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Review

The role of biochar and biochar-compost in improving soil quality and crop performance: A review

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ABSTRACT

Multiple nutrient deficiencies related to severe soil fertility depletion have emerged as the major constraint to the sustainability of agriculture on a global scale. Use of biochar and biochar-compost mixtures from different alternative organic sources have been proposed as an option for improving soil fertility, restoring degraded land, and mitigating the emissions of greenhouse gasses associated with agriculture. We review the findings of 634 publications in the last decade on biochar and biochar-compost mixtures as soil amendments in order to identify the potential gaps in our understanding of the role of these amendments in agriculture. We found that: i) the majority of published studies have been carried out in developed countries where soils are less impaired in terms of food production capacity than in many developing countries; ii) studies on biochar produced in small kilns are more common than biochars produced at commercial scale in developed countries, whereas biochars produced using traditional techniques are more commonly used than biochars produced in modern pyrolysis units in developing countries; iii) laboratory and greenhouse studies are more common than field studies; and iv) wood and municipal wastes were the major feedstock for the preparation of biochar compared to crop residues and manures. Although, biochar-compost application proved to be more generally effective in improving soil properties and crop yields (field crops and horticulture crops) than biochar alone, along with desired soil properties, could be a feasible alternative to remediate the degraded soils and improve their productivity potential in the long-term. Overall, a lack of long-term, well-designed field studies on the efficacy of biochar and biochar-compost mixtures on different soil types and agro-climatic zones are limiting our current understanding of biochar's potential to enhance crop production and mitigate climate change. We further suggest that greater collaboration between researchers, biochar producers, and policy makers is required to advance the research and uptake of this important technology at a global scale.

1. Introduction

Severe soil fertility depletion and declining agricultural productivity due to a reduction of soil organic matter (SOM) and nutrient imbalances are major constraints in most tropical agricultural soils (Lal, 2015b; Pender, 2009; Sanchez, 2002). Global soil acidity occupies 30% of ice-free land (Von Uexküll and Mutert, 1995). Soil salinization (20% of world irrigated land) is also a serious environmental issue, affecting about 8.31×10^8 ha of soil worldwide (Metternicht and Zinck, 2003; Pitman and Läuchli, 2002), roughly ten times the size of Venezuela and 20 times the size of France, with secondary salinization occupying an additional area of 7.7×10^7 ha, of which 58% occurs in irrigated areas (Li et al., 2014a). More than half of all African people are affected by land degradation, making it one of the continent's most urgent development issues with significant costs. For example, an estimated US $42 billion in income and 6 million ha of productive land are lost every year due to land degradation and declining agricultural productivity (Bationo et al., 2006).

Soil nutrient depletion is an important concern, directly linked to food insecurity due to unsustainable intensified land use (Henao and Baanante, 1999). Total nutrient deficits at the global scale have been estimated to be 20 Teragram (Tg, 10^{12} g) of which 75% occurred in developing countries, 14% in developed countries and 11% in least developed countries. Considering a total NPK deficit for four crops (rice, wheat, maize, and barley) with an individual nutrient deficit in the form of N accounted for 28%, (5.5 Tg), P for 12% (2.3 Tg), and K for 60% (12.2 Tg) (Tan et al., 2005). Assessments have shown that nutrient losses are only partially compensated by natural and man-made inputs, thus the nutrient balance for the total of Sub-Saharan Africa (SSA) appears to be negative, being currently minus 26 kg N, 3 kg P, and

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19 kg K ha^{-1} yr^{-1} (Drechsel et al., 2001). Sheldrick et al. (2002) developed a conceptual model for conducting nutrient audits at regional and global scales by which the global average nutrient depletion rate in the year 1996 was estimated to be 12.1, 4.5, and 20.2 kg N, P, and K ha^{-1} $year^{-1}$, respectively, implying a corresponding nutrient use efficiency of 50%, 40%, and 75%. Many tropical soils are poor in inorganic nutrients and rely on the recycling of nutrients from soil organic matter to maintain fertility. It has been determined that agriculture without supplementary fertilization can be economically viable for 65 years on temperate prairie but only for six years in cleared tropical semi-arid forest lands (Tiessen et al., 1994). An extremely nutrient-poor Amazonian soil showed no potential for agriculture beyond the three-year lifespan of the forest litter mat inputs, once biological nutrient cycles were interrupted by slash-burning (Tiessen et al., 1994).

The benefits of inorganic fertilizers have been widely demonstrated since the 'green revolution' (Vanlauwe et al., 2010), and inorganic fertilizers have played a significant role in increasing agricultural production and productivity over the last half century. However, the highly productive fertilizer and seed technologies introduced over the past decades may be reaching a point of diminishing returns (Gruhn et al., 2000; Rosset et al., 2000). The increase in human population pressure has decreased the availability of arable land and it is no longer feasible to use extended fallow periods to restore soil fertility in the tropics (Lal, 2008). In some areas the fallow period, which would previously have restored soil fertility and organic carbon, is so reduced that it cannot now regenerate soil productivity, in turn leading to the unsustainability of some farming systems (Bationo et al., 2007; Nandwa, 2001). Shrinking land area per capita and declining soil quality have led to a constant increase in the rate of inorganic fertilizer application from year to year to maintain or enhance agricultural productivity (Srivastava, 2009). However, the application of chemical fertilizer alone is not a sustainable solution for improving soil fertility and maintaining yield increases; rather, it has been widely realized that application of excessive inorganic fertilizer, especially N, may cause soil deterioration and other environmental problems due to more rapid organic matter mineralization and resultant decreases in soils carbon stocks (Foley et al., 2005; Liu et al., 2010; Palm et al., 2001).

Soil degradation is the most serious bio-physical constraint limiting agricultural productivity in many parts of the world (Lal, 2015b; Pender, 2009). Soils are becoming degraded (Fig. 1) in many areas worldwide (UNEP, 2002). The long-term benefit of assigning more land to agriculture will not offset the negative environmental impacts of land degradation in the future (Tilman et al., 2002). Instead, a more promising approach to ensuring food security is to increase yield from currently cultivated land where productivity is low (Foley et al., 2011). Sustainable agricultural intensification, increasing productivity per unit land area, is thus necessary to secure the food supply for the increasing world population (Godfray et al., 2010; Tilman et al., 2011). In most tropical environments, sustainable agriculture faces significant constraints due to low nutrient status and rapid mineralization of SOM (Zech et al., 1997). Decline in SOM content leads to decreased cation exchange capacity (CEC). Under such circumstances, the efficiency of applied mineral fertilizers is low (Agegnehu et al., 2016c; Glaser et al., 2002). In addition, most small-scale and subsistence oriented farmers cannot afford to apply the recommended mineral fertilizers regularly due to high costs. Thus, nutrient deficiencies prevalent in many crop production systems of the tropics continue to constrain productivity.

The majority of the agricultural production depends on synthetic fertilizers. In the 21st century, agriculture faces various challenges. It has to meet food and industrial needs of the growing population while protecting the environment. In 2015, the world population was 7.35 billion while projections show that population will reach 9.72 billion by 2050 (UN, 2015). Thus, the world food production must increase by ~70% from its current level to satisfy food needs by 2050 (FAO, 2009). The majority of the agricultural production depends on synthetic fertilizers, and one of the major problems is over application of fertilizers, especially N fertilizers such as urea. The total global demand for NPK fertilizer was 180 million tons in 2012, of which nitrogen fertilizer alone constituted 110 million tons (~61%). The world nitrogen fertilizer demand is expected to be around 116 million tons in 2016 at an annual growth rate of 1.3%. Of the overall increase in demand for 6 million tons nitrogen between 2012 and 2016, 60% will be in Asia, 19% in America, 13% in Europe, 7% in Africa and 1% in Oceania (FAO, 2012). Assuming a 33% N recovery efficiency (Raun et al., 2002) and $USD 255 ton^{-1} (World Bank, 2015) this equates to an $18.8 billion annual loss in N fertilizer costs. On the other hand, the global bio-fertilizers market size (nitrogen fixers and phosphate solubilizers account for 75% and 15%, respectively, of global revenue share) is estimated to be $USD 535.8 million in 2015. The North America bio-fertilizer market is the largest followed by Europe, accounting for over 54% of the global revenue, produced using organic wastes such as struvite and compost acting as substitute to chemical-based fertilizers (www.grandviewresearch.com).

Maintaining an appropriate level of soil organic matter and ensuring the efficient biological cycling of nutrients is crucial to the success of soil management and agricultural productivity strategies (Bationo et al., 2007; Vanlauwe et al., 2010). These practices include the application of organic and inorganic fertilizers combined with knowledge of how to adapt these practices to local conditions, aiming to maximize agronomic use efficiency of the applied nutrients and thus crop productivity (Vanlauwe et al., 2010). However, in the tropics, naturally rapid mineralization of soil organic matter is a limitation on the

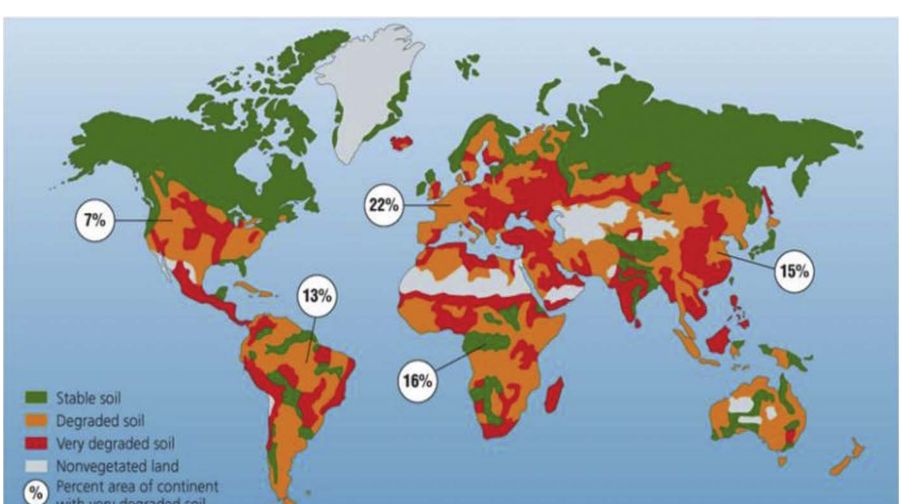

Fig. 1. Soil degradation: A global concern (UNEP, 2002); 2013 Pearson Canada Inc.