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Biochar vs. clay: Comparison of their effects on nutrient retention of a tropical Arenosol

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ABSTRACT

The use of biochar as a soil amendment is being widely studied, whereas clay addition to meliorate soils has only been considered in a few studies. However, there is a limited understanding of the impact of biochar and clay on nutrient retention under field conditions, especially in seasonally dry tropical forests in semi-arid regions. In this study, biochar and clay were added to a tropical Arenosol to quantify nutrient leaching as a measure of nutrient retention to test the potential of both amendments for soil amelioration.

In a field experiment, planting holes were prepared with 5 vol% medium-temperature biochar made of *Prosopis juliflora* (SW) DC, produced locally in the traditional manner in a kiln, or 10 vol% clayey sediment from a temporarily dry lake. Both amendments and control were tested as fertilised and unfertilised treatments. Then seedlings of the endemic tree *Spondias tuberosa* Arr. were planted. Self-integrating accumulators (SIAs) were used to quantify nutrient leaching at a depth of 0.7 m for ammonium-N ($NH_4^+ - N$), nitrate-N ($NO_3^- - N$), and potassium (K^+). Leaching was assessed for two consecutive periods of eight months each.

In the fertilised treatments, biochar addition significantly reduced $NO_3^- - N$ leaching by 46% in the first period; leaching of all other nutrients was reduced but remained non-significant. In contrast, clay addition significantly reduced $NH_4^+ - N$ leaching by 79% in the second period, K^+ leaching by 51% in the first period, and by 45% in the second period, but significantly increased $NO_3^- - N$ leaching by 57% in the second period. Both treatments showed pronouncedly different leaching patterns over time. Between the first and second period, the ability of biochar to reduce leaching relative to the control decreased by about half for the nutrients tested, whereas the ability of the clay treatment remained rather stable over 1.5 years for $NH_4^+ - N$ and K^+. The reason for the distinct decrease in nutrient retention of biochar in the second period may be the rapid decomposition of biochar carbon by 51% within 16 months.

Under the given conditions, only clay can be recommended as a sustainable land management strategy to enhance $NH_4^+ - N$ and K^+ retention capacity of Arenosols in seasonally dry tropical forests.

1. Introduction

The Caatinga, located in semi-arid north-eastern Brazil, extends over almost 1 million km^2 and is one of the world's largest seasonally dry tropical forests (Sampaio, 1995). With about 27 million inhabitants (Ministério do Meio Ambiente, 2011), it is also one of the most densely populated semi-arid areas worldwide (Salcedo and Menezes, 2009). The population pressure is often accompanied by degraded soils of low

Abbreviations: AEC, Anion exchange capacity; AR, Arenosol treatment (control); BC, Biochar treatment; CAL, Calcium-acetate-lactate; CEC, Cation exchange capacity; CL, Clay treatment; FDR, Frequency domain reflectometry; MRT, Mean residence time; RD, Relative difference; RDCL, Relative difference of cumulative leaching; SIA, Self-integrating accumulator; SIA 1, First SIA observation period; SIA 2, Second SIA observation period; SOC, Soil organic carbon; SSA, Specific surface area; SSP, Single super phosphate; SWC, Soil water content; VM, Volatile matter

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productivity (Menezes et al., 2012), and soil amelioration methods are urgently needed.

In the Itaparica region in Pernambuco, Brazil, Arenosols are one of the predominant soil types (Araújo Filho et al., 2013). These coarse-textured sandy soils have low contents of organic matter and clay, resulting in a marginal ability to retain water and nutrients. One possible land management measure is to augment levels of soil organic carbon (SOC) through the addition of biochar and to increase the share of fine-textured material through the addition of clayey material. This may enhance the nutrient retention of Arenosols, leading to more efficient use of fertiliser along with higher yields and may offer an opportunity to contribute to food security in the region.

Biochar is an organic material which is being widely studied for its suitability to ameliorate soils. It is the charred product of biomass pyrolisation, characterised by large carbon (C) contents (e.g. Verheijen et al., 2010), large surface area (e.g. Glaser et al., 2002), and a high degree of aromaticity, which results in strong resistance against degradation (Wu et al., 2012) with assumed long mean residence times (MRTs) of several hundreds to thousands of years (e.g. Knoblauch et al., 2011; Major et al., 2010; Singh et al., 2012). Many studies have confirmed the soil-improving qualities of biochar, including its ability to increase cation exchange capacity (CEC) (e.g. Glaser et al., 2000; Laird et al., 2010; Liang et al., 2006), available water capacity (e.g. Abel et al., 2013; Basso et al., 2013; Bruun et al., 2014; Laghari et al., 2015), and for its liming effects (e.g. Jeffery et al., 2011). Consequently, various studies have documented an increase in crop yields for a wide range of biochars, soil types and regions (e.g. Jeffery et al., 2011; Laghari et al., 2015; Steiner et al., 2007; Xu et al., 2015; Zhang et al., 2015).

The capability of biochar to retain nutrients has been studied in various experiments both in the laboratory and in the field with a strong focus on lysimeter experiments. Because nitrogen (N), one of the key nutrient elements, is highly mobile in its nitrate (NO_3^-) form, many biochar studies focus on mitigating NO_3^- losses. A number of studies have shown significant reduction in NO_3^- leaching after biochar addition to soils (e.g. Knowles et al., 2011; Raave et al., 2014; Sika and Hardie, 2014; Zheng et al., 2013a). Biochar has also been reported to significantly reduce leaching of ammonium (NH_4^+) (e.g. Ding et al., 2010; Lehmann et al., 2003; Sika and Hardie, 2014; Zheng et al., 2013a), phosphorus (P) (e.g. Major et al., 2012; Raave et al., 2014), and potassium (K^+) (e.g. Major et al., 2012). At the same time, several studies showed no effects or even an increase in nutrient leaching after biochar addition (Angst et al., 2014; Bruun et al., 2012b; Eykelbosh et al., 2015; Hardie et al., 2015; Iqbal et al., 2015; Lehmann et al., 2003; Raave et al., 2014). However, most studies on biochar effects on nutrient retention were conducted in the laboratory, whereas experiments at the field scale, especially in seasonally dry tropical forests in semi-arid areas, are still scarce.

Compared to the large number of biochar studies, the soil-amending potential of clay has only been considered in a few studies. Research regarding clay addition, which is sometimes referred to as “claying”, has mainly been conducted on sandy soils with low levels of clay in semi-arid to arid climates located in the tropics and subtropics. In Saudi Arabia, Al-Omran et al. (2005) added clay deposits to sandy calcareous soils in order to enhance water-use efficiency and *Cucurbita pepo* yield. In Western Australia, several studies demonstrated the ability of clay amendment to reduce hydrophobicity of sandy soils (e.g. Blackwell, 2000; Cann, 2000; McKissock et al., 2002; Shanmugam and Abbott, 2015). When studying the effects of clay addition to sandy soils on nutrient retention, Reuter (2001) stated that clay-substrate application to sandy soils can reduce leaching of plant nutrients and therefore diminish the risk of ground-water contamination. In another review, Reuter (1994) reported a reduction in P and K^+ leaching of sandy soils after the addition of brick clay. The addition of bentonite had the same effect. Addition of clayey subsoil to a Sodosol reduced NH_4^+ leaching compared to the control but did not affect NO_3^- retention (Dempster et al., 2012). In an incubation experiment, addition of fine-textured soil reduced N and P leaching (Nguyen and Marschner, 2013). To our knowledge, there are as yet no published studies that quantify nutrient retention following clay addition at the field scale, especially none that focus on semi-arid areas.

The objective of this study was to assess whether the nutrient-retention potential of a sandy soil in a semi-arid seasonally dry tropical forest could be improved by combining low-cost planting techniques with the application of locally available and inexpensive materials. Locally produced biochar and clayey sediment of a temporarily dry lake located close to the study site were added to planting holes of *Spondias tuberosa* Arr. seedlings. In this study, leaching losses of $NH_4^+ - N$, $NO_3^- - N$, K^+, and phosphate ($PO_4^{3-} - P$) were determined over two consecutive periods for an Arenosol amended with biochar and clay, respectively, and an unamended Arenosol as control treatment. We hypothesised that the addition of biochar and clay to an Arenosol would have significant effects on leaching of (i) $NH_4^+ - N$, (ii) $NO_3^- - N$, (iii) K^+, and (iv) $PO_4^{3-} - P$ due to enhanced nutrient retention. In particular, we expected that biochar will decrease leaching of $NH_4^+ - N$ and $NO_3^- - N$, and clay will decrease leaching of $NH_4^+ - N$, K^+, and $PO_4^{3-} - P$. We also hypothesised that (v) the nutrient-retention efficiency of biochar and clay would remain relatively stable over the 1.5 years of the field experiment.

2. Materials and methods

2.1. Natural conditions of the project area

Our experimental site is located in the Itaparica region of Pernambuco state, north-eastern Brazil, at 8°57′24.1″S, 38°15′00.4″W, 344 m above sea level. It is on the outskirts of the irrigation project Apolônio Sales, close to the city of Petrolândia, at a distance of about 45 km from Floresta. The area is part of the Jatobá-Tucano sedimentary basin, which consists of Paleozoic and Mesozoic sandstones covered by Tertiary and Quaternary sandy sediments. These have mainly evolved to deep Arenosols, one of the predominant soil types of the Itaparica region (Sampaio, 1995; Araújo Filho et al., 2013). The climate is semi-arid with mean annual temperature of 26.5°C (Floresta; 1961–1990; da Silva, 2004) and 497.7 mm mean annual precipitation (Floresta; 1912–2014; ANA - Agência Nacional de Águas, 2016), with the latter showing great inter-annual variability. Most of the precipitation occurs in a few heavy rain events, mainly from November to April, while the rest of the year arid conditions dominate (da Silva, 2004). Due to these factors, Caatinga tropical thorn forest is the predominant vegetation type (da Silva, 2004). The majority of crops can only be cultivated close to the river, where sufficient water is available for irrigation (Cierjacks et al., 2016). Consequently, the main land-use type for the unirrigated areas is livestock farming of goats, sheep, cattle, and donkeys (Sampaio, 1995; Schulz et al., 2016).

2.2. Experimental site: characteristics, set-up, and management

Our field trial was set-up in early 2013 on a 4.5 ha site. The site has no history of intensive agricultural use or irrigation, but was previously extensively grazed by goats. The entire site was therefore fenced before the set-up of the field experiment to prevent further grazing. The soil on our study site was classified as a Protic Arenosol (according to IUSS Working Group WRB, 2014) and has a sandy texture with low contents of clay and silt. It is also low in total C and total N. with low pH values and low cation exchange capacity (Table 1).

The biochar applied in this experiment was made of trunks and branches of *Prosopis juliflora* (Sw) DC, which is an invasive Fabaceae tree species in the area and therefore has no harvesting restrictions. As the biochar was produced traditionally by a local charcoal burner through slow pyrolysis, using a burrow sealed with a corrugated sheet and clay as a charcoal kiln, no data on pyrolysis temperature and