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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

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* 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 time (time_{i+1} – time_i).

2.3. Climate data

Long term daily maximum and minimum temperature, radiation and rainfall data (1984–2015) were obtained from the national weather station at Matopos Research Institute. The average seasonal rainfall for the 30-year period was 567 mm; the average maximum and minimum temperatures were 26.2 °C and 11.6 °C respectively whilst the solar radiation averaged 21.7 MJ m^{-2}. The long-term rainfall data was used to determine seasons with a false start. Daily rainfall measurements were also collected from the farms hosting the trial between October 2012 and July 2015 for model testing.

For semi-arid Zimbabwe, the start of the season has been defined as the first day after 1 October when the rainfall accumulated over 1 or 2 days is at least 20 mm and not followed by a period of more than 10 consecutive dry days in the following 30 days (Stern et al., 2006; Mupangwa et al., 2011a). A false start to the season would therefore occur when 20 mm of rainfall or more is received in 1–2 days then followed by a dry spell of more than 10 consecutive dry days.

2.4. Model description

In this study, APSIM version 7.8 (available at www.apsim.info) was used to simulate the crop system. The system was represented by four modules which require several parameters: the soil water (SOILWAT2), soil N and fertiliser module (SOILN2), surface organic matter for crop residue dynamics (surfaceOM) and the maize module. The APSIM crop module contains a short duration hybrid maize variety SC401 which was used to represent the SC403 used in the field trials.

2.4.1. Description of N mineralisation in the APSIM SoilN2 module

In APSIM, the SoilN2 module simulates the transformations of C and N in the soil which include fresh organic matter decomposition, N mineralisation and immobilisation, urea hydrolysis, ammonification, nitrification and denitrification (Gaydon et al., 2012). It operates on a daily time step, and decomposition of the fresh organic matter pool (FOM) occurs simultaneously in the two soil organic matter pools (BIOM and HUM) (Mohanty et al., 2011). The flows between the different pools are calculated in terms of carbon, with the corresponding nitrogen flows depending on the C:N ratio of the receiving pool (www.apsim.info). A constant C:N is assumed for BIOM; C:N for HUM is derived from the C:N ratio of the soil which is an input. Mineralisation in APSIM is also driven by soil moisture and temperature. Decomposition of BIOM and HUM pools are calculated as first-order processes (Probert et al., 1998), as proposed in empirical models (Stanford and Smith, 1972; Cabrera and Kissel, 1988). APSIM also assumes that part of the HUM pool is stable and the decomposition rate of the HUM pool is calculated with the equation of Bartholomew and Kirkham (1960) which follows the two-pool exponential mineralisation model (Probert et al., 1998, 2005).

2.5. APSIM model parameterisation

The soil parameters (Table 1) were partly derived from the soil analysis described in section 2.2). For the SOILWAT2 module, the soil characteristics of drained upper limit (DUL), saturation (SAT) and lower limit (LL15) (Table 1) were adopted from the sandy soils at Lucydale farm, Matopos Research Station (Masikati, 2006), which are similar in terms of parent material and texture to those at the study site in Nqindi, Matobo district. The U and CONA were set at 8.0 mm day^{-1} and 3.5 mm day^{-1} respectively, values suitable for tropical conditions and a value of 0.7 was used for the SWCON, a coefficient that specifies the proportion of the water in excess of field capacity that drains to the next layer in one day (Chikowo, 2011; Rurinda, 2014).

The bare runoff curve number was set at 85 and 55 for the plough and ripper tillage respectively. These curve numbers were chosen to account for the high runoff and low infiltration associated with excessive ploughing of sandy soils (plough treatment), and for high infiltration rates and low runoff under conservation tillage (ripper treatment) (USDA-SCS, 1986; Mupangwa, 2010). In addition to the difference in curve number, the user defined fraction of surface residues to incorporate under the plough and ripper tillage was set at 0.8 and 0.2 respectively.

The two mulch levels of the experiment (Section 2.1) were mimicked in the surfaceOM module where the initial surface residue was defined: 0 or 2 000 kg ha^{-1} for the 0 and 100% mulch retained treatments respectively and applied at the start of each simulation run. The C:N ratios of the maize residue and manure were set at the measured values of 80 and 20 respectively. The manure and fertiliser application rates as defined in the five fertility amendment treatments in Section 2.1 were specified in the APSIM manager.

2.6. Model testing

The model set up as described above was used as the baseline scenario which reflects the actual conditions at the site where the field experiments were set up. The APSIM model was used to simulate maize grain and stover yields at harvesting from the three seasons in which the field experiment was run (2012/13–2014/15) and daily N mineralisation from one season (2013/14). Model outputs were compared with observed field data from the field experiment. The statistical expressions used to compare the observed and simulated data are root mean square error (RMSE) and the modelling efficiency (EF). The EF (Eq. (2)) compares the deviation of the observed and predicted values to the variance of the observed values (Moriasi et al., 2007):

$$\text{Root Mean Square Error } (RMSE) = \left[\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2\right]^{0.5} \tag{1}$$

$$\text{Modelling Efficiency } (EF) = \frac{[\sum_{i=1}^{n}(O_i - O_m)^2 - \sum_{i=1}^{n}(P_i - O_i)^2]}{\sum_{i=1}^{n}(P_i - O_i)^2} \tag{2}$$

Where P_i is simulated values; O_i is measured values; O_m is mean of measured values, and n is number of the observations.

Table 1
Soil physical and chemical properties used for the APSIM simulations.

Soil depth (m)	Bulk density (Mgm^{-3})	pH (H_2O)	OC (%)	LL15 (mm/mm)	DUL (mm/mm)	SAT (mm/mm)	NO_3-N ($kgha^{-1}$)	NH_4-N ($kgha^{-1}$)
0.00-0.15	1.43	5.69	0.66	0.04	0.14	0.44	0.51	0.42
0.15-0.30	1.42	5.68	0.42	0.07	0.15	0.45	0.84	0.62
0.30-0.45	1.42	5.76	0.35	0.13	0.20	0.45	1.18	0.62
0.45-0.60	1.55	5.77	0.25	0.13	0.20	0.40	0.55	0.67
0.60-0.75	1.55	5.91	0.14	0.18	0.22	0.40	0.37	0.68
0.75-1.00	1.61	5.99	0.11	0.22	0.24	0.38	0.32	1.17

2.6.1. Model simulations

Following model testing, the model was used to simulate the effects of different management options reflecting the field trial treatments combining tillage (plough and ripper), mulch (two levels 0% and 100%) and fertility amendments (five levels: 0; 20 and 40 kg N ha^{-1}; 5 t manure and 5 t manure + 20 kg N ha^{-1}) on crop yields and their intermediary effects on cumulative infiltration, runoff, water stress and N stress. Rain water infiltration and N stress were investigated for three "typical" season types in terms of the rainfall amount relative to the long-term average and the frequency of dry spells longer than 14 days: normal (2000/01), wet (2005/06) and dry (2012/13). In this study, we defined a dry season by the occurrence of dry spells longer than 14 days in addition to receiving rainfall that was less than 450 mm, whilst a wet season did not have long dry spells and received at least above 600 mm rainfall which are the lower and upper limits (respectively) of a normal season. A normal season also did not have the long dry spells and received rainfall in the range 450–600 mm. Soil water stress was investigated throughout each season. When the simulated water and N stress value was 1, the crop experienced no stress and when the value was 0, the crop was under severe stress.

The calibrated and tested APSIM model was further used to explore the riskiness of maize production. Different planting rules were compared (Table 2): (i) planting on a fixed date irrespective of the rainfall received and (ii) planting using a variable rule based on the rainfall amount received. For each of the scenarios, annual grain yields and the daily net N mineralised over the 30-year period (1 September 1984 to 30 June 2015) were simulated. The model was reset every 1 July to initial water, N, surface OM and phosphorus to remove the year-to-year effects. The riskiness of the planting date strategy was evaluated with the 30-years simulated yield data based on (i) the probability of complete crop failure and (ii) the probability of achieving the annual maize grain requirement for an average family from an average farm entirely cropped with maize. The daily energy requirement of a male adult equivalent is 2500 kcal (FAO, 2004). If this energy requirement is met by consuming maize, this translates to a per capita maize grain requirement of 256 kg $year^{-1}$ (FAO, 1995). An average family in Matobo district comprises a male adult equivalent of approximately 5.5 on an average farm size of 1.3 ha (Musiyiwa, 2014). Therefore, the annual maize threshold yield to meet the grain requirement for an average family is approximately 1080 kg ha^{-1}.

From the daily N mineralisation output, the number of seasons in which the mineral N flush coincided with planting was determined for each planting scenario. The N flush was diagnosed when the simulated N mineralisation increased with the first rains of the season from zero in the dry season to 0.1–2.0 kg N ha^{-1} day^{-1} and falling back to zero after a few days. The yield gain was calculated as the difference between the mean yield when the mineral N flush coincided with planting and the mean yield when the planting missed the mineral N flush. Based on Chikowo et al. (2003), this "coincidence" is achieved when the N flush occurs within seven days before or after planting.

Table 2
Summary of the seven scenarios examined in the simulation experiment.

Scenario	Planting rule	Name	Details
1	Fixed date	Very early planting	• Tillage on 1 November every year • Sow on 1 November every year
2	Fixed date	Early planting	• Tillage on 15 November every year • Sow on 15 November every year
3	Fixed date	Normal	• Tillage on 30 November every year • Sow on 30 November every year
4	Fixed date	Normal	• Tillage on 15 December every year • Sow on 15 December every year
5	Fixed date	Late planting	• Tillage on 31 December every year • Sow on 31 December every year
6	Fixed date	Very late planting	• Tillage on 15 January every year • Sow on 15 January every year
7	Variable date	First effective rains	• Amount of rainfall: 20mm • Number of days of rainfall: 3 • Minimum allowable soil water: 12 mm

The effect on grain yield of a false seasons start (as defined in Section 2.3) was determined only for the variable planting scenario. The yield penalty when planting coincided with a false season start was calculated as the difference in mean yields from seasons that experienced a false start and seasons without a false start.

2.7. Data analyses

Both single factor (planting date scenario, mulch, tillage, fertility treatments) and the interaction effects on simulated maize yields and net N mineralisation were estimated using ANOVA procedure (Tukey's test at $P \le 0.05$) using Genstat 18th edition (VSN International Ltd., http://www.vsni.co.uk/). Correlation and linear regression analyses were performed to test the strength of the relationship between net N mineralised in-season and maize grain yield over the 30-year period. The significance of the model was tested with the F value and variables were included in the final model only if they were significant at $P < 0.05$.

3. Results

3.1. Model performance

The APSIM model performed well in terms of capturing the observed grain and stover yield response to tillage, mulch and fertility amendment application (Fig. 1). The EF values were generally high (> 50%) with good predictions for grain yields for the wet season 2013/14 and the dry seasons 2012/13 and 2014/15 which received below average rainfall (272 and 432 mm respectively). The predictions for the stover yields were satisfactory although the model tended to overestimate stover production.

The model under-estimated both soil N mineralisation (EF = 0.58) and N uptake (EF = 0.40) (Fig. 2) but the general pattern of the cumulative N mineralised agreed well with the measured data across the treatments (EF ranged between 0.91 and 0.96) (Fig. 3). The model predicted a net immobilisation for all tillage, mulch and fertiliser treatments in the on-farm trial in the first 10–15 days after planting, which could not be confirmed through observations at that time interval.

3.2. Tillage, mulch and soil fertility amendment effects on infiltration, runoff and N stress

The model predicted that across the 30-year simulation period, most of the seasonal rainfall, 60–98 %, infiltrated. The proportion of rain that infiltrated was higher in the dry years, 90–98%, where rainfall was < 450 mm compared with 60–88 % in the wet years. Tillage and mulch application influenced runoff and infiltration. Cumulative infiltration (Fig. 4) was highest under the ripper + mulch (93–97 %) and least with the plough - no mulch (60–67 %) regardless of the season. Infiltration was only marginally higher under the manure treatments than under the fertiliser only treatments (0 N, 20 N and 40 N).

N stress was generally least severe in the first 30 days after planting across the three season types: normal, wet and dry (Fig. 5). Under the 0 N fertility treatment maize experienced the most severe stress from approximately 30 days after planting regardless of season type, tillage type and mulch application. For the other fertility treatments, differences in N stress depended on the season type. Firstly, in a normal

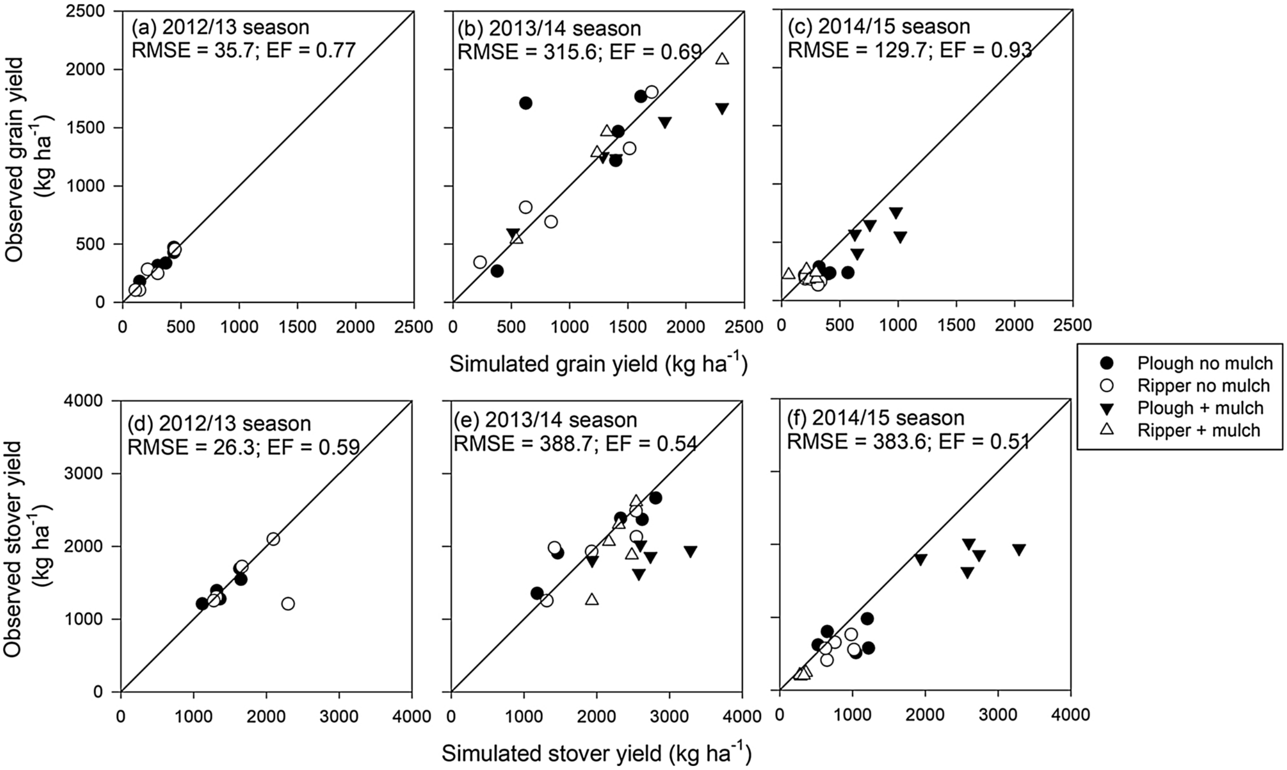

Fig. 1. On-farm trials observed versus APSIM predicted maize grain and stover yields for the seasons 2012/13 – 2014/15.

season, the least N stress was experienced with the manure + 20 N, although moderate N stress was experienced under this treatment at the end of the season under both tillage treatments with or without mulch. Secondly, in the wet season, there was generally severe N stress regardless of tillage and mulch. N stress transitioned from moderate < 30 days after planting to severe > 30 days after planting until the end of the season regardless of tillage or mulch. Finally, in the dry season, N stress was moderate from day 10 to day 50 after planting generally across all fertility treatments, thereafter N stress increased under the ripper tillage and under plough + mulch. The manure + 20 N treatment also resulted in severe N stress from 60 days after planting until crop maturity under the ripper tillage.

3.3. Treatment effects on in-season N mineralisation

Simulated nitrogen mineralised in season was significantly different between planting date strategies, fertility treatment, mulch application and tillage treatment and the interactions between these factors were significant ($P < 0.05$) (Supplementary table). The earlier the planting, the higher the net N mineralised in season because of a generally longer growing season compared with the later planting dates (Fig. 6; Supplementary table). It followed the trend: planting after 20 mm rain > 15 Nov > 1 Nov > 30 Nov > 15 Dec > 31 Dec > 15 January for the plough (no mulch), ripper (no mulch) and ripper + mulch regardless of fertiliser or manure input. Under the plough + mulch treatment however, N mineralised in season followed the trend 1 Nov > 20 mm

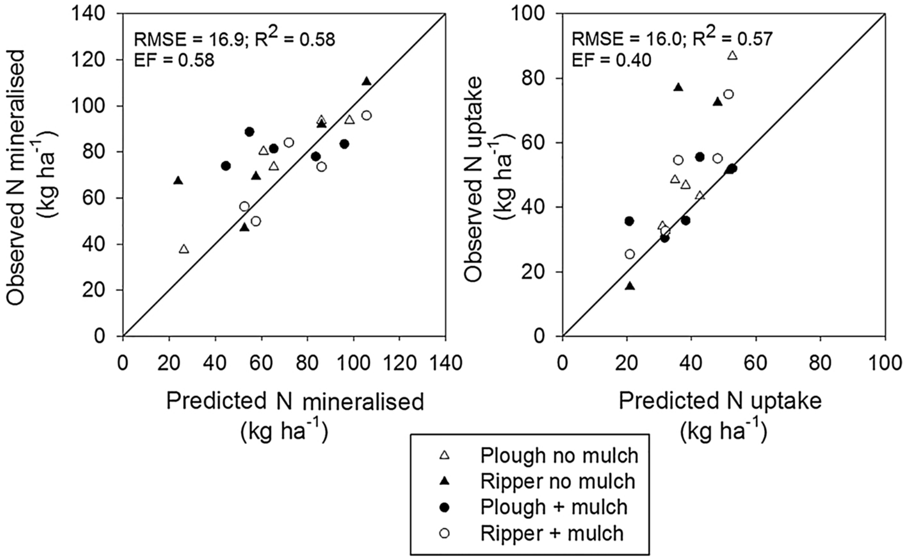

Fig. 2. Observed vs. predicted seasonal N mineralised and maize N uptake in the 2013/14 season.

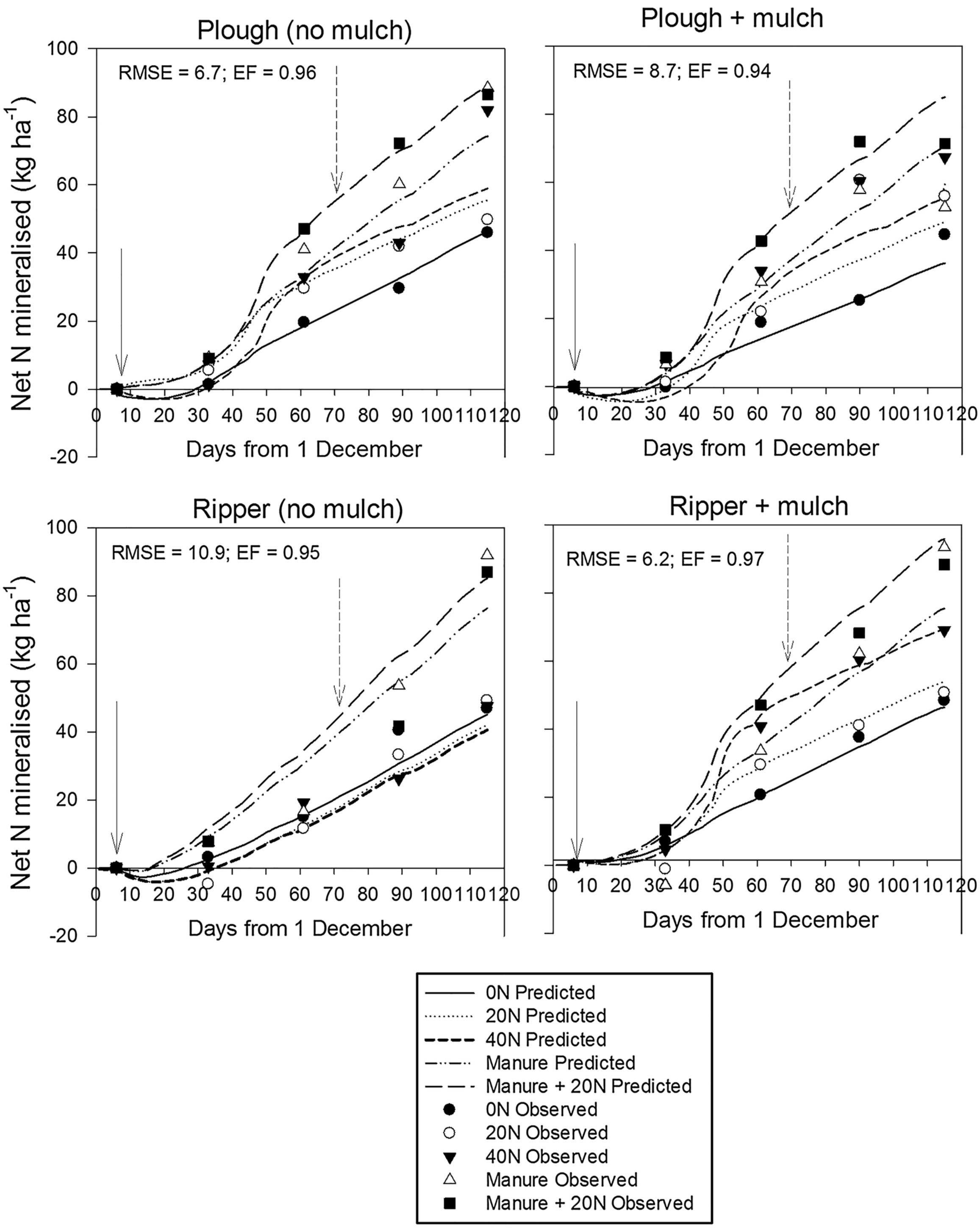

Fig. 3. Field measured and APSIM predicted N mineralised over time in the 2013/14 season. The solid and dotted arrows indicate the date of planting and the start of flowering stage respectively.

rain > 15 Nov > 30 Nov > 15 Dec > 31 Dec > 15 Jan. The average amount of mineral N available (i.e. that available from mineral fertiliser plus net N mineralisation), over 30 years was highly variable but largely followed the trend: manure + 20 N > manure only > 40 N > 20 N > 0 N. With respect to tillage and mulch application, the amount of net mineral N followed the trend ripper + mulch > plough (no mulch) > plough + mulch > ripper (no mulch).

The chance that the mineral N flush coincided with planting varied depending on the planting strategy and was higher for the early planting strategies (before 30 November and planting after 20 mm rain), whereas the flush was always missed when planting was done after 15 December. The total amount of N released in the mineral flushes varied by season and fertility amendment and ranged from 0.3 to 30 kg N ha^{-1}. With respect to fertility treatment effects, the amount released followed the trend manure + 20 N > manure only > 40 N > 20 N > 0 N over the 30-year period. The mineral N flush with the start of the rains occurred more frequently with the manure + 20 N (80–87 % of the seasons) followed by the 40 N treatment (60–80 %). The manure only and 0 N treatments experienced the mineral N flush in 40–67 % of the 30 seasons.

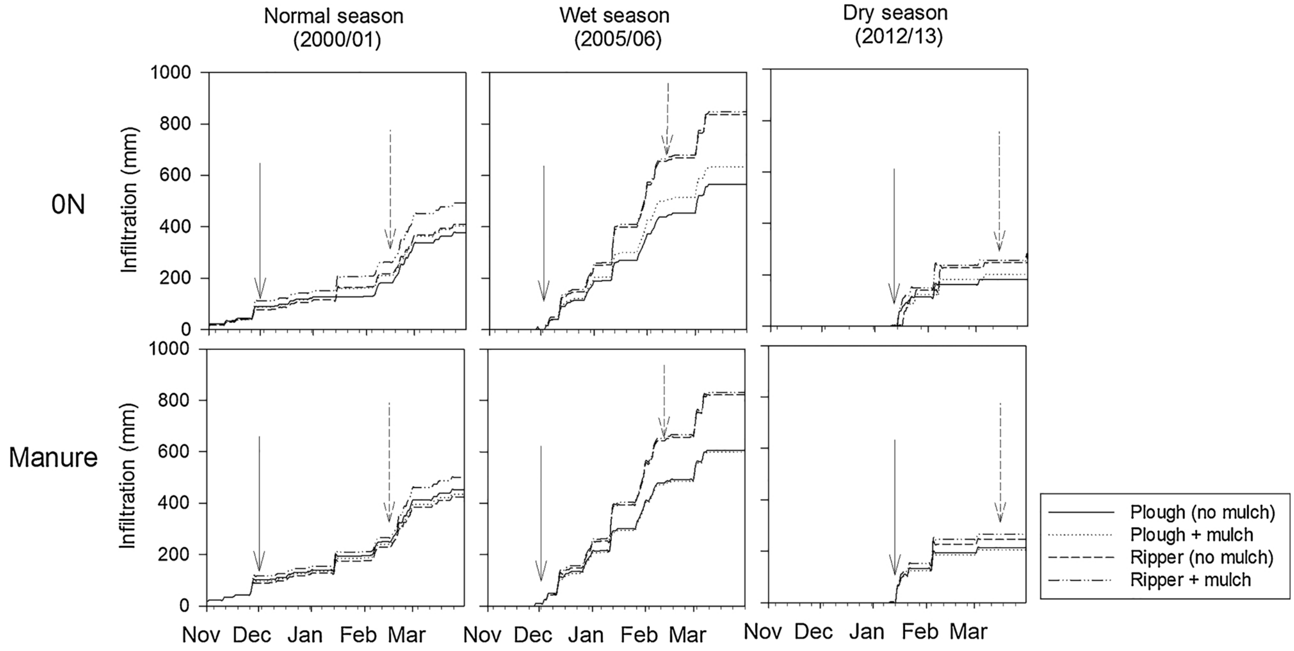

Fig. 4. Simulated effect of tillage, mulch and fertility amendment on the cumulative infiltration on a sandy soil in semi-arid Zimbabwe for selected soil fertility management practices and in selected seasons representing normal (a and d), wet (b and e) and dry (c and f) years with respect to rainfall amount. The solid and dotted arrows indicate the date of planting and the start of flowering stage respectively.

3.4. *Treatment effects on grain yield and production risks*

There was a strong positive and significant relationship between net N mineralised in season and maize grain yields ($r = 0.74$; $P < 0.05$). This corresponded with maize grain yield differences between N application rates, which varied in the order 40 N > manure + 20 N > manure only > 20 N > 0 N averaging 1485, 1202, 1095, 1026 and 397 kg ha^{-1} respectively (Fig. 6). The maize grain yields were also significantly different between the different planting date strategies (Fig. 6). The highest yielding scenario (planting on 15 November) had an average yield of 755 kg ha^{-1}, whereas very late planting (15 January) gave the lowest yield of 550 kg ha^{-1} over the 30-year period and across all fertility and tillage treatments. Average yield loss per day from planting date 15 November through to 15 December averaged 4,

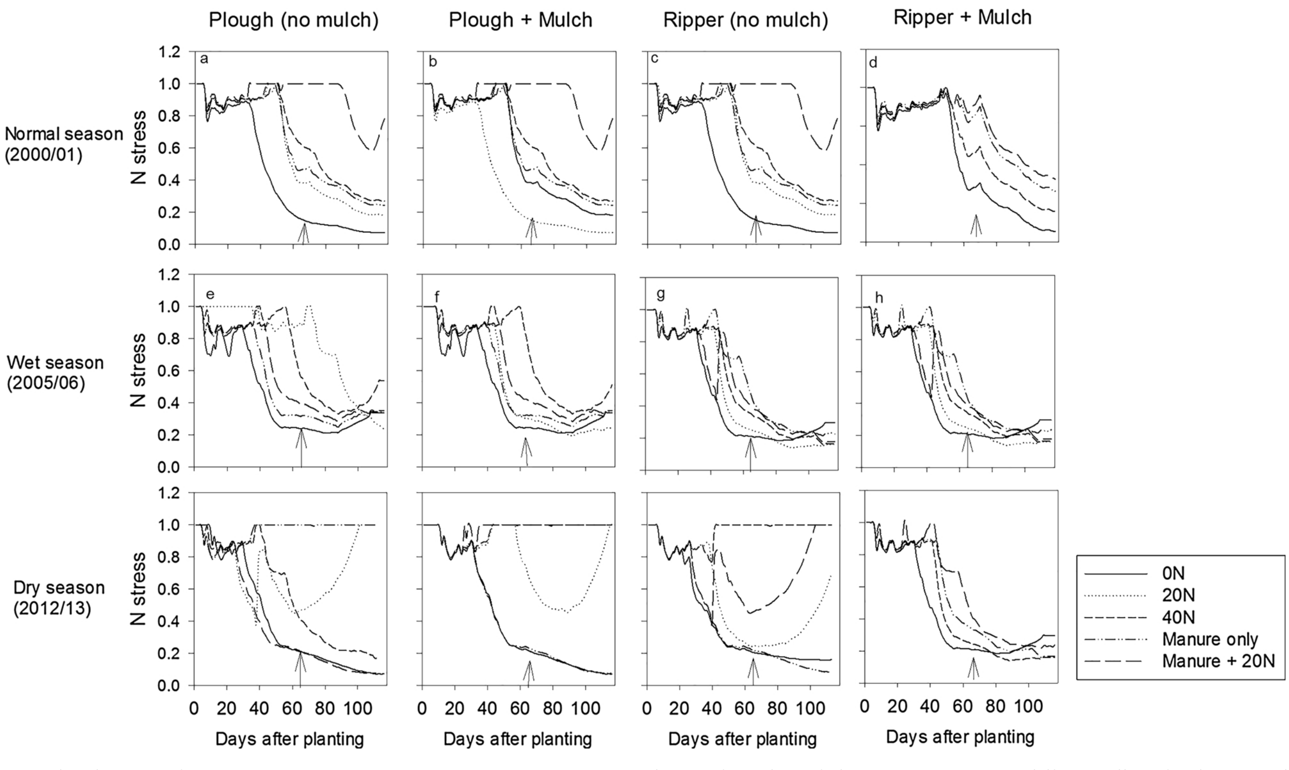

Fig. 5. Simulated N stress factors (1 = no stress; 0 = extreme stress) in maize production from date of planting in response to different tillage fertility amendments under plough only (a, e and i), plough + mulch (b, f and j), ripper only (c, g and k) and ripper + mulch (d, h and l) on a sandy soil in semi-arid Zimbabwe in selected seasons representing normal (a–d), wet (e–h) and dry (i–l) years with respect to rainfall amount. The arrows indicate the start of the flowering stage.

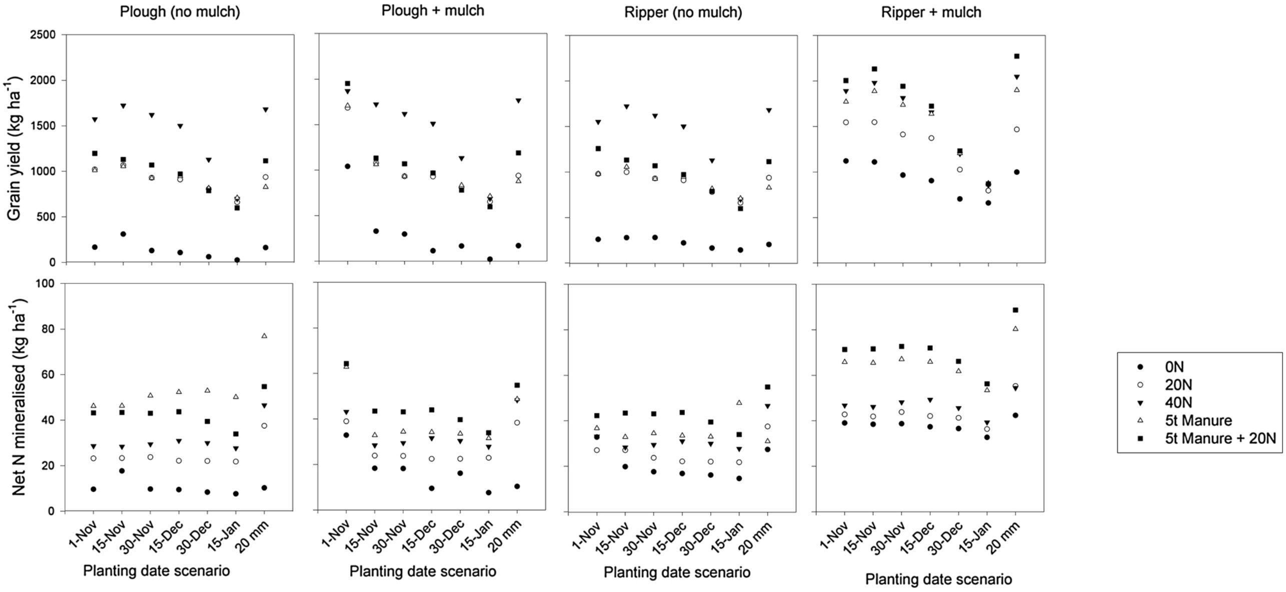

Fig. 6. Impact of different planting strategies and fertility amendments on average maize grain yields (a – d) and net N mineralised in season (e – h) under plough only (a and e), plough + mulch (b and f), ripper only (c and g) and ripper + mulch (d and h) on a sandy soil in semi-arid Zimbabwe (simulated average for the period 1984–2015).

14, 23, 14 and 15 kg ha^{-1} for the five fertility treatments 0 N, 20 N, 40 N, manure only and manure + 20 N respectively. From 15 December to 15 January, the yield loss per day delay in planting averaged 14, 21, 26, 25 and 29 kg ha^{-1} for the five fertility treatments.

3.4.1. *Effects of a false season start*

In the 30-year period, there were seven seasons with false rainfall onsets where 20 mm was accumulated in 1–2 days, followed by a dry spell of more than 10 consecutive days within 30 days after sowing. Only the 2002/03 season was considered a drought season of these seven seasons. On average, the false start to the season had negative effects on grain yields depending on the fertility treatment, tillage and mulch application. Addition of fertility amendments made crops susceptible to yield reduction, which followed the trend manure + 20 N > manure > 40 N > 20 N with yield losses averaging 218, 212, 198 and 97 kg ha^{-1} compared to the yields in seasons without a false start. There was no yield penalty with a false start under the 0 N treatment regardless of tillage and mulch combinations although this treatment, in the event of a false season start, was associated with failure to meet the household yield threshold of 1080 kg ha^{-1}. With respect to tillage and mulch across the fertility treatments, the grain yield penalties with a false start followed the trend: ripper + mulch > plough + mulch > ripper (no mulch) averaging 256, 190 and 182 kg ha^{-1} respectively. There was no yield penalty but a yield benefit averaging 88 kg ha^{-1} under the plough (no mulch) tillage. In general, the false season starts were associated with soil water stress during the emergence stage although this stress was low (> 0.8) and experienced for no longer than five days. This soil water stress did not exhibit any specific trend with tillage, mulch application or soil fertility amendment.

3.4.2. *Effects of the N flush*

The yield benefits when planting coincided with the N flush were significant under the following planting date scenarios: 1 Nov, 15 Nov, 30 Nov and planting after 20 mm averaging 430, 132, 4 and 152 kg ha^{-1} respectively across the fertility and tillage treatments (Table 3). The yield benefits differed significantly between tillage and mulch applications. Overall, the yield benefits were highest with the ripper + mulch in combination with early planting and in these cases, the yields exceeded the required household grain yield threshold of 1080 kg ha^{-1}.

3.4.3. *Risk of crop failure and not attaining maize self-sufficiency*

The simulation results suggested that there was a higher risk of complete crop failure when no fertiliser was applied (0 N) regardless of planting date scenario, tillage and mulch application relative to the other fertility amendments (Fig. 7). The risk of crop failure under 0 N further increased with later planting dates, whereas early planting and planting with the first effective rains could limit the probability of crop failure to 40%. The risk of crop failure was lowest under ripper + mulch with the risk of complete crop failure in the range 0–30% depending on planting date and fertility treatment.

The risk of not meeting the household maize grain yield threshold of 1080 kg ha^{-1} increased with later planting dates (Fig. 8). Planting with the first effective rains resulted in the highest probability of exceeding the threshold yield although this probability was highly variable (23–83% where fertility amendments were incorporated and 0–40% under the 0 N fertility treatment). In comparison, with the latest planting date, 15 Jan, the probability to meet the same yield was only 0–30%. The 0 N treatment had 0–7% chance of meeting the household maize grain requirement under the plough (no mulch) and ripper (no mulch) tillage whilst under the plough + mulch and ripper + mulch the probability was in the range 10–43%. Under the plough (no mulch), plough + mulch and ripper (no mulch), the 40 N treatment gave the highest probabilities of exceeding 1080 kg ha^{-1} in the range 23–77%. Under ripper + mulch, the manure + 20 N gave the highest probabilities of yields exceeding 1080 kg ha^{-1} in the range 27–83%. Overall, the combination of early planting, ripper + mulch and N fertility amendment led to good yields and a low risk of complete crop failure and not meeting self-sufficiency.

4. Discussion

4.1. *Performance of the model*

The APSIM model reasonably predicted grain and stover yields, N mineralised and N uptake. The model overestimated maize grain and stover yields under the plough + mulch treatment (Fig. 1c and f) in the dry season of 2014/15. Similarly, Mupangwa et al. (2011b) observed an over prediction of grain and stover yields especially at low mulch levels < 2 t ha^{-1} in dry seasons, which they attributed to the model underpredicting immobilisation of the applied N at the low mulch rates.

Table 3
Yield benefits when planting coincides with a mineral N flush under different tillage, mulch and fertility amendments for selected planting date scenarios. Figures in brackets denote standard deviation.

Tillage	Planting date scenario	Mean yield (kg ha^{-1}) when planting coincided with N flush	Mean yield (kg ha^{-1}) when planting missed the N flush	Mean yield benefit (kg ha^{-1})				
				0 N	20 N	40 N	Manure	Manure + 20 N
Plough (no mulch)	01-Nov	1718 (193)	1472 (395)	534	220	288	259	−69
	15-Nov	1113 (546)	1042 (657)	276	161	36	147	−265
	30-Nov	963 (494)	1096 (388)	−335	−14	−17	−345	48
	20-mm	1068 (563)	924 (521)	−128	45	189	588	26
Plough + mulch	01-Nov	1814 (996)	1428 (1196)	485	493	151	391	410
	15-Nov	1145 (915)	1121 (987)	−363	102	186	249	−56
	30-Nov	1028 (816)	1009 (965)	−218	181	14	101	14
	20-mm	1084 (905)	993 (753)	−136	188	376	314	206
Ripper (no mulch)	01-Nov	1834 (959)	1377 (1164)	613	622	299	279	464
	15-Nov	1146 (919)	1079 (968)	−334	153	243	270	3
	30-Nov	1055 (832)	950 (966)	−54	118	119	240	103
	20-mm	1248 (872)	1147 (812)	−74	37	114	−188	212
Ripper + mulch	01-Nov	1952 (997)	1321 (1062)	672	842	605	785	251
	15-Nov	1919 (1133)	1419 (1219)	396	712	441	445	505
	30-Nov	1672 (1142)	1637 (1100)	334	131	−137	127	−280
	20-mm	1885 (1270)	1459 (1148)	699	567	−259	778	344

	P value	SED
Tillage	0.006*	212.5
Mulch	0.013*	107.2
Fertility amendment	0.328	174.4
Planting date	0.012*	148.7

In the model, mineralisation/immobilisation of N is determined as the balance between the release of N during decomposition and N immobilisation during microbial synthesis and humification (Probert et al., 1998). In our case, no immobilisation was observed from the simulated daily N dynamics for the 2014/15 season (results not shown), whereas immobilisation was predicted for the wet 2013/2014 season (Fig. 3). For 2014/2015, the model indicated an adequate supply of mineral N to satisfy the microbial demand therefore favouring net mineralisation leading to simulated yields that were larger than the observed.

The model predicted in-season net N mineralisation reasonably well (Fig. 3). Also, the model predicted N mineralisation with the first rains, which we equated to the "Birch effect", even though no specific mechanisms are included in APSIM to simulate this effect. When the soil is dry (in the dry season) the model simulates the daily net N mineralisation to be zero. In reality, although nitrification ceases, ammonium-N continues to accumulate when soil moisture content is below wilting point (Robinson, 1957; Giller et al., 1997). Part of the N flush with the first rains is due to rapid nitrification of this ammonium-N as the soil is rewetted (Giller et al., 1997).

The N released in the soil has a fertilising effect of economic significance, especially for smallholder farmers who are unable to afford N containing fertilisers. Using APSIM, we contributed to a better understanding of in-season N mineralisation and the "Birch effect", towards optimising the efficient use of farmer-available N resources. Fine-tuning of model predictions of N mineralisation would require further field measurements of N dynamics during and at the start of the rainy season.

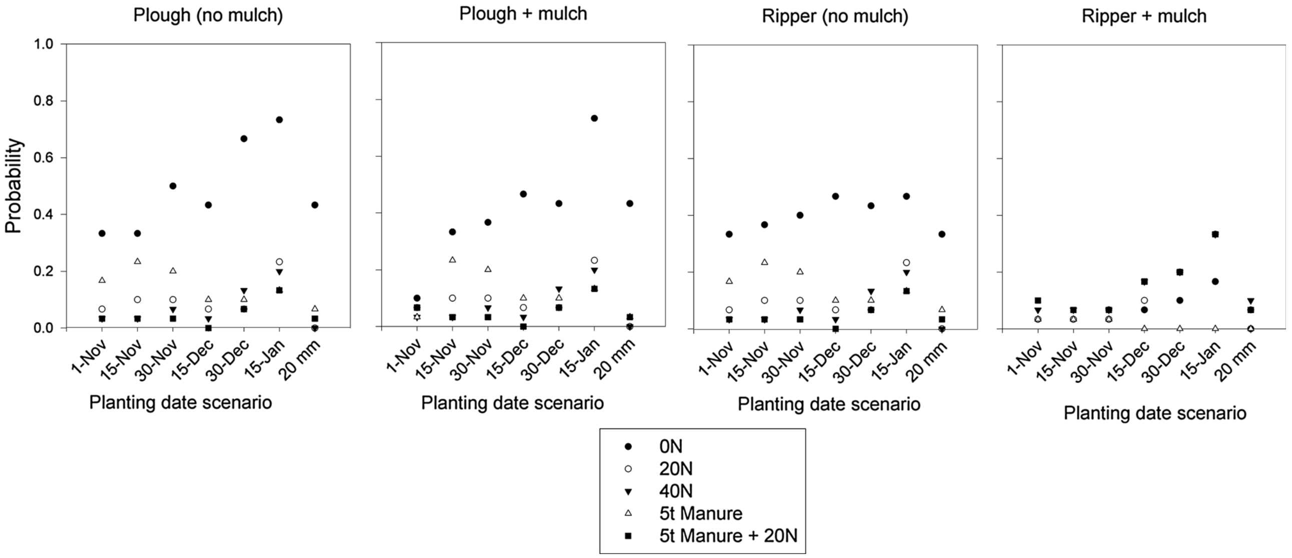

Fig. 7. Probability of complete crop failure under different planting date strategies, tillage treatments and fertility amendments on a sandy soil in semi-arid Zimbabwe over a 30-year period (1984–2015).

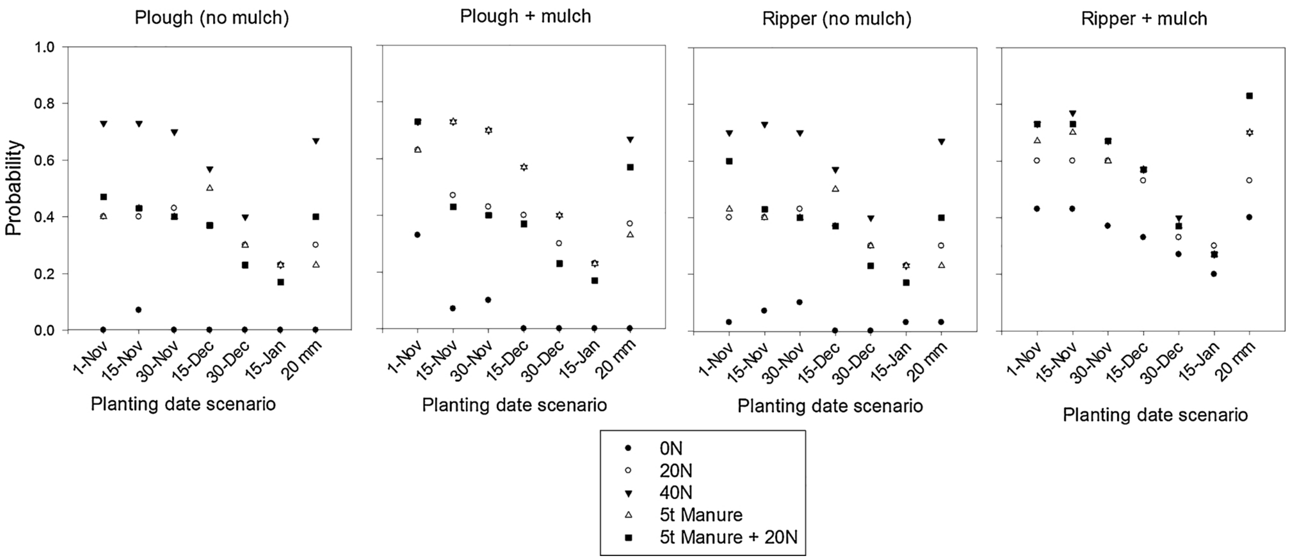

Fig. 8. Probability of meeting and exceeding the annual household maize grain self-sufficiency yield of 1080 kg ha^{-1} under different planting date strategies, tillage treatments and fertility amendments on a sandy soil in semi-arid Zimbabwe over a 30-year period (1984–2015).

4.2. Tillage and mulch application effects on maize yields

The ripper tillage in conjunction with mulch application yielded significantly more compared with plough tillage over the 30-year simulation period and across all planting date scenarios and fertility treatments. We attributed the higher maize yields to differences in availability of soil moisture due to higher infiltration as observed in this (Fig. 4) and other studies (Thierfelder and Wall, 2009; Nyamadzawo et al., 2012). The model settings with a lower runoff curve number for ripping mimic reality where furrows created by ripping were reported to create more surface depressions compared with ploughing resulting in superior rainwater capture and therefore better infiltration (Mupangwa et al., 2016). The model was set to incorporate only 20% of the surface residues under the ripper tillage whilst the remainder of the residues remained on the surface as mulch. The mulch further increased infiltration and reduced runoff as we observed with the simulation study (Fig. 4). Conservation tillage methods such as ripping have been reported to result in high pore volumes consequently increasing the infiltration capacity of a soil (Nyamangara et al., 2014) thus reduced water stress. The increased infiltration observed with ripping and mulching may also explain why there was least risk of crop failure (0–30%) under ripper + mulch across the different planting date scenarios and across fertility treatments. The use of animal drawn tillage implements such as the ripper tine also reduces the labour and draught power requirement at land preparation compared with ploughing therefore offering a better chance of timely planting. Both the increase in infiltration and the early planting made possible thanks to the reduced labour requirements for the ripper tillage have been shown in our simulation study to lead to increased maize yields.

4.3. Risk management by early planting

Early planting has been reported to positively influence crop yields in other studies in the region (Nyagumbo et al., 2017). We attributed the increased maize yields associated with the early planting date to an extended growing period and therefore high in-season rainfall and net N mineralisation. Further yield benefits were obtained when early planting coincided with the N flush with the first rains of the season. A similar observation was made in some field experiments that quantified the amount of N released during the N flush (Salinas-Garcia et al., 1997; Riley, 1998). In our simulation experiment, the amount of N released by the flush was highly variable across seasons and fertility amendment. Franzluebbers et al. (1995) reported that the amount of N released is highly dependent on the quality and quantity of organic inputs among other factors which may explain the highly variable amount of N observed in our study.

Early planting can lead to increased yields but is very risky due to the high probability of false season starts. False season starts have been reported in several studies to be a high risk to crop production in SSA (Raes et al., 2004; Kniveton et al., 2009; Lone and Warsi, 2009; Mupangwa et al., 2011a). In our study the false season starts occurred, approximately, in one out of four seasons. Other studies have reported even higher frequencies of false season starts in 40–50% of seasons in semi-arid southern Africa (Benoit, 1977; Raes et al., 2004). In our study, although the false season starts resulted in low yields, they did not always result in complete crop failure as we hypothesised. The false season starts only led to some water stress in the early crop stages (emergence and juvenile) and not in the most critical stage when kernel weight and number is determined which is between two weeks before and 2–3 weeks after silking (NeSmith and Ritchie, 1992; Singh and Singh, 1995). When longer durations of water stress occur, they cause near total crop failure (NeSmith and Ritchie, 1992), but in our simulation such long periods of water stress were not linked to the false season starts.

Smallholder farmers use staggered opportunistic plantings to spread the risk associated with false season starts and dry spells in semi-arid southern Africa (Milgroom and Giller, 2013; Moyo et al., 2012). With this strategy, however, farmers tend not to invest in improved seed and manure/fertiliser application (Vanlauwe et al., 2014; Njoroge et al., 2017), thus limiting the opportunity to maximize yields when planting coincides with the optimum planting window. Seasonal, weekly or fortnightly weather forecasts are therefore important in aiding farmers to make tactical within-season decisions on when to plant, weed and apply fertiliser (Moyo et al., 2012).

Our study only considered a few of the possible management options that could lead to attainment of household maize self-sufficiency in semi-arid southern Africa. Other studies have identified drivers of the whole aspect of food availability in the region that also include household incomes, labour availability, livestock production, market access and land availability (e.g. Homann-Kee Tui et al., 2015; Komarek et al., 2015 and Frelat et al., 2016). However, the fact that crop production remains the major source of energy and contributes up to 60% of food availability (Frelat et al., 2016) underscores the importance of improved management options that potentially increase yields, while reducing the risk of crop failure. Our study showed that the strategic application of different agronomic management practices such as early planting in combination with reduced tillage, mulch and N containing fertility amendments is critical to reduce risk of crop failure and improve crop yields in the smallholder cropping systems of semi-arid areas of southern Africa.

5. Conclusions

We conclude that early planting in combination with reduced tillage, mulch application and N fertiliser application allows an 'average' farm household to at least meet their household grain requirement as well as reduce the risk of complete crop failure. The yield benefits from planting early resulted from capturing the N released from the "Birch effect", total in-season mineral N and rainfall. However, when there is a false start to the season, farmers risk attaining low maize yields and not achieving food self-sufficiency. It is important that smallholder farmers be equipped and guided by reliable seasonal weather forecasts to enable them to plan their land preparation and planting operations to ensure they reap the benefits of timely planting. Practices such as reduced tillage that ease the labour and draught power burdens at the start of the season can be employed to allow farmers to plant early. This, in combination with other agronomic practices such as the application of fertility amendments and mulch may increase crop yields. As such, smallholder farmers can manage and mitigate risk and achieve maize self-sufficiency in the event of dry spells and low rainfall associated with rainfed cropping in semi-arid areas.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.fcr.2018.09.002.

References

Anderson, J.M., Ingram, J., 1993. Tropical Soil Biology and Fertility: A Handbook of Method. CAB International.

Bartholomew, W., Kirkham, D., 1960. Mathematical description and interpretations of culture-induced soil nitrogen changes. Trans. 7th Int. Congr. Soil Sci. 2, 471–477.

Baudron, F., Tittonell, P., Corbeels, M., Letourmy, P., Giller, K.E., 2012. Comparative performance of conservation agriculture and current smallholder farming practices in semi-arid Zimbabwe. Field Crop Res. 132, 117–128.

Benbi, D.K., Richter, J., 2002. A critical review of some approaches to modelling nitrogen mineralization. Biol. Fert. Soils 35, 168–183.

Benoit, P., 1977. The start of the growing season in Northern Nigeria. Agric. For. Meteorol. 18, 91–99.

Birch, H., 1960. Nitrification in soils after different periods of dryness. Plant Soil 12, 81–96.

Bognonkpe, J.-P., Becker, M., 2009. Native soil N mineralization in major rice based cropping systems. J. Anim. Plant Sci. 4, 384–398.

Bremner, J.M., Mulvaney, C.S., 1982. Nitrogen—Total. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties. Am Soc Agron, pp. 595–624 Madison, WI,.

Cabrera, M., 1993. Modeling the flush of nitrogen mineralization caused by drying and rewetting soils. Soil Sci. Soc. Am. J. 57, 63–66.

Cabrera, M., Kissel, D., 1988. Evaluation of a method to predict nitrogen mineralized from soil organic matter under field conditions. Soil Sci. Soc. Am. J. 52, 1027–1031.

Chikowo, R., 2011. Climatic Risk Analysis in Conservation Agriculture in Varied Biophysical and Socio–economic Settings of Southern Africa. FAO Regional Emergency Office for Southern Africa (REOSA), Johannesburg.

Chikowo, R., Mapfumo, P., Nyamugafata, P., Nyamadzawo, G., Giller, K.E., 2003. Nitrate-N dynamics following improved fallows and maize root development in a Zimbabwean sandy clay loam. Agro. For. Syst. 59, 187–195.

Chivenge, P., Murwira, H., Giller, K., Mapfumo, P., Six, J., 2007. Long-term impact of reduced tillage and residue management on soil carbon stabilization: implications for conservation agriculture on contrasting soils. Soil Tillage Res. 94, 328–337.

FAO, 1995. Sorghum and Millets in Human Nutrition. Food and Agriculture Organization of the United Nations, Rome Accessed 27 April 2018. http://www.fao.org/docrep/t0818e/T0818E0b.htm.

FAO, 2004. Human energy requirements. Report of a Joint FAO/WHO/UNU Expert Consultation, Rome. pp. 17–24 October 2001.

Franzluebbers, A., Hons, F., Zuberer, D., 1995. Tillage and crop effects on seasonal soil carbon and nitrogen dynamics. Soil Sci. Soc. Am. J. 59, 1618–1624.

Frelat, R., Lopez-Ridaura, S., Giller, K.E., Herrero, M., Douxchamps, S., Djurfeldt, A.A., Erenstein, O., Henderson, B., Kassie, M., Paul, B.K., 2016. Drivers of household food availability in sub-Saharan Africa based on big data from small farms. Proc. Natl. Acad. Sci. 113, 458–463.

Gaydon, D., Probert, M., Buresh, R., Meinke, H., Suriadi, A., Dobermann, A., Bouman, B., Timsina, J., 2012. Rice in cropping systems—modelling transitions between flooded and non-flooded soil environments. Eur. J. Agron. 39, 9–24.

Giller, K.E., Cadisch, G., Ehaliotis, C., Adams, E., Sakala, W.D., Mafongoya, P.L., 1997. Building Soil Nitrogen Capital in Africa. Replenishing Soil Fertility in Africa. pp. 151–192.

Homann-Kee Tui, S., Valbuena, D., Masikati, P., Descheemaeker, K., Nyamangara, J., Claessens, L., Erenstein, O., van Rooyen, A., Nkomboni, D., 2015. Economic trade-offs of biomass use in crop-livestock systems: exploring more sustainable options in semi-arid Zimbabwe. Agric. Syst. 134, 48–60.

Kniveton, D.R., Layberry, R., Williams, C.J.R., Peck, M., 2009. Trends in the start of the wet season over Africa. Int. J. Climatol. 29, 1216–1225.

Komarek, A.M., Li, L., Bellotti, W.D., 2015. Whole-farm economic and risk effects of conservation agriculture in a crop-livestock system in western China. Agric. Syst. 137, 220–226.

Lone, A.A., Warsi, M.Z.K., 2009. Response of maize (Zea mays L.) to excess soil moisture (ESM) tolerance at different stages of life cycle. Bot. Res. Int. 2, 211–217.

Masikati, P., 2006. Tillage and manure interactions under dryland cropping in semi-arid Zimbabwe. MPhil Thesis. Department of Soil Science and Agricultural Engineering, University of Zimbabwe, Harare, Zimbabwe.

Masvaya, E.N., Nyamangara, J., Descheemaeker, K., Giller, K.E., 2017. Tillage, mulch and fertiliser impacts on soil nitrogen availability and maize production in semi-arid Zimbabwe. Soil Tillage Res. 168, 125–132.

Matthews, R., Stephens, W., Hess, T., Middleton, T., Graves, A., 2002. Applications of crop/soil simulation models in tropical agricultural systems. Adv. Agron 76, 31–124.

Mavhura, E., Manatsa, D., Mushore, T., 2015. Adaptation to drought in arid and semi-arid environments: case of the Zambezi Valley, Zimbabwe. Jàmbá 7, 1–7.

Milgroom, J., Giller, K., 2013. Courting the rain: rethinking seasonality and adaptation to recurrent drought in semi-arid southern Africa. Agric. Syst. 118, 91–104.

Mohanty, M., Reddy, K.S., Probert, M., Dalal, R.C., Rao, A.S., Menzies, N., 2011. Modelling N mineralization from green manure and farmyard manure from a laboratory incubation study. Ecol. Model 222, 719–726.

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D., Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. T ASABE 50, 885–900.

Moyo, M., Mvumi, B.M., Kunzekweguta, M., Mazvimavi, K., Craufurd, P., Dorward, P., 2012. Farmer perceptions on climate change and variability in semi-arid Zimbabwe in relation to climatology evidence. Afr. Crop Sci. J. 20, 317–335.

Mupangwa, W., 2010. Water and nitrogen management for risk mitigation in smallholder cropping systems. PhD Thesis. University of the Free State, South Africa.

Mupangwa, W., Walker, S., Twomlow, S., 2011a. Start, end and dry spells of the growing season in semi-arid southern Zimbabwe. J. Arid Environ. 75, 1097–1104.

Mupangwa, W.T., Dimes, J., Walker, S., Twomlow, S., 2011b. Measuring and simulating maize (Zea mays L.) yield responses to reduced tillage and mulching under semi-arid conditions. Agric Sci 2, 167–174.

Mupangwa, W., Twomlow, S., Walker, S., 2016. Reduced tillage and nitrogen effects on soil water dynamics and maize (Zea mays L.) yield under semi-arid conditions. Int. J. Agric. Sustain. 14, 13–30.

Musiyiwa, K., 2014. . Climate change in rural Zimbabwe: an assessment of the influences of gender in smallholding and its contribution towards adaptation to climate change in rural Zimbabwe. PhD Thesis. Manchester Metropolitan University.

Ncube, B., Dimes, J.P., van Wijk, M.T., Twomlow, S.J., Giller, K.E., 2009. Productivity and residual benefits of grain legumes to sorghum under semi-arid conditions in south-western Zimbabwe: unravelling the effects of water and nitrogen using a simulation model. Field Crop Res. 110, 173–184.

NeSmith, D., Ritchie, J., 1992. Maize (Zea mays L.) response to a severe soil water-deficit during grain-filling. Field Crop Res. 29, 23–35.

Njoroge, S., Schut, A.G.T., Giller, K.E., Zingore, S., 2017. Strong spatial-temporal patterns in maize yield response to nutrient additions in African smallholder farms. Field Crop Res. 214, 321–330.

Nyagumbo, I., 2008. A review of experiences and developments towards conservation agriculture and related systems in Zimbabwe. In: Goddard, T., Zoebisch, M.A., Gan, Y.T., Ellis, W., Watson, A., Sombatpanit, S. (Eds.), No-till Farming Systems. World Association of Soil and Water Conservation, Bangkok, Thailand, pp. 345–372.

Nyagumbo, I., Mkuhlani, S., Mupangwa, W., Rodriguez, D., 2017. Planting date and yield benefits from conservation agriculture practices across Southern Africa. Agric. Syst. 150, 21–33.

Nyamadzawo, G., Nyamugafata, P., Wuta, M., Nyamangara, J., Chikowo, R., 2012. Infiltration and runoff losses under fallowing and conservation agriculture practices on contrasting soils, Zimbabwe. Water SA 38, 233–240.

Nyamangara, J., Marondedze, A., Masvaya, E., Mawodza, T., Nyawasha, R., Nyengerai, K., Tirivavi, R., Nyamugafata, P., Wuta, M., 2014. Influence of basin-based conservation agriculture on selected soil quality parameters under smallholder farming in Zimbabwe. Soil Use Manage. 30, 550–559.

Probert, M., Dimes, J., Keating, B., Dalal, R., Strong, W., 1998. APSIM's water and nitrogen modules and simulation of the dynamics of water and nitrogen in fallow systems. Agric. Syst. 56, 1–28.

Probert, M.E., Delve, R., Kimani, S., Dimes, J.P., 2005. Modelling nitrogen mineralization from manures: representing quality aspects by varying C: N ratio of sub-pools. Soil Biol. Biochem. 37, 279–287.

Raes, D., Sithole, A., Makarau, A., Milford, J., 2004. Evaluation of first planting dates recommended by criteria currently used in Zimbabwe. Agric. For. Meteorol. 125, 177–185.

Riley, H., 1998. Soil mineral-N and N-fertilizer requirements of spring cereals in two long-term tillage trials on loam soil in southeast Norway. Soil Tillage Res. 48, 265–274.

Robinson, J., 1957. The critical relationship between soil moisture content in the region of wilting point and the mineralization of natural soil nitrogen. J. Agric. Sci. 49, 100–105.

Rurinda, J., 2014. Vulnerability and Adaptation to Climate Variability and Change in Smallholder Farming Systems in Zimbabwe. Wageningen University, Wageningen, pp. 168.

Rurinda, J., Mapfumo, P., van Wijk, M.T., Mtambanengwe, F., Rufino, M.C., Chikowo, R., Giller, K.E., 2013. Managing soil fertility to adapt to rainfall variability in smallholder cropping systems in Zimbabwe. Field Crop Res. 154, 211–225.

Rurinda, J., Wijk, M.T., Mapfumo, P., Descheemaeker, K., Supit, I., Giller, K.E., 2015. Climate change and maize yield in southern Africa: what can farm management do? Global Change Biol. 21, 4588–4601.

Salinas-Garcia, J., Hons, F., Matocha, J., Zuberer, D., 1997. Soil carbon and nitrogen dynamics as affected by long-term tillage and nitrogen fertilization. Biol. Fert. Soils 25, 182–188.

Shamudzarira, Z., Robertson, M., 2002. Simulating response of maize to nitrogen fertilizer in semi-arid Zimbabwe. Exp. Agric. 38, 79–96.

Shumba, E., Waddington, S., Rukuni, M., 1992. Use of tine-tillage, with atrazine weed control, to permit earlier planting of maize by smallholder farmers in Zimbabwe. Exp. Agric. 28, 443.

Singh, B., Singh, D., 1995. Agronomic and physiological responses of sorghum, maize and pearl millet to irrigation. Field Crop Res. 42, 57–67.

Spear, A.J., 1968. Tillage Problems of Peasant Agriculture in Rhodesia. Supplement to Modern Farming, Salisbury, pp. 57–59.

Stanford, G., Smith, S., 1972. Nitrogen mineralization potentials of soils. Soil Sci. Soc. Am. J. 36, 465–472.

Stern, R., Rijks, D., Dale, I., Knock, J., 2006. Instat Climatic Guide. Statistical Service Center, Reading.

Tadross, M., Suarez, P., Lotsch, A., Hachigonta, S., Mdoka, M., Unganai, L., Lucio, F., Kamdonyo, D., Muchinda, M., 2007. Changes in growing-season rainfall characteristics and downscaled scenarios of change over southern Africa. Implications for Growing Maize. IPCC regional Expert Meeting on Regional Impacts, Adaptation, Vulnerability, and Mitigation, Nadi, Fiji, pp. 193–204.

Thierfelder, C., Wall, P.C., 2009. Effects of conservation agriculture techniques on infiltration and soil water content in Zambia and Zimbabwe. Soil Tillage Res. 105, 217–227.

USDA-SCS, 1986. Urban hydrology for small watersheds. Tech. Release 55, 2–6.

Vanlauwe, B., Wendt, J., Giller, K., Corbeels, M., Gerard, B., Nolte, C., 2014. A fourth principle is required to define Conservation Agriculture in sub-Saharan Africa: the appropriate use of fertilizer to enhance crop productivity. Field Crop Res. 155, 10–13.

Vincent, V., Thomas, R., Staples, R., 1960. An Agricultural Survey of Southern Rhodesia. Part 1. Agro-ecological Survey. Government Printers, Salisbury.

WRB, 2006. Working group (2006) world reference base for soil resources. A framework for international classification, correlation and communication. World Soil Resources Reports 103, 2nd edn. Food and Agriculture Organization of the United Nations, Rome.