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Strong spatial-temporal patterns in maize yield response to nutrient additions in African smallholder farms

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ABSTRACT

Large variability in crop responses to macronutrient application at various spatial scales present challenges for developing effective fertilizer recommendations for crop production in smallholder farming systems of sub-Saharan Africa. We assessed maize yield responses to nitrogen (N), phosphorus (P) and potassium (K) application and evaluated relationships between crop responses to N, P and K application and soil analysis data. Nutrient omission trials were conducted on 23 farms located in Sidindi, Western Kenya, selected to be representative of the main soil and management factors in maize based systems in Siaya County. Treatments included a control and PK, NK, NP and NPK applications. The trials ran for six consecutive cropping seasons, without changing treatments or plot location, covering the period 2013–2015. Strong spatial-temporal patterns in maize yield responses to N, P and K applications were observed. Average maize yields in the control, PK, NK, NP and NPK treatments were 2.8, 3.2, 5.1, 5.1 and 5.5 t ha^{-1} at 88% dry matter respectively in the first cropping season, and 1.1, 1.4, 2.9, 3.6 and 5.3 t ha^{-1} at 88% dry matter respectively in the sixth cropping season. In all seasons, variability in maize yield between fields was greatest in the control treatment followed by the NK treatment and least in the NPK treatment. Mean relative yield was 0.6, 0.92 and 0.93 for N, P and K respectively, in the first cropping season, and 0.25, 0.52 and 0.68, respectively, in the sixth cropping season. Six main maize yield response categories were identified that differed in the maize grain yield responses to recursive N, P and K applications. Maize yield responses to N, P and K were not fully accounted for by soil organic matter, soil available P and exchangeable K respectively. Our results indicate that current methods for soil analysis do not adequately predict the response to application of N, P and K fertilizer under the highly variable soil fertility conditions encountered in smallholder farming systems. The strong spatial-temporal patterns observed present major challenges for the development of effective site-specific fertilizer recommendations. Potential avenues for future research and options for more effective intensification strategies are discussed.

1. Introduction

Crop production in smallholder systems in sub-Saharan Africa (SSA) is strongly limited by poor soil fertility that results from continuous cropping with little or no nutrient replenishment (Kihara et al., 2015; Sanchez, 2002), with an average fertilizer application rate of 13 kg ha^{-1} (Minot and Benson, 2009). Soil deficiencies of macronutrients are widespread in the region, with negative nutrient balances reported for nitrogen (N), phosphorus (P) and potassium (K) in most parts of SSA (Xu et al., 2014). As a result, the yields obtained by farmers using local practices of important food crops in the majority of smallholder farming systems in SSA are far below the attainable yield (Van Ittersum et al., 2016) resulting in yield gaps, defined as difference between actual and potential yields under rainfed conditions without nutrient deficiency, pest or diseases (Van Ittersum and Rabbinge, 1997). In the last decade for SSA, actual rainfed maize yields ranged from 1.2 to 2.2 t ha^{-1}, representing only 15–27% of the potential yield under rainfed conditions (Van Ittersum et al., 2016). Consequently, SSA has been identified as one of the regions in the world with the lowest cereal sufficiency ratio defined as the ratio between domestic production and total consumption (Van Ittersum et al., 2016).

Given that up to 75% of the population in SSA depend directly or indirectly on agriculture as a livelihood source (Nziguheba et al., 2010; Sanchez et al., 2007), the sector's large contribution to the overall economy (Diao et al., 2010), and the projected decrease in cereal self sufficiency over time (Van Ittersum et al., 2016), agricultural intensification is urgently needed (Tittonell and Giller, 2013). Considerable 'low hanging' opportunities exist for intensification of production

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of major cereals in SSA (Mueller et al., 2012) when N, P and K deficiencies are addressed (Adediran and Banjoko, 1995). Since the launch of the Alliance for Green Revolution in African (AGRA) in 2006 (AGRA, 2016), and the recommendations of the Africa fertilizer summit of 2006 (Summit, 2006), a number of research programmes have focused on intensification of crop productivity in smallholder farming systems in SSA (Chikowo et al., 2014). Although fertilizer use has increased in a number of countries in SSA, its use efficiency remains low due to poor crop management practices (Byerlee et al., 2007; Sheahan and Barrett, 2014), the predominance of inherently low fertility sandy soils (Bationo et al., 2012), and unbalanced blanket fertilizer recommendations that do not address the complexity of smallholder farming systems (Chikowo et al., 2014; Giller et al., 2011). Further, the occurrence of “non-responsive soils” where application of available fertilizers does not result in increased crop productivity (Vanlauwe et al., 2010) has an additional adverse effect on fertilizer use efficiency. Such non-responsiveness may be due to a range of factors including macro- and micronutrient depletion, poor germination due to slaking or top-soil erosion, aluminium toxicity in relation to soil acidification and increased sensitivity to drought conditions (Tittonell and Giller, 2013; Vanlauwe et al., 2015). As a result, crop productivity intensification programmes in SSA have faced large variations in yield responses to applied nutrients at farm and field scales (Tittonell et al., 2008b; Vanlauwe et al., 2006). This raises the need for fertilizer recommendations that are tailored for specific farm and field conditions (Smaling et al., 1992; Tittonell et al., 2008a). Although, inherent soil fertility is related to soil forming factors including geomorphology, local climate and vegetation (Deckers, 2002; Smaling et al., 1993), cropping intensity and past soil management have been identified as major drivers of variability (Tittonell et al., 2005). The centripetal net transport of nutrients by animals also results in strong gradients at landscape level (van Keulen and Breman, 1990). The strong effects of management often result in patterns of decreasing soil fertility with increasing distance from homesteads within farms (Tittonell et al., 2005; Zingore et al., 2007a) and decreasing soil fertility with decreasing resource availability and use among farms (Giller et al., 2006; Tittonell et al., 2005). Consequently, regions and or farms with similar inherent soil fertility may over time develop strong heterogeneity in soil fertility and associated responses to macronutrients (N, P and K) applications. There is a paucity of information on both spatial and temporal patterns of such responses. Spatio-temporal patterns refer to differences in the dynamics of crop yield responses to macronutrients applications in an area with similar climatic conditions. This is because most nutrient management technologies were developed at research stations without sufficiently acknowledging the complexity of farming systems (Chikowo et al., 2014). Such information would help to target the right fertilizer and application rates to specific crops and locations and improve the efficiency of fertilizer use (Kihara et al., 2016). Further, understanding the relationships between spatial-temporal responses to macronutrients application and soil analysis results would help in quantifying the value of soil analysis, which is considered an important component of restoring and managing soil fertility in smallholder farming systems (Sanginga and Woomer, 2009). Controlled experiments in a series of heterogeneous farmers’ fields therefore offer the most conceptually straight forward way to study spatial temporal variations in responses to macronutrients (Lobell et al., 2009; Vanlauwe et al., 2006). Further insight on the magnitude, and consistency of observed spatial temporal patterns over time can then be achieved using cluster analysis (Perez-Quezeda et al., 2003). Cluster analysis allows for the grouping of fields showing similar responses over time into distinct classes (Fridgen et al., 2004), and was used effectively to identify various classes of nutrient response patterns in smallholder farming systems in SSA (Kihara et al., 2016).

The specific objectives of this study were to: (i) assess the magnitude and spatial-temporal patterns of maize yield responses to N, P and K application; (ii) identify and characterize clusters of farms with similar yield response patterns to N, P and K; (iii) assess the utility of soil chemical properties in predicting maize responses to N, P and K application. We hypothesize that patterns of crop responses to N, P and K fertilization over a combination of space and time in heterogeneous farms provide an important basis for developing site-specific fertilizer recommendations.

2. Materials and methods

2.1. Study site

The study was conducted in Sidindi, western Kenya. A 10 km by 10 km site previously used to collect soil mapping data under the African Soil Information Services (AfSIS) project was selected (AfSIS, 2016). The site is centred at a latitude of 0.15 °N, a longitude of 34.4°E and at about 1240 m above sea level. Annual rainfall ranges from 1600 to 2000 mm and is distributed over two distinct seasons with a long rains (LR) season from March to July and short rains (SR) season from September to December. Maize is the main staple food crop and is cultivated on more than 80% of the crop area in western Kenya (Place et al., 2006). Despite water limited yields (Yw) which refers to the yield achievable in farmer’s fields with best nutrient, pest, and crop management practices under rainfed conditions (Van Ittersum et al., 2013) of 12 t ha^{-1} and 8 t ha^{-1} in the long and short rains seasons respectively, actual maize yields on majority of smallholder farms in western Kenya are low at about 1.9 t ha^{-1} (Van Ittersum et al., 2016). The area is also characterized by large within and between farm heterogeneity in soil fertility (Tittonell et al., 2005).

2.2. Selection of trial sites

On-farm nutrient omission trials were established in 2013 across 24 sites representative of major soil units in the study area. Selection of trial sites was conducted on the basis of a previous survey conducted by the AfSIS project (AfSIS, 2016) that collected socio economic and agronomic data from 300 farmers within the study site (data not shown). From this survey, stratified random sampling was conducted to select an initial sample containing 48 farms representative of the study area based on land size, socio-economic characteristics and soil type.

From this sample, eight fields within each of the three sub-locations in the study area namely Sirembe, Malanga, and Ndere were selected based on the availability of land for trial set-up to make a total of 24 fields. Seasonal rainfall data in each of the sub-locations was collected using rain gauges located at each of the sub-locations. The experiments were conducted for six consecutive cropping seasons in 2013–2015 (Fig. 1).

2.3. Site characterization

Prior to the establishment of the trials, the position of each field was

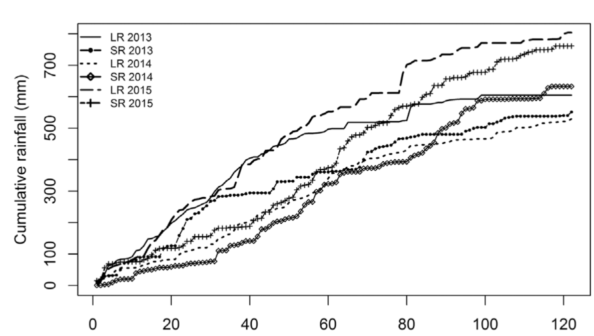

Fig. 1. Cumulative average rainfall in the long rain (LR) and short rain (SR) seasons of 2013–2015.