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Comparative fertilization effects on maize productivity under conservation and conventional tillage on sandy soils in a smallholder cropping system in Zimbabwe

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ABSTRACT

Components of conservation agriculture (CA) are being widely promoted in southern Africa as one of the strategies to increase food security and mitigate rural poverty, despite there being scarce empirical evidence on their efficacy on degraded soils. On-farm trials were established in Eastern Zimbabwe to assess the effects of tillage systems on maize grain yields under rain-fed conditions across a soil organic matter gradient. The study compared the effects of a) conventional tillage (CT), b) basins-based CA (B-CA), and c) furrow-based CA (F-CA) on sandy soils with contrasting soil organic carbon (SOC). Fields had SOC ranging from 0.18 to 0.89% and clay content from 60 to 150 g kg^{-1}. A nutrient omission trial using nitrogen (N), phosphorus (P), potassium (K), cattle manure (M) and their combinations was set up on twenty farms each with two fields selected by the host farmer as either poor or rich in soil fertility in Study 1, and ten farms in Study 2, each with two fields selected as in Study 1. Fields selected by farmers as poor fields had SOC < 0.4%, were more acidic, had lower amounts of exchangeable bases (Mg, Ca, K), available P and total N. These lab-based results corroborated well with farmers' local rating of soil fertility. For Study 1, nutrient management significantly increased maize yields across the three years ($P < 0.001$) but there were no significant tillage effects observed. Grain yields increased from 0.3 Mg ha^{-1} for unfertilized control to 4.1 Mg ha^{-1} for the NPKSM treatment. Yield response to N was consistently larger than for P or K, irrespective of soil fertility status. Response to N increased with increase in soil fertility, suggesting higher N use efficiency for soils with higher SOC. Except for NPKSM, no significant yield differences were observed under the residual and additive plots for treatments, when N was added each year. At productivity levels of < 4 Mg ha^{-1}, there was no yield gain in applying both P and K for consecutive years, suggesting that nutrient investments by resource constrained farmers for Year 2 could target only N application. For Study 2, maize grain yields were significantly higher under B-CA compared with both F-CA and CT in the second year ($P < 0.01$). The consistently larger NPKSM yields highlight the importance of integrated nutrient management, combining mineral and organic sources of nutrients to ensure maize productivity on poor soils in agro-ecologies receiving unreliable rainfall.

1. Introduction

Intensification of agricultural production is seen as the pathway to combat food insecurity and to meet growing food demand by a rapidly increasing population in sub-Saharan Africa (SSA) (Sanchez, 2010). Approaches to meet this objective are still divergent and rarely tailored to respond to the particular needs of local biophysical, environmental and socio-economic circumstances. Agricultural development programs often promote technologies for crop production intensification before empirical evidence is generated for their suitability under local farm conditions through a rigorous scientific process. Such technologies are often presented as solutions that guarantee improved productivity universally across heterogeneous farms. However, failure to address the variability of smallholder farms when developing and disseminating technologies often leads to poor performance, sub-optimal economic benefits to farmers and fizzling of the momentum around the technology over time.

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Maize is Zimbabwe's staple crop, but sustainable intensification of its production is hampered by inherently poor and declining soil fertility particularly on granite-derived sandy soils predominant in the smallholder sector (Grant, 1981), poor access to nutrient resources, and erratic rainfall (Mupangwa et al., 2007; Rurinda et al., 2013; Twomlow et al., 2008a, 2008b). It has been established that response to fertilizer inputs is also differentiated by soil quality, with some fields poorly responsive to nutrient applications (Tittonell and Giller, 2013; Zingore et al., 2007). Therefore, more innovative approaches are required in assisting farmers in targeting their meagre nutrient resources to fields that offer the best returns, while also actively pursuing practices that regenerate the nutrient-depleted soil resource base (Snapp et al., 2003). Arguably, strategies that concurrently ensure increased nutrient and water availability present the greatest opportunity for increasing maize productivity by several fold from the current average 1 Mg ha^{-1} (Rockström et al., 2007).

Conservation agriculture (CA) has been promoted in southern Africa as one of the technologies that respond to the afore-mentioned challenges. Conservation agriculture is characterised by three principles: minimum soil disturbance, permanent residue soil cover and diversified crop rotations. Inclusion of legumes in the cropping sequences ensure harnessing the ecological benefits of biological N_2-fixation, while both minimum soil disturbance and permanent residue soil cover improve soil structure and ensure better rainfall infiltration and reduced evaporative soil losses. Minimum soil disturbance promotes soil aggregation that is associated with higher soil organic carbon (SOC) sequestration (Govaerts et al., 2009; Lal, 2011; Six et al., 2000). The key mechanism associated with this lies in macro-aggregate formation and degradation, and subsequent micro-aggregation formation (Six et al., 2000). The formed stable micro-aggregates are more effective at SOC protection and sequestration (Blanco-Canqui and Lal, 2004). However, under very sandy soils, the physico-chemical environment does not allow for substantial SOC gains (Six et al., 2002a).

A key constraint that hinders wholesome implementation of CA is poor availability of crop residues that are essential for soil cover, in farming systems that also have competing claims for any crop residues that may be generated (Giller et al., 2011; Rusinamhodzi et al., 2015; Valbuena et al., 2012). Where farmers actively protect crop residues from livestock grazing, there is a trade-off related to the potential reduced productivity of the livestock component (Rusinamhodzi et al., 2011).

Implementation of CA often leads to positive results but sometimes unintended results ensue. Soil moisture availability may increase under CA due to mulching by increasing infiltration and reduced surface sealing and soil compaction. This leads to improved yields on well drained soils and in low-rainfall areas but may lead to reduced yields in high rainfall areas due to water logging (Rusinamhodzi et al., 2011). The use of high C:N mulching materials in the form of grass or cereal stover results in increased short-term immobilization of nitrogen (N) in environments where farmers cannot invest in large amounts of N fertilizer to offset the negative effects of immobilization on the crops. Net N mineralization from crop residues may only be achieved in the long-term. These processes have potential to affect crop nutrient response in CA systems.

Practically, for most smallholder farmers, implementation of CA only involves partial utilization of the three CA principles. While CA aims to address the problems of soil degradation and increase rainfall infiltration, proper fertilization as a fourth principle has recently been added to the discourse (Vanlauwe et al., 2013), triggering a rebuttal from CA proponents (Sommer et al., 2014). Vanlauwe et al. (2013) argue that crop production in SSA would largely benefit from the prioritization of fertilizer use, as this would ensure the enhanced availability of crop residues that can be used as crop cover. On large-scale commercial farms, CA practice is characterized by high mineral fertilizer inputs. Rusinamhodzi et al. (2011) concluded that the success of CA in Southern Africa is highly dependent on high mineral fertilizer use. Recognizing the importance of fertilizer in increasing crop production in SSA, the Abuja Declaration on Fertilizer for an African Green Revolution (2006) committed to increase fertilizer use in Africa to 50 kg nutrients ha^{-1} by 2015. Current fertilizer use by the majority of smallholder farmers suggests that this target has been missed by a large margin. The best opportunity for farmers to increase productivity in the short-term is, therefore, to use the limited fertilizer resources efficiently.

Most studies have focused on the adoption and performance of CA (e.g., Knowler and Bradshaw, 2007; Rusinamhodzi et al., 2011; Six et al., 2002b). However, there is little knowledge on how the CA systems will perform in a farming system that is dominated by conventional tillage (CT) and little fertilizer use. There is also little empirical evidence on the performance of CA in smallholder cropping systems and how the system compares with the widely adopted moldboard conventional tillage (CT) system. Often, demonstration plots established by development agencies promoting CA in southern Africa are unbalanced, where CA systems with fertilizer use are compared with farmer's practice of CT without fertilizer, leading to assertions that CA was always superior to CT. The key objectives of the current study were therefore to 1) assess the influence of soil fertility on the performance of CA and CT technologies under similar production environments in the smallholder farming systems, 2) determine the interaction of soil fertility and tillage system on maize yield response to application of macronutrients, and 3) determine the conditions that support viability of fertilizer investments in maize production. In this paper, we adopt the CA terminology as widely applied in the region, even though strictly, these are often simply tillage systems being compared as a result of deficiencies in meeting all the three pillars of CA.

2. Materials and methods

2.1. Study site

The study was carried out in Murewa district (17°49′S, 31°34′E; 1400 masl) in Eastern Zimbabwe, between 2013 and 2016 cropping seasons. The area is characterized by a unimodal rainfall pattern which is spread between November and March. Daily rainfall was recorded for the three cropping seasons using two rain gauges installed at two farms in the study site area. Seasonal rainfall varied from 587 mm to 1047 mm, with marked differences in within season distribution (Fig. 1). Murewa has mean temperatures of 24 °C. The predominant granite-derived soils are characterized by infertile sandy lixisols with poor SOC content (Grant, 1981). The farming system involves strong crop-livestock integration as livestock are fed on crop residues and the manure produced is in turn used to fertilize cropped fields. Maize is the major crop, while groundnuts, sweet potato, sunflower and millets are grown mainly for subsistence.

2.2. Selection of farms for soil characterization and subsequent experimentation

An exploratory survey involving 70 farms was conducted before the 2013/2014 cropping season. Each of the surveyed farmers was asked to identify one field that they perceived as the most fertile on their farm (rich field) and one that was least fertile (poor field). Farmers also provided the main criteria they used to identify these fields (Table 1). The soil fertility rating was mainly based on historical crop productivity, previous crop response to manure or fertilizer, indicator weed species, soil color, and previous nutrient management on the farms. For each of identified fields, composite soil samples consisting of five sub-samples collected along the field's diagonal line were collected from the plough layer (0–20 cm depth) and bulked. The soil samples were air-dried, and those for total N, available P, extractable bases analysis were passed through a 2 mm sieve, while those for SOC analysis were passed through a 0.5 mm sieve. Total SOC was determined by the modified