., 2006), or combinations of these mechanisms. For less degraded soils, enrichment of the biochar with nutrients by co-composting or mixing with urine or mineral nutrients can still result in positive biochar effects on crop yield, especially in those cases where nutrient availability of the main growth-limiting factor (Hagemann et al., 2017a; Kammann et al., 2015; Schmidt et al., 2017; Schmidt et al., 2015).

Large variations in biochar effectiveness on crop harvest in the tropics have been shown, from minor, generally insignificant effects to strongly positive effects, with the median effect (taken from a meta-analysis study) being an increase of about 20% (Jeffery et al., 2017). The effect of biochar is usually strong in tropical soil (Agegnehu et al., 2016; Asai et al., 2009; Jeffery et al., 2017; Jeffery et al., 2011; Major et al., 2010; Yamato et al., 2006) in comparison to soils in temperate zones where the effect of biochar on the yield and soil properties is usually low (Bonanomi et al., 2017; Jeffery et al., 2017; Jeffery et al., 2011). Soils of high fertility (high cation exchange capacity, water retention, neutral pH) have shown to benefit less from biochar addition (Bass et al., 2016; Cornelissen et al., 2013; Jones et al., 2012). Effects tend to be a bit more strongly positive for acidic (pH < 5) and weathered soils with coarse or medium/heavy texture which are characteristic of tropical soils (Crane-Droesch et al., 2013; Jeffery et al., 2017). The effect of biochar seems to be thus strongly connected to the soil properties and the climate, but thus far correlations with crop yield are not completely clear. Several authors (including meta-analysis studies) state the yield increases are related to an overall improvement of soil qualities (Agegnehu et al., 2016; Asai et al., 2009; Crane-Droesch et al., 2013; Jeffery et al., 2017; Jeffery et al., 2011), also in tropical soils (Biederman and Harpole, 2013; Gurwick et al., 2013; Jeffery et al., 2017), however pin pointing the exact mechanism behind the increase in yields can be challenging.

In extensive four-season field trials in Thailand and the Philippines with rice husk biochar, Haefele et al. (2011) observed increased yields of 16–35%, and hypothesized that the increase was a result of improvements in water retention and increased available K and P. Steiner et al. (2007) tested biochar effects over four planting seasons in an acidic soil in Brazil ($pH_{H_2O} = 4.5$), and found positive effects of biochar that faded over time in multiple seasons. Major et al. (2010) studied biochar effects in an acidic oxisol in Colombia for 4 years, and did not find any effects in the first year, but maize yield increases in the three subsequent seasons. Griffin et al. (2017) investigated the amendment of walnut shell biochar over four years in a field experiment, and found a short-lived effect on maize crop yield in the second year. A long-term wheat/maize field experiment in a calcareous soil (pH 7.1–7.8) with extremely high biochar dosages (30, 60, and 90 t ha^{-1}) revealed a slight increase in cumulative yield over four seasons (Liang et al., 2014), due to lower bulk density, improved soil moisture and K addition. Jones et al. (2012) did a three-year study of biochar on maize and grass yield, in pH-neutral (pH 6.6) sandy clay loam in Wales, UK. Biochar effects were stronger in year two than in year one. After three years in the field, biochar had caused beneficial changes in the microbial community.

Despite their merit of drawing general conclusions from a plethora of data, the meta-analyses on biochar effect on crop yield have necessarily pooled the available data without considering the time since biochar application or inter-season variation for studies carried out over multiple years. The reason is that there are too few studies carried out for longer time spans. A recent review reported that 60% of the 428 data points reviewed were based on one year trials or simply used data corresponding to the first year of multiple-year studies (Bach et al., 2016). Thus, there is a need for well-controlled, replicated and longer-term field studies on representative soils. Here, we contribute to closing this gap, as information will be obtained related to trends observed for yields from a highly acidic soil up to five seasons since biochar application, with two very different biochars. The mechanism explaining the soil enhancement effect of biochar will also be investigated, as well as and how often one would need to replenish the biochar in order to maintain the positive soil fertility effects.

Ultisols in the humid tropics such as the presently studied soil require significant liming or addition of organic matter to remediate Al toxicity, which is acknowledged as one of the major causes for crop failure (Bloom et al., 1979). Biochar often contains a major ash component, which is alkaline in nature, and may be used as an alternative for lime, with the co-benefits of carbon sequestration and other improved soil characteristics (Cornelissen et al., 2013; Kelly et al., 2014; Kimetu et al., 2008; Martinsen et al., 2015; Yamato et al., 2006). The two biochars tested for their effects on crop yield and soil properties were made from cacao shell and rice husk, strongly differing in acid neutralization capacity (ANC) and cation exchange capacity (CEC). A high ANC of a biochar can probably alleviate soil acidity and reduce available Al concentrations (Gruba and Mulder, 2015; Major et al., 2010; Martinsen et al., 2015; Steiner et al., 2007). Also P availability can be positively impacted by an increasing pH (Lajtha and Schlesinger, 1988; Martinsen et al., 2014).

The hypotheses for this study were 1) that the agronomic effects of biochar in this soil could be explained by reduced soil acidity, as expressed by reduced exchangeable Al^{3+} concentrations as well as increased pH, Ca/Al ratios, and base saturation. As a result it was also hypothesized that the biochar with highest ANC would give the strongest yield effects in a soil where crop growth is mainly limited by soil acidity, and 2) that the biochar effectiveness on crop yield would decline over time, due to continued nutrient leaching and rapid depletion of the alkalinity added via the biochar (Glaser et al., 2002; Lehmann and Rondon, 2006).

2. Materials and methods

2.1. General outline

To investigate the longevity and mechanism of biochar effects on maize production in highly acidic soils of the humid tropics, an extensive field trial was carried out over five cropping seasons, with two biochars and five replicates at an experimental farm in the Lampung district, South Sumatra, Indonesia. The soil was classified as a Typic Kanhapludult Ultisols with high levels of exchangeable aluminum (Al; around 2 $cmol_c$ kg^{-1}) and very low pH (3.6 in KCl and 3.7 in water). The Lampung district has high rainfall (1796 mm) and temperatures (30 °C) throughout the year, and thus a high soil leaching and weathering potential.

Both biochars were applied in dosages of 0, 5 and 15 t ha^{-1} and mixed into the upper 10 cm of the soil. Soil bulk density was 1.30 g cm^{-3}. Percent addition of biochars (w/w) was thus 0.4% and 1.2% for the 5 and 15 t ha^{-1} additions, respectively. Both soil chemical parameters and maize yields were monitored over the five growth seasons.

2.2. Biochars

Biochars were prepared from rice husk and cacao shell, two common agricultural wastes in Indonesia. Pyrolysis was carried out in a simple kiln without a retort function, and the procedure and conditions for making the biochars have been extensively described in refs. (Alling

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