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Occurrence of poorly responsive soils in western Kenya and associated nutrient imbalances in maize (*Zea mays* L.)

Ruth Njoroge[a,b,*], Abigael N. Otinga[b], John R. Okalebo[b], Mary Pepela[b], Roel Merckx[a]

[a] Division of Soil and Water Management, KU Leuven, Kasteelpark Arenberg 20 box 2459-3001, Leuven, Belgium
[b] Department of Soil Science, University of Eldoret, Box 30100-1125, Eldoret, Kenya

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ABSTRACT

A poor response to fertilizer application is one of the persisting constraints preventing closure of the maize yield gaps in Sub-Saharan Africa (SSA). It is speculated that nutrient imbalances derived from deficient and/or excessive concentrations could be one of the causes of this limited response of maize to fertilizer. This is however not confirmed and the extent of such poor response is ill-documented. To investigate this, we conducted 44 on-farm trials with a two treatment structure (with and without NPK fertilizer) in two subsequent seasons, the 2014 long rains (LR) and short rains (SR) distributed across two sites: Bungoma-Southwest and Busia-North in western Kenya. As a discriminating criterion between responsive and poorly responsive soils, we used a Value Cost Ratio (VCR) of 2 of NPK fertilizer use. Nutrient sufficiency ranges were developed using compositional nutrient diagnosis (CND method) and then used to identify both deficient and/or excessive nutrient concentrations occurring in maize grown in the poorly responsive soils.

Results show that 48% of all fields from both sites could be classified as 'poorly responsive', with small VCR values ranging between 0.1 and 1.99. Nutrient deficiencies were more prevalent than situations of excessive concentrations in such fields. N-deficiency was the most common in the unfertilized (control) plots occurring in between 80 and 89% of the poorly responsive plots. Zn-deficiency became apparent in the fertilized plots and was observed at similar frequencies in this treatment. The next most widespread nutrient deficiencies in poorly responsive soils were those of P and Cu affecting between 70 and 79% of both control and fertilized plots. K and Mg deficiencies were rare in both treatments. This study indicates that the occurrence of poorly responsive soils in Bungoma-southwest and Busia-North is likely related to micronutrient deficiencies. These findings necessitate further investigation on the bioavailability of these micronutrients nutrients in such soils and a validation trial to evaluate the extent of crop responses.

1. Introduction

Maize is the primary staple food for most Kenyans accounting for 36% of their calorie intake and therefore, it is the most grown cereal in the country (Hassan and Karanja, 1997; Lewis et al., 1998). Ninety-eight percent of the country's average annual production, ranging between 2.5 and 3 million tons, is achieved by small-scale farmers who are spread across different production potential zones (Kibaara and Kavoi, 2012; FAO, 2014). However, the country's annual maize demand estimated at 98 kg per capita surpasses the production and inevitably leads to net imports (Nyoro et al., 1999). The quantity of the imported maize fluctuates considerably over a given period. For example, between the years 2003 and 2013, the imports ranged between 3% and 60% of the annual maize production (FAO, 2015).

Western Kenya is considered as a medium to high maize production zone with attainable yields of 4–5 t ha^{-1} (Jaetzold et al., 2005). However, actual average grain yield in the region ranges between 0.4 and 2 t ha^{-1}, 60–90% below the yield potential (Jama et al., 1997). These low maize yields sustain most of the families for only 6 months a year (Salasya et al., 2007). The persistent maize yield gaps have been attributed to both biophysical and socio-economic factors such as (i) inherent and/or induced low soil fertility, (ii) inadequate and erratic rainfall, (iii) diseases and pests, (iv) limited access to farm inputs and (v) lack of technology adoption (De Groote et al., 2010; Wambugu et al., 2012). Among these factors, the low soil fertility can be considered as one of the key constraints leading to insufficient maize production (Sanchez et al., 1997; De Groote et al., 2005; Tittonell et al., 2008). While nitrogen and phosphorus have been known to be major nutrients limiting crop production in most of the tropical soils, Tittonell et al. (2005) have acknowledged the occurrence of occasional

* Corresponding author at: Division of Soil and Water Management, KU Leuven, Kasteelpark Arenberg 20 box 2459-3001 Leuven, Belgium.
E-mail address: ruth.njoroge@kuleuven.be (R. Njoroge).

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potassium deficiencies. Several studies suggest that maize yields can increase by 200–500% when nutrients limiting crop growth and development are adequately addressed (Gachengo et al., 1999; Mucheru-Muna et al., 2011; Ngome et al., 2013). For instance, 25 on-farm trials conducted during the period between 1969 and 2009 in western Kenya showed that application of NPK-fertilizers resulted in an average extra yield of 2.5 t ha^{-1} above a control (zero NPK) (Kihara and Njoroge, 2013). Other studies in the same region showed yield increases of 2–4 t ha^{-1} above the control, specifically in soils that responded well to the NPK-fertilizers (Vanlauwe et al., 2006; Tittonell et al., 2008).

Soil fertility gradients at farm level have also been documented to significantly affect the NPK fertilizer responses. These soil fertility gradients are mainly caused by (i) differences in inherent soil properties due to specific landscape positioning (soil scapes) as described by Deckers (2002) and (ii) differences induced by farm management practices (Vanlauwe et al., 2010). As a consequence of these two interacting factors, two broad categories of NPK fertilizer responses are distinguished: (i) responsive (soils that respond well to standard application of NPK) and (ii) poorly responsive (soils with negligible responses due to other constraints besides those contained in the standard fertilizer) (Rusinamhodzi et al., 2013). Responsive soils can be found in the relatively fertile fields near the homestead while outfields are usually degraded, showing severe nutrient depletion and as such are likely poorly responsive (Vanlauwe et al., 2015). The occurrence of the latter not only results in reduced crop yields below the potential but also leads to negligible economic benefit from fertilizer use (Vanlauwe et al., 2015) and poor adoption of its use.

While responsive soils only require maintenance fertilization for continued productivity, the poorly responsive soils require a prior restoration strategy, often including multiple nutrient replenishment. For example, Zingore et al. (2008) observed that depleted sandy outfields in Zimbabwe responded weakly to N fertilizer in combination with relatively small rates of manure (6 t ha^{-1}). The authors observed that such fields had small N, P, Ca and Zn contents and required much larger quantities of farmyard manure (17 t ha^{-1}) before responding well and restoring their productivity. Likewise, Kihara et al. (2016) showed that addition of Ca, Mg, S, Zn, B and manure improved NPK-fertilizer responses in four different SSA countries, without specifying the exact location of the studied fields within the farms.

Given the scarce information on the occurrence of nutrient deficiencies in SSA and on whether nutrient deficiencies solely contribute to low crop production in poorly responsive soils, we decided to investigate whether a wider analysis of nutrient imbalances could explain the responses in more detail. As a matter of fact, we tested whether an existing method (CND, compositional nutrient diagnosis, (Parent and Dafir, 1992)) − based on high-throughput plant tissue and yield data analysis – to determine nutrient imbalances could be used to predict soil responses to fertilizers. Nutrient imbalances are the result of a chemical soil degradation process which can be reversed if timely diagnosed (Osman, 2014). They can be expressed either as deficient and/or excessive nutrient concentrations in a plant. While nutrient deficiencies can be inherent or induced through continuous depletion via crop harvest (Bationo and Waswa, 2011), excessive concentrations would occur (i) when some other nutrient is limiting and no growth dilution occurs or (ii) when a non-limiting nutrient is supplied in large quantities and as a consequence of ion competition during uptake and translocation in a plant (Smaling and Janssen, 1993; Van Wijk et al., 2003). This study, therefore, sought to (i) quantify the prevalence of poorly responsive soils in Bungoma-Southwest and Busia-North of western Kenya and (ii) determine the occurrence of deficient and/or excessive nutrients in maize grown in such soils.

2. Materials and methods

2.1. Description of the study area

The study was conducted in Bungoma and Busia counties of western Kenya. Bungoma covers an area of 3032 km^2 and is located on the slopes of Mt. Elgon between longitude 34° 20′ and 35° 15′ East and latitude 0° 28′ and 1° 30′ North. The county borders Trans-Nzoia county to the northeast, Kakamega county to the east and southeast, Busia county to the west and southwest and the Republic of Uganda to the northwest. Busia county is located between longitude 33° 55′ and 34° 25′ East and latitudes 0° 30′ and 0° 45′ North and covers a total area of 2207 km^2. Busia borders Kakamega county to the east, Bungoma to the north, Lake Victoria and Siaya county to the south and the Republic of Uganda to the west. The two counties have a bimodal rainfall pattern with long rains (LR) lasting from March to July and short rains (SR) lasting from September to December. Annual rainfall largely varies between 800 and 1800 mm with a reliability of 66% across the seasons. A comparison between the actually recorded rainfall during the study period (long rains (LR) and short rains (SR)) of 2014 and a 25-year long-term data series obtained from several meteorological stations located within close proximity to the study fields in each county demonstrates a normal distribution during the study period (Fig. 1). The region under consideration is dominated by deeply weathered soil types that include Acrisols, Nitisols, Ferralsols and Cambisols (Jaetzold et al., 2005). Selected topsoil properties for the study sites are presented in Table 1.

2.2. Selection of the experimental sites

Two study sites, located in Bungoma-Southwest and Busia-North, were chosen from sentinel sites used by the Africa Soil Information Service (AFSIS) (Vågen et al., 2010). A sentinel site measures 10 × 10 km and is specifically located in a region based on the Köppen and Geiger climatic zones in Africa (Kottek et al., 2006). Each site contains quantitative and qualitative biophysical data comprising of soil properties that can be used as indicators of soil fertility variability within a landscape (Vågen et al., 2010). In this study, we chose to use the following two indicators: (i) soil texture and (ii) slope. Next, these two parameters were used as a criterion of mapping out 4 landscape domains from the study areas (i) > 50% silt and clay, < 5% slope (ii) > 50% silt and clay, > 5% slope (iii) < 50% silt and clay, < 5% slope (iv) < 50% silt and clay, > 5%. In each of these landscape domains, 10 geo-referenced coordinates were randomly selected to locate the actual experimental fields. Therefore, the total number of the fields was theoretically eighty (40 in every site).

The rationale behind our procedure to rely on landscape domains was to ensure that a wide range of soil fertility gradients was considered. On the one hand, a landscape domain with more than 50% silt and clay has a higher probability of a larger nutrient and moisture retention capacity and was therefore hypothesized to be more responsive to fertilizer applications in comparison to those with less than 50% silt and clay (Silver et al., 2000; Tremblay et al., 2012). On the other hand, a field with a gentle slope of less than 5% is presumed to have an adequate rooting depth, unlike the shallow depths often observed on steep slopes (> 5%) (Kravchenko and Bullock, 2000). A good rooting depth, in turn, translates into a larger pool of accessible nutrients and water and, again, is likely to respond well to fertilizer applications.

Finally, in each field, we took a composite soil sample from 9 random spots to verify the silt and clay contents and to determine other soil chemical properties prior to the experimental setup. Soil pH, available P and texture analyses were conducted in the Soil Science laboratory of the University of Eldoret, Kenya following the standard procedures described by Okalebo et al. (2002). The analyses of total N, organic carbon and cation exchangeable capacity were conducted at the Soil and Water Division of KU Leuven, Belgium. Dumas combustion