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Nitrogen fertilization modifies maize yield response to tillage and stubble in a sub-humid tropical environment

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ABSTRACT

Controversy around the benefits of NT and stubble retention, and weaknesses in the underpinning science arise from a limited understanding of the mechanisms that operate in these systems. Two experiments were conducted at the Kenya Agricultural and Livestock Research Organization research station in Embu (0.515°S and 37.273°E) over three seasons during the 2015 long rains, 2015/2016 short rains and 2016 long rains to explore the mechanisms that regulate crop growth, nitrogen uptake and yield in maize (*Zea mays* L.). In the first experiment, crops were grown in a factorial combination of conventional tillage (CT) and no-till (NT), three amounts of stubble (0, 3 and 5 t ha^{-1}) and three N rates (0, 80 and 120 kg N ha^{-1}). The second experiment investigated the interaction between tillage (CT, NT) and timing of N supply (80 kg N ha^{-1}) that was supplied at sowing, six- (V6) and 12-leaf stage, with 5 t ha^{-1} of stubble. Grain yield ranged from 2.3 to 5.3 t ha^{-1}, with small effects from tillage and stubble retention. Nitrogen had the largest impact on grain yield and influenced crop response to tillage and stubble by modifying crop growth rate (CGR) and nitrogen nutrition index (NNI). However, the effects of N timing on crop growth, yield and traits associated with N use efficiency were independent of tillage system. High CGR between V6 and flowering was associated with high NNI, which led to increased grain number. The value of stubble in water storage at sowing, and crop growth and yield was greater in a dry season (< 300 mm rainfall) compared with wet seasons (> 600 mm). Irrespective of tillage system, moderate amounts of stubble, higher N rates and better matching of N supply to the critical window for yield determination could improve maize yields in sub-humid tropical environments.

1. Introduction

The benefits of no-till (NT) and stubble retention to the improvement of water and nitrogen use efficiency, and grain yield in sub-humid environments are controversial (Giller et al., 2009). In addition, the underpinning science is only partially understood (Giller et al., 2015). These uncertainties raise questions as to the circumstances where these practices improve yield and how physiological mechanisms regulate crop growth and yield under these conditions (Verhulst et al., 2011; Brouder and Gomez-Macpherson, 2014). Some of the limitations concern the fertilizer N rates that are required to increase yield and counter possible N immobilisation by cereal stubble, the minimum amount of stubble required to provide the benefits of mulching where there are trade-offs in stubble allocation between soil cover and livestock feeding, and potential avenues to increase N use efficiency (Giller et al., 2009; Giller et al., 2011).

A key attribute of NT and stubble retention is water conservation, an important driver for yield, increases in many dryland systems (Rusinamhodzi et al., 2011; Scott et al., 2013; Thierfelder et al., 2013). Stored subsoil moisture allows for early sowing and supports post-flowering growth when grain filling is sensitive to water deficit (Kirkegaard and Hunt, 2010; Sadras et al., 2012). However, the contribution of NT and stubble retention depends on rainfall pattern, evaporative demand and soil type (Kirkegaard, 1995; Monzon et al., 2006; Kirkegaard and Hunt, 2010; Verburg et al., 2012).

Insufficient use and inappropriate management of fertilizer N limits not only the productivity of NT and stubble retention systems but is a widespread challenge in smallholder systems sub-Saharan Africa

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Abbreviations: SSA, sub-Saharan Africa; CA, conservation agriculture; NT, no-till; CT, conventional tillage; N, nitrogen; NNI, N nutrition index; CGR, crop growth rate; Nc, critical N concentration; DM, dry mass; S, south; E, east; kg, kilogram; ha, hectare; t, tonnes; NUE, N use efficiency; AE, N agronomic efficiency; RE, N recovery efficiency; IE, N internal efficiency; PE, N physiological efficiency; NRE, N remobilization efficiency; NHI, N harvest index; V6, six-leaf stage; V12, 12-leaf stage; WUE, water use efficiency

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(Sommer et al., 2014; Vanlauwe et al., 2014). Yield declines under NT-stubble retention systems are larger without N addition in sub-humid environments than in drylands (Pittelkow et al., 2015b). Based on co-limitation principles, yield is maximised when both water and N are equally limiting (Sadras, 2005; Cossani et al., 2010; Riar et al., 2016). Sadras et al. (2012) discuss how N is critical to capture the benefits of water conservation and the requirement for an adequate water supply to capture the benefits of N supply. Knowledge is limited, however, on the rate and timing of N supply required to capture the benefits of water conservation, and on the means to counter possible N-immobilisation by cereal stubble to increase grain yield in NT and stubble retention systems (Giller et al., 2009; Giller et al., 2011).

Nitrogen use efficiency (NUE), the efficiency with which available N is absorbed and converted into grain (Dobermann, 2007), is frequently low in NT and stubble retention systems, due largely to N immobilisation in stubble (Grahmann et al., 2013). There is a need to adjust the rate and timing of N supply (Dobermann, 2007; Verhulst et al., 2014), and to reduce losses through leaching and denitrification (Angás et al., 2006; Verachtert et al., 2009). Improving both N uptake and utilization efficiency could increase yield and grain quality of maize (Ciampitti and Vyn, 2012). N uptake involves N recovery by the crop and agronomic efficiency of the applied N, while N use is facilitated through physiological efficiency and increasing N harvest index (Dobermann, 2007; Setiyono et al., 2010; Ciampitti and Vyn, 2012). In SSA, the soils are inherently infertile and have limited response to NT and stubble retention practices under current low N rates, which have stagnated since 1960s (Dimes et al., 2015).

Nitrogen economy is a critical driver for biomass accumulation and grain production (Sadras and Lemaire, 2014), and the assessment of crop N nutrition is a prerequisite for the interpretation of agronomic data (Gastal et al., 2015). Crop N nutrition can be quantified by nitrogen nutrition index (NNI), a ratio of actual N concentration to critical N concentration required to achieve maximum biomass (Gastal et al., 2015). On the other hand, understanding of the mechanisms that regulate crop growth, N uptake and use efficiency, and grain yield in maize would improve options for better N management.

In light of the constraints to the application of NT and stubble in sub-humid environments, this paper reports on two studies that evaluate the effects of tillage, stubble amount and nitrogen on crop growth, N nutrition and yield. The first study aims to (i) understand the contribution of the management practices and their interactions by exploring underlying physiological mechanisms that regulate crop growth, N nutrition and yield. The second study provides an understanding of how the interaction between tillage and timing of N supply impact crop growth, N and yield in NT and stubble retention systems. In these studies we hypothesise that (i) the effect of tillage and stubble retention on water conservation and yield in sub-humid environments is dependent on seasonal rainfall, and that (ii) both the rate and timing of N supply will modify crop growth, N use and yield response to NT and stubble retention.

2. Materials and methods

2.1. Site

Field experiments were conducted at the Kenya Agricultural and Livestock Research Organisation Research Station at Embu, 0.515°S and 37.273°E, 1425 m above sea level. The site is sub-humid with mean temperature of 22 °C (Jaetzold et al., 2006). Rainfall is bimodal, with a long rains season from April to August and a short rains season from October to February (Jaetzold et al., 2006). Soils are deep (> 2.5 m) highly weathered humic nitisols with low exchangeable bases, relatively high P-sorption, and with medium to low fertility (Jaetzold et al., 2006). Table 1 presents initial soil characterisation at 0–15 cm and 15–30 cm depth.

At the onset of the experiments during 2015 long rains, soils were sampled at 0–15 and 15–30 cm layers in each replicate, bulked and analysed for pH (1:2.5, soil/water), organic carbon, total N, mineral N, potassium, calcium, magnesium, phosphorus and cation exchange capacity (CEC). Organic carbon was extracted using acidified dichromate while total N was determined by wet oxidation using the Kjeldahl method (Dai et al., 2013). Calcium and magnesium were extracted using 1 N KCl and determined using a spectrophotometer while phosphorus and potassium were determined using a modified Olsen method (Okalebo et al., 2002).

2.2. Treatments and experiment design

2.2.1. Experiment 1

Two tillage systems (conventional tillage, CT and no-till, NT), three amounts of stubble (0, 3 and 5 t ha^{-1}) and three fertilizer N rates (0, 80 and 120 kg N ha^{-1}) were evaluated under continuous maize cropping for three consecutive seasons. The experiment was laid out in a split-split-plot design with three replications. Tillage system was allocated to the main plots, stubble amount was assigned to the sub-plots while N rate formed the sub-sub plots. Main plot size was 31 m × 12.25 m, the sub-plots were 28 m × 3.75 m and sub-sub plot size was 7 m × 3.75 m.

Nitrogen was supplied as urea and provided as ⅓ at sowing and ⅔ at six leaf stage (V6), for both 80 and 120 kg N ha^{-1}. Top dressing fractions were banded around plants, prior to sufficient amounts of rainfall to promote movement of urea into soil.

2.2.2. Experiment 2

Treatments were control (no fertilizer; N0), and 80 kg N ha^{-1} applied at sowing (N1) or applied as ⅓ at sowing and ⅔ at six-leaf stage (N2), ⅓ at sowing, ⅓ at six-leaf and ⅓ at 12-leaf stage (N3), and ½ at six-leaf and ½ at 12-leaf stage (N4). These treatments were evaluated under both CT and NT with the application of 5 t ha^{-1} of stubble. The experiment was laid out in a split-plot design with three replications. Tillage system was allocated to the main plots while N supply formed the sub-plots. Main plots measured 31 m × 12.25 m while the sub-plots were 7 m × 3.75 m.

2.3. Management

Prior to the establishment of both experiments, one season lag phase was used to even-out the experimental block and the soils were not tilled. To mine soil N, closely spaced maize was sown during the short rains season of 2014, without the addition of N fertilizer.

Tillage and stubble treatments were applied two weeks before sowing in the same plot every season. Exact amounts of stubble were maintained at the onset of each season, whereby additional stubble allowed for undecomposed material. Conventionally tilled plots were prepared by digging to 15 cm depth to thoroughly disturb the soil. Under CT, maize stubble was allocated at prescribed rates, chopped into less than 5 cm long pieces and incorporated into the soil when digging. No-till plots were left undisturbed and stubble mulch was spread on the soil surface at the prescribed rates. In all plots, sowing was done manually by opening 5 cm deep holes to hold seed and fertilizer. All plots received basal fertilizer of triple super phosphate at the rate of 60 P kg ha^{-1} which was side banded on the sowing rows.

A locally adapted hybrid of maize DeKalb (DK) 8031 was used in both experiments. Crops were sown at the onset of rains: on 25th March for 2015 long rains season, 19th October for 2015/2016 short rains season and 3rd April for 2016 long rains season. Seed was sown in rows 0.75 m apart with 0.25 m between holes in a row. Two seeds were sown per hole and thinned at the three leaf stage (V3) to one plant per station, to achieve a plant population density of approximately 5.3 plants m^{-2}.

Weeds were controlled with 1.5 L ha^{-1} of Roundup® (glyphosate) before sowing and 1.5 L ha^{-1} Dual Gold® (960 g L^{-1} S-metolachlor) after sowing in both tillage systems. In-crop weeds were removed by