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Modelling maize yield response to plant density and water and nitrogen supply in a semi-arid region

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ABSTRACT

Nitrogen (N) fertiliser use in Mozambique is very low, but blanket recommendations on higher fertiliser application rates may not be appropriate for small-scale rainfed farms in different edaphic and climate regions of the country. Data from field experiments with two water levels, three tillage methods (only one tillage method was used in the present study) and two fertiliser N application rates to maize (*Zea mays* L.) were used to calibrate and validate the Agricultural Production System Simulator (APSIM) model. The model was subsequently used to simulate multiple-season scenarios (25 years) and determine adequate fertiliser rates for rainfed and supplemental irrigation conditions on sandy loam soil in Southern Mozambique. For this, APSIM was configured to simulate long-term maize response to varying N application (0–120 kg ha^{-1}) and planting density (1, 4.2 and 8.4 plants m^{-2}) in a rainfed or supplemental irrigation system.

The APSIM maize model proved capable of producing fairly accurate predictions of observed trends in soil moisture under rainfed and irrigation conditions in a semi-arid region. The model was also able to predict maize grain and biomass yield well.

Multiple-season analysis of grain yield revealed that, compared with the medium (recommended) plant density (4.2 plants m^{-2}), in rainfed conditions low plant density and high plant density (8.4 plants m^{-2}) reduced overall grain yield by 1281 kg ha^{-1} (40%) and 242 kg ha^{-1} (8%), respectively. With high plant density, grain yield was below 1000 kg ha^{-1} in 20% of simulated years, whereas with low planting density the lowest grain yield was around 500 kg ha^{-1} (4% of simulated years). Irrigation stabilised grain yield in most simulated years, except in some years with high planting density.

Fertiliser and supplemental irrigation increased yield for all scenarios except those with low plant density. The optimal N fertiliser rate was identified as 33–102 kg ha^{-1} in the rainfed system and 38–86 kg ha^{-1} in the supplemental irrigation system, compared with the national blanket recommendation of 120 kg N ha^{-1}. The simulation results suggested that the national recommended rate is only appropriate for years and regions with adequate rainfall distribution (>300 mm per cropping season).

1. Introduction

Agricultural systems in semi-arid regions of Africa that rely on rainfall as a main source of water supply are prone to a high risk of variable production levels (Vlek et al., 2012). According to Whitbread et al. (2010), smallholder farmers in semi-arid regions face serious challenges in maintaining food security, exacerbated by low soil fertility, limited resources to purchase inputs and high variable rainfall. Rainfall is a major driver of enhanced efficient response to fertilisers applied in small-scale farming systems under arid and semi-arid conditions (Shamudzarira & Robertson, 2002).

It is known that fertiliser efficiency and agricultural productivity are low in most parts of Africa and Mozambique (Kisaka et al., 2015; Silici et al., 2015). The efficiency with which soil and water resources are utilised in sub-Saharan African cropping systems is especially critical, as these resources are generally scarce in that region (Chikowo et al., 2008). In this regard, Kloss et al. (2012) highlighted the need for strategies to improve crop growth, make irrigation more efficient and sustainable and conserve farmlands. In addition, grain yield is influenced by inter-row spacing and sowing density (Testa et al., 2016). In Mozambique, the standard recommended plant density for maize is 4.4 plants m^{-2} (Roxburgh

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& Rodriguez, 2016), regardless of the soil type and water supply method. However, small-scale farmers use a higher plant density than the recommended level (Sitole, 2012), sometimes with a greater row spacing, thus reducing the planting density. Maize irrigation is currently not a common practice in Mozambique (Benson et al., 2014), although supplemental irrigation can increase grain yield (Magaia et al., 2015). The actual recommended fertiliser rate for maize varies from 100 to 120 kg ha^{-1} for a target yield of 5–6 ton ha^{-1} (Fato et al., 2011). However, Mozambique has a blanket recommended nitrogen fertiliser rate of 120 kg ha^{-1} (Fato et al., 2011) for maize production (Rware et al., 2014). This rate does not account for climate variability or field management strategies (e.g. planting density) under rainfed, semi-arid conditions.

Models of agricultural systems are useful tools for understanding complex system interactions. Models have been tested in Africa to evaluate crop production under a wide range of management systems (Masikati et al., 2014) and to simulate the low-input farming systems common in sub-Saharan African (Shamudzarira & Robertson, 2002; Kisaka et al., 2015). A major constraint in modelling work is the lack of reliable, comprehensive datasets for calibration and validation of crop models (Archontoulis et al., 2014).

Model simulations have shown that a supply of only 50 kg N and 18 kg P ha^{-1}, which is less than one-third of the current level in high-input countries, would double maize yield in most areas of sub-Saharan Africa (Folberth et al., 2013). The Agricultural Production System Simulator (APSIM) model has been used in South and East African countries to explore possible management changes in smallholder systems (Roxburgh & Rodriguez, 2016). Many studies (Shamudzarira & Robertson, 2002; Masikati et al., 2014; Kisaka et al., 2015) have shown that APSIM can adequately simulate grain yield under different agro-climate conditions and enhance understanding of different farmers' strategies in maize cropping. There have been no long-term experiments on maize productivity under rainfed, semi-arid conditions in small-scale farming in Mozambique that consider the impact of tillage, low rates of fertiliser application, planting density and supplemental irrigation, but long-term crop simulations can help assess the combined effects of these factors.

The aims of this study were thus to: (1) evaluate the performance of the APSIM model in simulating maize grain yield response to varying water supply (rainfed and supplemental irrigation) and nitrogen (N) application (0 and 48 kg ha^{-1}) on a sandy loam soil under disc tillage; and (2) assess long-term yields under different levels of N application (0–120 kg ha^{-1}) and plant density (1, 4.2 and 8.4 plants m^{-2}) in rainfed and supplemental irrigation conditions.

2. Material and methods

2.1. Study site and experimental set-up for model calibration and validation

A maize trial was conducted at Sábiè Agronomic Centre (CEDAS) in Mozambique, a semi-arid region, during the main cropping season, November-March, in three consecutive years (2012/2013, 2013/2014 and 2014/2015). The site is located in Sábiè village in Moamba district (25°19′08.0′íS, 032°15′55.3′íE), which is situated about 100 km north-west of Maputo. Total rainfall during the cropping seasons studied was 400.2, 373.4 mm and 307.4 mm, respectively. The long-term average rainfall (1990–2015) in the region for the cropping season is 507 mm, but in some seasons it is >800 mm (Fig. 1). We therefore took an average of the years with <800 mm and thus our reference average rainfall for the cropping season was 425 mm. Rainfall amount in the three cropping seasons studied corresponded to 95%, 88% and 62% of the reference average rainfall. Daily temperature

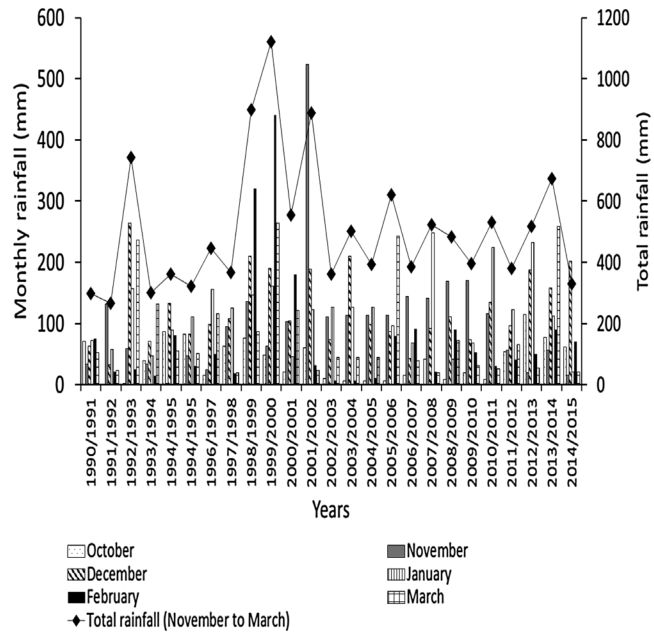

Fig. 1. Long-term (1990–2015) rainfall in the main cropping season (November-March) in the study region.

ranged from a minimum of 12.3 °C to a maximum of 41 °C for season 2012/2013 (12.3 °C–39 °C), 2013/2014 (13 °C–40 °C) and 2014/2015 (13.8 °C–41 °C), respectively.

The field trials comprised a factorial experiment with a randomised complete block design on a sandy loam soil. The main treatments were tillage (three methods), water supply (two levels) and fertiliser (two levels). The tillage methods were hand hoe (T1), strip tillage (T2) and disc tillage (T3). In the modelling, only disc tillage was considered. The water supply levels were rainfed (W1) and supplemental drip irrigation (W2). The fertiliser levels were without N (F1) and with 40% of the recommended N dose of 120 kg N ha^{-1} (F2). Each combination of treatments had three replicates. The plot size was 6.0 m × 14.0 m, each with eight rows of maize, and with 1 m between plots. The crop was Matuba, an open-pollinated maize cultivar common in Mozambique. Target plant density was 4.2 plants m^{-2}, with 0.3 m spacing within rows and 0.8 m spacing between rows.

Fertilisation comprised three equal split applications providing a total of 48 kg N ha^{-1}: 16 kg ha^{-1} at sowing, 16 kg ha^{-1} at seven visible leaf stage (V7) and 16 kg ha^{-1} at tasselling (VT). NPK (12-24-12) fertiliser was applied as a starter, followed by urea (46% N). Weeding was performed manually using a hand hoe one day before fertiliser application, at V7 and VT. Care was taken during weeding to avoid disturbing the tillage treatment. The experiment was kept free of weeds and pests.

Supplemental irrigation was applied in the irrigated treatment only (W2), thus in 18 out of the 36 plots. The aim with irrigation was to keep the soil moisture content above 50% of plant-available water (PAW) (46 mm to 0.6 m depth) in all seasons. Soil moisture was measured daily during the season with a profile probe (PR2, Delta-t Co., United Kingdom), with one access tube to 100 cm depth in each plot. Fraction of PAW at each measurement occasion was calculated according to the equation:

$$PAW_f = \frac{(MSM - PWP)}{(FC - PWP)} \times 100\% \quad (1)$$

where MSM is measured soil moisture (%vol.), PWP is the soil permanent wilting point (%vol.) and FC is the soil field capacity (%vol.) (where FC-PWP = PAW). Soil moisture was not measured during

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