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Integration of biochar with animal manure and nitrogen for improving maize yields and soil properties in calcareous semi-arid agroecosystems

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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 soil and provide only a transitory improvement in soil quality. Biochar, which can potentially persist 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 between conventional NPK fertilisers, 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.

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 that exist in the system including disconnects in nutrient supply, demand and recycling as well as those in water use efficiency (Lal, 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

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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 (through the sorption or stabilisation of nutrient ions), 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 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 (Cornelissen et al., 2013; Zhang et al., 2011), whilst others have reported no net effect (Jones et al., 2012) suggesting that the response may be to some extent specific to particular environmental conditions and soil types, or agronomic practices, e.g. differences in crop cultivar or fertiliser and pesticide applications. Compared to biochar research in the temperate soils of Europe and North America, relatively little work 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. Although there are a growing number of studies investigating the effect of biochar application to tropical soils, many of these focus on acidic soils and the liming effect of biochar (Major et al., 2010). Subsequently, there is a significant lack of data on biochar amendment of agronomic calcareous soils in semi-arid areas such as regions of northern Pakistan.

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, e.g. through leaching, 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; Arif et al., 2015). 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}).

Table 1
Description of treatment combinations used for each replicated (n = 3) experimental plot.

Biochar (t ha^{-1})	FYM (t ha^{-1})	Feriliser N (kg ha^{-1})	Abbreviation[a]
0	0	0	Control
0	5	75	B0-HM-HF
0	5	150	B0-HM-FF
0	10	75	B0-FM-HF
0	10	150	B0- FM-FF
25	5	75	B25-HM-HF
25	5	150	B25-HM-FF
25	10	75	B25-FM-HF
25	10	150	B25-FM-FF
50	5	75	B50-HM-HF
50	5	150	B50-HM-FF
50	10	75	B50-FM-HF
50	10	150	B50-FM-FF

[a] HM, half manure rate (5 t ha^{-1}); FM, full manure rate (10 t ha^{-1}); HF, half fertiliser rate (75 t ha^{-1}); FF, full fertiliser rate (150 t ha^{-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 (V8). Single super phosphate (SSP) was applied at the rate of 90 kg ha^{-1} as a basal dose. Diary cattle FYM was obtained from The University of Agriculture, Peshawar, Pakistan 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 400–500 °C, 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 × 4.5 m in size with strong ridges placed around each plot for delineation and to prevent biochar migration. Between row and within row 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