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ABSTRACT

Declining soil quality is commonplace throughout Southern Asia and sustainable strategies are required to reverse this trend to ensure food security for future generations. One potential solution to halt this decline is the implementation of integrated nutrient management whereby inorganic fertilisers are added together with organic wastes. These organic materials, however, are often quickly broken down in the soil providing only a transitory improvement in soil quality. Biochar, which persists in soil for centuries, may offer a more permanent solution to this problem. To address this, we undertook a 2-year field trial to investigate the interactions of conventional NPK fertilisers with farmyard manure (FYM) and biochar in a maize cropping system. Biochar application to the nutrient poor soil increased maize yields after year one by approximately 20% although the yield increase was lower in the second year (ca. 12.5%). Overall, there was little difference in grain yield between the 25 t ha^{-1} and the 50 t ha^{-1} biochar treatments. In terms of soil quality, biochar addition increased levels of soil organic carbon, inorganic N, P and base cations and had no detrimental impact on pH and salinity in this calcareous soil. Overall, this field trial demonstrated the potential of biochar to induce short-term benefits in crop yield and soil quality in maize cropping systems although the long-term benefits remain to be quantified. From a management perspective, we also highlight potential conflicts in biochar availability and use which may limit its adoption by small scale farming systems typical of Southern Asia.

Keywords: calcareous soil; crop production; integrated nutrient management; Pakistan; soil organic matter

1. Introduction

Progressive declines in soil quality and poor nutrient use efficiency continue to hamper agricultural productivity and food security in many developing countries (Vagen et al., 2005; Jones et al., 2013). These problems are further exacerbated by increasing pressures on agronomic systems posed by increases in human population growth and urbanization, uncertainties in the global climate and the need for agriculture to deliver a range of other ecosystem services in addition to food production (e.g. carbon sequestration, biodiversity, flood risk mitigation, water quality; Lal, 2009). There is therefore an urgent need to redesign agroecosystems to rectify the wide range of inefficiencies which exist in the system including disconnects in nutrient supply, demand and recycling as well as those in water use efficiency (Lal et al., 2013). One potential solution includes the recycling of organic nutrients back to land which can help sustain soil organic matter levels which in turn typically brings about improvements in soil biological functioning, aeration, moisture retention, reduced compaction, pollutant attenuation and nutrient supply (Girmay et al., 2008). The types of organic matter that can be potentially added to soil are diverse ranging from crop residues, green manures, industrial wastes, animal wastes and household waste (Ali et al., 2011; Quilty and Cattle, 2011). However, their addition can have a range of benefits or even negative effects depending on the quality of waste added and the level of contaminants present (Jones and Healey, 2010). It is also likely that synergies may exist between the different organic wastes and thus co-application may represent the best option for maximizing the delivery of a range of ecosystem services.

The application of pyrolysed organic matter (biochar) to soils is currently gaining considerable interest worldwide due to its potential to improve soil nutrient retention capacity, water holding capacity and to sequester carbon in a largely recalcitrant form from decades to possibly thousands of years (Downie et al., 2009; Spokas et al., 2012). Although there is strong economic and social competition from the use of charcoal as a domestic fuel source (Maes and Verbist, 2012), there is no doubt that it is readily applicable for use in arable systems where it can be readily incorporated into soil. However, before we can advocate the wide scale adoption of biochar to resource poor farmers in developing countries, we must first provide the evidence base to show that it is beneficial in both agronomic and economic terms. A number of studies have reported positive effects of biochar amendments on maize yields and soil properties (Glaser et al., 2002; Lehmann et al., 2003; Zhang et al., 2012), whilst others have reported no net effect (Jones et al., 2012) suggesting that the response may be to some extent agronomically specific. To date, however, very little research has been undertaken on the potential use of biochar and its effects on the behaviour of organic and inorganic nutrients in semi-arid regions of the world where improvements in soil quality and food security remain critical.

As the supply of fertilizers in Pakistan is limited by a range of socioeconomic, political and geographical constraints, alternative sustainable strategies are required to optimize fertiliser integration (Gandah et al., 2003; Schlecht et al., 2006). Low fertilizer-use-efficiency and losses to the environment are major environmental problems both in Pakistan and globally, and there is an urgent need for research that aims to improve fundamental efficiencies of crop nutrient use (Tilman et al., 2002; Sanchez, 2002). The aim of the present study was therefore to determine the effectiveness of biochar, farmyard manure (FYM) and mineral nitrogen alone and in various combinations on aspects of crop yield and soil quality in maize cropping systems. Maize was chosen as the trial crop as it contributes >10% of the total agricultural produce and 15% of agricultural employment in Pakistan, the major share of which (over 50%) originates from small land holding farmers, who produce mostly for their own food needs (FAO, 2014). Within these farming systems, the intrinsically low fertility of the soil and increasing prices of chemical fertilizers represent the major constraints to increasing maize yields (Khan and Shah, 2011). The need to simultaneously increase yields, decrease production costs and maintain soil health has therefore become a major challenge in semi-arid agroecosystems (Anjum et al., 2010).

2. Materials and methods

2.1. Experimental site

The trial site was located at the New Developmental Farm of the University of Agriculture, Peshawar (34°1’21”N, 71°28’5”E) and the experiment was started in the summer of 2011. The site has a warm to hot, semi-arid, sub-tropical, continental climate with mean annual rainfall of 360 mm. Summer (May–September) has a mean maximum temperature of 40°C and mean minimum temperature of 25°C. Winter (December to the end of March) has mean minimum temperature of 4°C and a maximum of 18.4°C. The average winter rainfall is higher than that of the summer. The highest winter rainfall has been recorded in March, while the highest summer rainfall is in August. %. The soil is a silty clay loam, well drained and strongly calcareous (pH 8.23 ±0.09), with an electrical conductivity (EC) of 166 ±28.5 μS cm^{-1} and an organic matter content of less than 1%. The soil is deficient in nitrogen (23.72 ±1.75 mg kg^{-1}) and phosphorus (3.20 ±0.50 mg kg^{-1}) but has adequate potassium (85.80 ±6.56 mg kg^{-1}).

2.2. Experimental design

The study consisted of three levels of biochar (0, 25 and 50 t ha^{-1}), two levels of FYM (5 and 10 t ha^{-1}) and two levels of fertilizer-N (urea) (75 and 150 kg ha^{-1}) together with a control treatment (no biochar, FYM or fertilizer-N). A summary of the treatments and their abbreviations are provided in Table 1. Biochar and FYM were applied at the time of sowing at the beginning of year 1, and reflected typical FYM doses for the region. Half of the fertilizer-N was applied at sowing and the remaining half applied at the 8 leaf stage (V7). Single super phosphate (SSP) was applied at the rate of 90 kg ha^{-1} as a basal dose. The FYM was obtained from the Peshawar University of Agriculture dairy farm and the biochar was produced from Acacia (e.g. *A. nilotica* (Linn.) Delile) using traditional methods employed in the region (Amur and Bhattacharya, 1999). No commercial biochar production takes place in the Khyber Pakhtunkhwa region of Pakistan; however, a limited amount is produced domestically using small biochar furnaces. The biochar was prepared in an enclosed dome shaped room, with several small holes made in the roof which were sealed after about 12 h burning. The feedstock was composed of cuttings from the main stem and branches of > 3 y old Acacia trees with a trunk diameter greater than 15 cm. The highest temperature reached during pyrolysis was between 400 to 500 OC, and the final ash content of the biochar was 27 %. Characteristics of the FYM and biochar are shown in Table 2.

The experiment had four replicates per treatment, and was laid out in a randomized complete block design. The treatment plots were 4.0 m x 4.5 m in size with strong ridges placed around each plot for delineation and to prevent biochar migration. Row-to-row and plant-to-plant distance was 75 cm and 20 cm, respectively. The field was ploughed twice down to a depth of 30 cm, followed by planking to break the clods and level the field taking care not to disturb the ridges and to facilitate biochar movement from one plot to another. Biochar was crushed and sieved to pass 2 cm, spread uniformly on the surface of the soil of each sub plot and then ploughed-in with a rotivator, which thoroughly mixed the biochar into the soil surface to a depth of about 15 cm. Maize (*Zea mays* L. cv. Azam) was sown at a rate of 30 kg ha^{-1} on July 1st, 2011. Locally recommended irrigation schedules were followed, with modifications according to the prevailing weather condition as and when needed. Weeds were controlled manually by hoeing. All other standard agronomic practices were applied uniformly to each experimental unit.

2.3. Crop harvest

At harvest (Oct 1st, 2011), the following maize yield components were recorded: total aboveground biomass, grain yield, number of ears m^{-2}, number of grains per ear and the thousand grain weight. To determine total above-ground yield (t ha^{-1}), the plants from the four central rows in each plot were harvested, dried and weighed. The ears from these harvested plants were then removed, threshed and grain yield (t ha^{-1}) calculated. Ears were counted in the four central rows of the standing maize crop in each plot. Thousand grain weight was calculated from a sub-sample from of each plot.

2.4. Soil quality analysis

Replicate soil samples were taken from 0-15 cm depth within a week of harvest. Soil carbon was determined by the Walkley-Black procedure (Nelson and Sommers, 1996). Carbonates were not removed before soil C determination, but an excess amount of dichromates was used to oxidize all possible organic C. Total mineral N in the soil samples was determined after KCl extraction by the steam distillation method as described in Mulvaney (1996). Soil pH and EC were determined in a distilled water saturation paste extract (Rhoades, 1996) and determined with standard probes. Plant-available P and K in soil were determined in an ammonium bicarbonate-DTPA extract (1 M NH_4HCO_3, 0.005 M DTPA; pH 7.6) either colorimetrically (P) or by flame photometry (K) according to the procedure outlined in Soltanpour and Schwab (1977). Ca and Mg were determined in the saturation paste extracts by Atomic Absorption Spectrophotometry (Model 2380, Perkin Elmer Corp., Waltham, MA, USA).

2.5. Statistical analysis

Differences between each treatment (biochar, FYM and N fertiliser) in each year were compared by analysis of variance (three-way ANOVA) for each yield and soil quality parameter. The difference between year 1 and year 2 for each yield and each soil quality parameter was also compared by Student's t-test (Minitab 12.0 software, Minitab Inc., PA, USA).

3. Results

3.1. Yield and yield components

The addition of FYM and N fertiliser significantly increased the yield of maize compared to the unamended control plots (Fig. 1). Biochar application significantly increased the grain yield in both years (P < 0.001), although there was little difference in grain yield between the 25 t ha^{-1} and the 50 t ha^{-1} biochar treatments (Fig. 1). Biological yield was significantly higher in both years in plots treated with biochar, although the number of grains per ear was only higher in the first year (P < 0.001) and an increase in the thousand grain weight was only significantly higher in the second year (Table 3). The addition of FYM in the treated plots made no significant difference to grain yield in either year (Table 3), although it did significantly increase the grains per ear, the thousand grain weight and the biological yield in year 1. Nitrogen fertiliser significantly increased the grain yield and grains per ear in the first year (P < 0.001), but this was not repeated in the second year (Table 3). Two-way interactions between the biochar, FYM and the N fertiliser significantly increased grain yield in the first year ($P < 0.05$), but not the second year (Table 3), when there was no significant interaction between all three treatments on any of the yield parameters measured.

3.2. Soil properties

Overall, the addition of biochar made a significant difference to soil quality parameters in both cropping cycles (Table 4). There was a significant increase in soil pH ($P < 0.05$) following biochar application, i.e. 7.18 ±0.11; 7.43 ±0.10; 7.65 ±0.20 for 0, 25 and 50 t ha^{-1} biochar addition respectively (data from both cropping cycles combined).

In year 1, the concentration of soil organic carbon in the plots containing both biochar and the full rate of FYM (10 t ha^{-1}), was significantly higher than in plots containing biochar and the half rate of FYM (5 t ha^{-1}), or the non-biochar-amended plots (Fig. 2a); however, by year 2, soil organic carbon was significantly higher in plots amended with biochar and either rate of FYM ($P < 0.05$), with between 40 – 75 % more soil organic carbon in the plots containing 50 t ha^{-1} biochar compared to the plots containing 25 t ha^{-1} (Fig. 2a). Soil mineral N was significantly higher in year 1 compared to year 2 in the non-biochar-amended plots (Fig. 2b), although the concentration of soil N was not affected by the rate of N fertiliser that had been applied (half rate, 75 kg ha^{-1} or full rate, 150kg ha^{-1}). Although there was no significant interaction between biochar and the application of N fertiliser (Table 4), in year1 there was significantly higher concentrations of soil N in both biochar amended plots containing the higher rate of FYM (Fig. 2b). The addition of biochar increased the concentration of soil P in the first year (Fig. 2c). In the 50 t ha^{-1} biochar plots there was significantly more soil P compared to the plots containing 25 t ha^{-1} ($P < 0.01$), and in the plots with 50 t ha^{-1} biochar the highest concentration of soil P was coupled with the full rate of FYM (Table 4). By year 2 however, in the biochar-amended plots the concentration of soil P had significantly declined, although it remained significantly higher than in the no-biochar-amended plots ($P < 0.05$). In contrast, the increase in soil Ca/Mg was significantly higher after year 2 in both rates of biochar-amended plots (Fig. 3a), although there was a significant interaction effect between biochar and the FYM and the N (either singly or in combination with biochar) in year 1; by year 2 the concentration of soil Ca/Mg was not affected by either organic or inorganic fertilisers (Table 4). For K, the application of FYM and inorganic N fertiliser to the non-biochar-amended soil was no different to the control soil which contained neither fertiliser nor biochar (Fig. 3b), although there were significantly higher levels after the second year. The application of 50 t ha^{-1} biochar significantly increased the concentration of K in the soil (Fig. 3b), particularly in the first year when there was a significant interaction between the biochar and the FYM and the N fertiliser (Table 4). Consequently, the effect of an increased concentration of ions in the biochar-amended soil generated a significant increase in soil EC (Fig. 3c).

4. Discussion

4.1. Incorporating biochar and FYM into integrated nutrient management regimes

In order to tackle the increasing food insecurity in semi-arid agroecosystems there is an urgent need to make agricultural systems more productive, whilst simultaneously making them more sustainable. In Pakistan, current attempts at alleviating soil nutrient deficiencies through the increased application of inorganic fertiliser are both economically and agronomically unsustainable. However, using organic materials such as FYM as fertilisers is receiving increased attention for maintaining crop productivity (Ali et al., 2011). By decreasing the costs of input provisioning, integrated soil fertility management can offer a sustainable solution to nutrient input by supplementing smaller (and thus cheaper) quantities of synthetic fertilisers with locally available organic amendments. Furthermore, combining both organic and mineral fertilisers can increase land productivity and enhance soil fertility, whilst having a positive effect on a wide range of other ecosystem services, e.g. water quality (Tilman et al., 2002). Our results have demonstrated that the integration of biochar with inorganic N fertiliser and FYM application at the field-scale can improve the productivity of maize and could provide a more sustainable input of N and P to soil. Augmenting the soil organic matter content can also promote nutrient cycling, and adding biochar to soil in Pakistan could improve yield responses to inorganic N and P fertilizers.

4.2. Maintenance of soil nutrient levels associated with biochar application

While the short term impacts of biochar application are becoming clearer for temperate agricultural soils, we absolutely lack an adequate understanding of the longer-term impacts and implications of biochar use in the cereal cropping systems commonly used in South Asia. Following biochar application to temperate soils an initial transient flush of labile compounds into the rhizosphere can enhance nutrient cycling and increase crop yield (Quilliam et al., 2012). Similarly, biochar application to the nutrient poor soils of Pakistan used in these field trials increased maize yields after year one by approximately 20% although this magnitude of yield increase was not replicated in the second year.

Biochar application to agricultural soil can facilitate the sorption or stabilisation of solutes and nutrient ions, and reduce nutrient loss from leaching (Asai et al., 2009; Laird et al., 2010), and the maintenance of elevated levels of soil P and N after the second year harvest suggests that biochar is mediating the slow release of these nutrients. Depending on pyrolysis conditions, the total surface area and pore volume of biochar can be orders of magnitude greater than soil (Calvelo Pereira et al., 2011; Quilliam et al., 2013). Subsequently, biochar can provide multiple planar sites to strongly sorb soil mineral and organic compounds (Joseph et al., 2010), although cation exchange capacity and the hydrophobicity of the biochar surface can also significantly affect its sorptive ability (Pignatello, 2013). Absorption of nutrients contained within the inorganic N fertiliser and the FYM onto the surface of the biochar would effectively reduce bioavailability for microbial utilisation and prevent bound nutrients from being leached away following rainfall or irrigation and may reduce volatilization of NH_3. However, over time these nutrients will slowly be released back into the soil resulting in a more sustainable use of the farmer's original investment in synthetic fertiliser (Asai et al., 2009). In addition to the increased efficiency of nutrient input, incorporating biochar into agroecosystems has the potential to enhance wider ecosystem service delivery, for example, by reducing nutrient and pesticide mobilisation and transfer from soil into aquatic systems (Jeffery et al., 2013).

The continual successive cropping systems common in Pakistan result in a net offtake of nutrients from the soil, and while the application of synthetic NPK fertilisers can maintain yield, these fertilisers do not replenish essential micronutrients, such as Zn and Cu (Jones et al., 2013). The application of animal manures however, can be an important strategy for delivering both macro- and micronutrients, and maintaining levels of soil organic matter (Zingore et al., 2010). Amending calcareous soils with both FYM and biochar can decrease emissions of greenhouse gases from the soil (Zhang et al., 2012), and also have a positive effect on micronutrients, e.g. Mn (Lentz and Ippolito, 2012). Our results have suggested that Ca and Mg had become bound to the biochar surface and were being slowly released back into the soil over the growing season. The addition of biochar could be hugely significant for the improved delivery of these mesonutrients to impoverished soils, and this is clearly an important area of research that requires much more focussed process-based work to fully understand the interaction between biochar and micronutrient availability.

4.3. Could semi-arid agroecosystems provide enough organic feedstock for sustainable biochar production?

For this study we have applied fairly high rates of biochar in order to clearly demarcate potential differences between our treatments; however, there are also recent reports of lower biochar application rates being beneficial in calcareous soils (Zhang et al., 2012; Ippolito et al., 2014). To produce high quantities of biochar requires large volumes of feedstock, and there is justifiable concern about the implications of overharvesting existing forests for biochar production, as progressive deforestation in semi-arid ecosystems has already led to the deterioration of a range of ecosystem services. In Pakistan, nearly 62% of the population live in rural areas and are reliant on agriculture for their livelihoods. Consequently, there is a significant dependence on fuelwood as a source of energy, and in a country that already has low forest cover (of about 4.80%), the high consumption rate of fuelwood per household per day (6.70 kg) is contributing to the unsustainable use of the country's wood resources (Butt et al., 2013). In the rain-fed areas of Pakistan, e.g. the southern districts of Khyber Pakhtunkhwa, wild-growing Acacia is already seasonally pruned to make charcoal; however, any potential benefits of biochar application to agricultural soil are accompanied by some important trade-offs, such as the potential for deforestation and land degradation (Anjum et al., 2010), together with the behavioural and cultural implications associated with using a primary source of fuel as a soil amendment (Maes and Verbist, 2012).

Environmental degradation in semi-arid regions, as a consequence of biochar production, is undeniably not a sustainable strategy for improving soil nutrient use efficiency and delivering increased food security (Woolf et al., 2010). However, biochar can be produced from any organic material, and the pyrolysis of non-virgin feedstocks would allow the production of significant volumes of biochar without exacerbating the existing pressures on forest resources. Whilst there is the potential to produce biochar from 'on-farm' organic wastes, e.g. stover or maize cobs, in semi-arid agricultural systems much of this 'waste' biomass is already fully utilised, for example as animal feed, mulch or for constructing fences and roofs. Thus, short-term cycling of these streams of organic matter back through the agricultural chain is probably more beneficial than taking them out of the loop by converting them into biochar (Jones et al., 2013).

The production of biochar from urban and industrial wastes, such as municipal solid waste, sewage sludge, sawdust and food waste, offers a useful strategy to mitigate the increasing global problem of waste disposal. However, although the widescale production of biochar from waste offers much promise for recycling valuable nutrients back to agricultural land, it is not without considerable challenges. Potential contamination of waste organic materials, with pollutants such as heavy metals, could pose a very significant risk to soil quality and crop production (Jones and Quilliam, 2014); whilst addressing the challenges associated with the spatial disconnect between areas of waste production (urban areas) and areas of food production (rural areas) would require a level of infrastructure not often found in the developing world (Jones et al., 2013).

5. Conclusion

For resource-poor farmers living with soil of intrinsically low fertility, the cost and availability of chemical fertilizers is often the most prohibitive constraint to increasing crop yields; therefore the sustainable management of nutrients is critical for maximising the efficiency of crop nutrient use. Incorporating FYM and biochar into an integrated nutrient management regime could be an important strategy for improving the overall farm productivity of cereal-based cropping systems in Pakistan. However, this needs critical evaluation in a sustainable agricultural context. Central to this are participatory-based approaches to assess whether biochar can really make a practical contribution to agriculture in Pakistan by providing farmers with a sustainable solution to help alleviate the constraints driven by poor soil fertility. Crucially, an evaluation of the wider ecosystem services linked to the trade-offs associated with producing biochar in semi-arid ecosystems needs both careful consideration and robust evidence before it can be promoted as a sustainable option for optimising fertiliser use efficiency.

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Figure legends

Figure 1: Yield of maize in year 1 (grey bars) and year 2 (black bars) fertilised with FYM at either 5 t ha^{-1} (half manure; HM) or 10 t ha^{-1} (full manure; FM) and N fertiliser, at either 75 kg ha^{-1} (half fertiliser; HF) or 150 kg ha^{-1} (FF). All plots were amended with biochar at the application rates of 0, 25 or 50 t ha^{-1}. Control, 0 t ha^{-1} FYM, 0 kg ha^{-1} N fertiliser, and 0 t ha^{-1} biochar. Data points represent the mean of three replicates +SE.

Figure 2: Soil organic carbon (a), mineral nitrogen (b) and extractable phosphorus following the harvest of maize in year 1 (grey bars) and year 2 (black bars). Plots had been fertilised with FYM at either 5 t ha^{-1} (half manure; HM) or 10 t ha^{-1} (full manure; FM) and N fertiliser, at either 75 kg ha^{-1} (half fertiliser; HF) or 150 kg ha^{-1} (FF). All plots were amended with biochar at the application rates of 0, 25 or 50 t ha^{-1}. Control, 0 t ha^{-1} FYM, 0 kg ha^{-1} N fertiliser, and 0 t ha^{-1} biochar. Data points represent the mean of three replicates +SE.

Figure 3: Soil extractable Ca/Mg (a), extractable potassium (b) and soil electrical conductivity following the harvest of maize in year 1 (grey bars) and year 2 (black bars). Plots had been fertilised with FYM at either 5 t ha^{-1} (half manure; HM) or 10 t ha^{-1} (full manure; FM) and N fertiliser, at either 75 kg ha^{-1} (half fertiliser; HF) or 150 kg ha^{-1} (FF). All plots were amended with biochar at the application rates of 0, 25 or 50 t ha^{-1}. Control, 0 t ha^{-1} FYM, 0 kg ha^{-1} N fertiliser, and 0 t ha^{-1} biochar. Data points represent the mean of three replicates +SE.