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Risk management options in maize cropping systems in semi-arid areas of Southern Africa

Esther N. Masvaya[a,b,*], Justice Nyamangara[c], Ken E. Giller[b], Katrien Descheemaeker[b]

[a] International Crops Research Institute for the Semi-Arid Tropics, Matopos Research Station, P. O. Box 776, Bulawayo, Zimbabwe
[b] Plant Production Systems Group, Wageningen University, P.O. Box 430, 6700 AK, Wageningen, The Netherlands
[c] Department of Environmental Science and Technology, Chinhoyi University of Technology, P. Bag 7724, Chinhoyi, Zimbabwe

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ABSTRACT

Although rainfed cropping in semi-arid areas is risky due to frequent droughts and dry spells, planting early with the first rains is often expected to result in yield benefits. We hypothesised that planting early leads to yield benefits if the planting coincides with a mineral N flush at the start of the season but leads to crop failure if there is a false start to the cropping season. The effects of different management options, including tillage (ploughing and ripping), mulch (two levels 0 and 2 t ha^{-1}) and fertility amendments (five levels: 0; 20 and 40 kg N ha^{-1}; 5 t manure ha^{-1} and 5 t ha^{-1} manure + 20 kg N ha^{-1}) on grain yields were simulated using the calibrated and tested APSIM model over a 30-year period (1984–2015). Yields were simulated and compared across seven planting date scenarios (1 November, 15 November, 30 November, 15 December, 31 December, 15 January and planting when cumulative rainfall of 20 mm was received in three consecutive days). Planting with the first rains with manure + 20 kg N ha^{-1} resulted in the best average yield of 2271 kg ha^{-1} whilst the poorest average yields of 22 kg ha^{-1} were observed with planting on 15 January with no fertility amendment (0 kg N ha^{-1}). Planting early (1 Nov to 15 Nov) and with the first rains resulted in exceeding the food self-sufficiency threshold of 1080 kg ha^{-1} in 40–83 % of the cases if fertility amendments are applied, as well as a low probability of complete crop failure, ranging from 0 to 40%. Grain yield penalties due to a false start followed the trend: ripper + mulch > plough + mulch > ripper (no mulch) averaging 256, 190 and 182 kg ha^{-1} respectively across all the fertility treatments. The model was able to simulate the occurrence of the mineral N flush with the first rains. Its coincidence with planting resulted in average yield benefits of 712, 452, 382 and 210 kg ha^{-1} for the following respective planting dates: 1 Nov, 15 Nov, 30 Nov, variable date when > 20 mm rainfall was received. Early planting, in combination with reduced tillage, mulch and N containing fertility amendments is critical to reduce risk of crop failure in the smallholder cropping systems of semi-arid areas of southern Africa and achieve the best possible yields.

1. Introduction

Smallholder farmers in sub-Saharan Africa (SSA) face many production constraints that are exacerbated by climate variability and change. Droughts and dry spells are frequently experienced in semi-arid Zimbabwe during the growing season, making rain-fed cropping risky (Baudron et al., 2012; Rurinda et al., 2013). The climate in Zimbabwe is controlled by global atmospheric circulation patterns, chief amongst them the movement of the inter-tropical convergence zone (ITCZ) in the north and the tropical temperate troughs (TTTs) further south which determine the annual seasonality of precipitation across tropical Africa (Tadross et al., 2007; Mavhura et al., 2015). Mid-season dry spells of 10–20 days commonly occur around late December/early January following the movements of these systems (Tadross et al., 2007) and are disastrous for crop production if the air systems migrate too far such that the dry spells become extremely long. The inter-seasonal rainfall variability in semi-arid Zimbabwe is characterised by early rains in some seasons whilst the rain may arrive late in others (Mupangwa et al., 2011a). Also at the end of the growing season rains may stop early, which happens regularly in semi-arid parts of Zimbabwe (Mupangwa et al., 2011a). This rainfall variability makes the selection of crop types and varieties, and the planning of planting dates critical for successful cropping in rain-fed systems.

The impact of planting date on crop production has been evaluated in Zimbabwe with a focus on escaping dry spells that typically occur in January (Spear, 1968). It has been recommended that farmers plant

* Corresponding author at: International Crops Research Institute for the Semi-Arid Tropics, Matopos Research Station, P. O. Box 776, Bulawayo, Zimbabwe.
E-mail address: E.Masvaya@cgiar.org (E.N. Masvaya).

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with the first effective rains to minimise reduction in maize grain yield of up to 32% associated with delayed planting, which is attributed to the shorter day-lengths as the season progresses (Shumba et al., 1992). However, in a crop modelling study in semi-arid Zimbabwe, Rurinda et al. (2015) found that planting in current and future climates (up to 2099) can be delayed to some extent without any yield penalties. Nevertheless, in the current farming systems, the shortage of animal traction for land preparation often leads to delays in planting time. This results in serious yield penalties if the short window when the first rains wet the soil enough to be tilled is missed.

Farmers use a range of planting dates and plant at almost any opportunity because of the rainfall pattern, input access, and the availability of draught power and labour (Milgroom and Giller, 2013; Rurinda et al., 2013; Nyagumbo et al., 2017). Conservation agriculture (CA) can provide a major benefit by reducing the tillage requirement, thus allowing farmers to plant on time at the start of the season. Nyagumbo et al. (2008) indicated that in Zimbabwean cropping systems, the major benefit of CA for crop yields comes from timely planting and not from the specific tillage employed. The onset of the first rains stimulates soil microbial activity resulting in a peak of soil N mineralisation (Birch, 1960). This so-called mineral N flush (Birch effect) is usually of short duration due to losses through leaching, denitrification, volatilisation and plant uptake (Chikowo et al., 2003; Bognonkpe and Becker, 2009). The magnitude of the mineral N flush is dependent on a number of factors which include the quantity and quality of organic matter (Franzluebbers et al., 1995), the occurrence and duration of dry spells at the onset of the rainy season and rainfall variables such as the intensity and quantity of rainfall (Bognonkpe and Becker, 2009). Planting early with the first rains may be beneficial to crops if the planting coincides with this mineral N flush or risky if these first rains appear to be a false start to the cropping season. Such false starts are not uncommon in semi-arid areas, as early-season rains are commonly followed by a dry spell, which is detrimental to crop establishment (Chikowo, 2011).

Several approaches from simple functional approaches to predict net N mineralisation (Stanford and Smith, 1972; Cabrera, 1993) to mechanistic approaches for simulating mineralisation-immobilisation turnover in soils have been used to model and thus describe N mineralisation kinetics in soils (Benbi and Richter, 2002; Mohanty et al., 2011). The Agricultural Production Systems sIMulator (APSIM) is a crop growth simulation model that can be used to predict N dynamics in soils. APSIM has been calibrated and validated for Zimbabwean conditions and crop cultivars. The model has been used previously to simulate maize response to N application (Shamudzarira and Robertson, 2002) and manure inputs in humid and dry regions (Chivenge et al., 2007), N and water stress dynamics in cereal-legume rotations (Ncube et al., 2009), the effects of mulch on crop yields and soil water dynamics under different tillage systems (Mupangwa et al., 2011b) and as a climate risk assessment tool (Chikowo, 2011; Rurinda et al., 2015). Experimental data on the effects of tillage systems on mineralisation and crop yields in the variable climates of SSA are not readily available thus calibrated and tested models such as APSIM can potentially be used as tools for strategic, tactical and operational decision support in crop management on-farm (Matthews et al., 2002).

It is important to know which management options in terms of planting dates, tillage and fertility amendments offer the greatest pay offs in terms of crop yields in different types of seasons, and in terms of reducing the risk of crop failure. Such information can enable farmers to plan on how to optimise resources available to improve crop production by being able to synchronise nutrient supply with crop demands. We hypothesised that under the current climate of semi-arid southern Africa, planting early is risky, as it: (1) leads to yield benefits to crops if the planting coincides with a mineral N flush at the start of the season, but (2) leads to crop failure if there is a false start to the cropping season. The specific objectives of this study were to (a) calibrate and test the APSIM model for maize production and N mineralisation in semi-arid Zimbabwe (b) to simulate the effects of tillage system and fertilisation on seasonal N mineralisation and crop yields and (c) apply the model to determine the effect of different planting date, tillage and soil fertility management strategies on the probabilities of experiencing complete crop failure and achieving maize grain yields that ensure household food self-sufficiency under the current climate.

2. Materials and methods

2.1. Study site

The site chosen for this study was Nqindi ward, Matobo district, Matabeleland South, Zimbabwe (20 39.58′S, 28 15.58′ E; 900 masl). The district lies in Agroecological Zone IV, characterised by semi-arid climate. Rainfall is unimodal with a distinct wet (November – March) and dry (April - October) season. The long-term average rainfall in the district is 580 mm. Droughts are frequent as are severe dry spells during the wet season (Vincent et al., 1960). The dominant soils are Eutric Arenosols derived from granite (WRB, 2006).

2.2. Field experiment set up for model calibration and testing

Maize growth and development data for the model calibration and testing were collected from an on-farm field trial carried out in Nqindi ward for three seasons 2012/13–2014/15. The field trial was set up as a split-split plot with plots arranged in a randomised complete block design with three replicates. The tillage system was the main plot treatment with two levels (ox-drawn ploughing and animal drawn ripping, both to a plough depth of 0.15 m) and the mulch management was the sub plot treatment with two levels (100% residue removed, and 100% residues retained after harvest). The mulch sub-treatment was not applied in the 2012/13 season as this was the first season. In subsequent seasons, the mulch retained averaged 2 t ha^{-1}. With tillage, a fraction of the retained residues was incorporated, approximating 20 and 80% under the ripper and plough tillage respectively. Five fertility amendments (mineral fertiliser at 0, 20 and 40 kg N ha^{-1}, 5 t ha^{-1} manure only and 5 t ha^{-1} manure + 20 kg N ha^{-1}) were randomised as the sub-sub plot treatment. The mineral fertiliser was applied at planting at a rate of 14 kg N ha^{-1}, the difference in N for the 20 and 40 kg N ha^{-1} treatment was applied six weeks after planting as top dressing. With the manure treatments, the manure was applied at planting and in the manure + 20 kg N ha^{-1} treatment, the mineral fertiliser was applied at six weeks after planting as top dressing. A short duration hybrid maize variety SC403 was planted in the trial (Masvaya et al., 2017). Plant (at harvesting) and manure (at application) samples were analysed for total C and N content (Bremner and Mulvaney, 1982; Anderson and Ingram, 1993) to determine the C:N ratios which were 80 and 20 respectively.

Initial soil samples were collected from each block at incremental depths of 0.10 m up to 1 m, the soil depth. The samples for each depth were bulked, mixed and analysed separately. Soils were air dried, passed through a 2 mm sieve and analysed for pH, texture, total and mineral N, Olsen P and organic C (Anderson and Ingram, 1993). Bulk density measurements were also derived from field measurements.

Nitrogen mineralisation in the field trial was estimated by an *in-situ* incubation technique. Detailed field measurements of inorganic N dynamics were made using in-situ incubation of undisturbed soil cores throughout the 2013/14 growing season (Masvaya et al., 2017). Mineral N (NH_4^+ and NO_3^-) was determined from the cores, which were removed and replaced at four-week intervals from planting until harvesting (days 28, 56, 84 and 112 after planting). N was extracted from the soil samples by shaking the field fresh sample in 0.5 M K_2SO_4 and the NH_4^+-N and NO_3^--N content was determined using methods described in Anderson and Ingram (1993). The net amount of mineralised N was calculated as the difference in mineral N between two points in