



Nitrogen management strategies for smallholder maize production systems: Yield and profitability variability

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Received 27 February 2014; Accepted after revision 18 July 2014; Published online 26 October 2014

Abstract

Maize (*Zea mays* L.) production requires large amounts of nitrogen (N) that directly affect production cost. Poultry litter can be used as an alternative source of N. To optimize its use, poultry litter requires technical and economic feasibility analyses. Crop simulation models have proven to be efficient tools to support this type of research. The objectives of this study were to determine yield and net return of maize production fertilized with both mineral fertilizer and poultry litter. High inter-annual variation was observed in simulated yield for all fertilization strategies evaluated. The higher the mineral N rate, the higher the yield. Among the treatments fertilized with poultry litter the highest yield was obtained with a rate equivalent to 240 kg ha⁻¹ of N. The trend of the economic net return for the different rates of mineral fertilizers was in the opposite direction of the trend in yield, i.e., the higher the rate of mineral fertilizer, the lower the economic return. Among the poultry litter fertilization strategies, the average economic net return increased up to a rate equivalent to 210 kg ha⁻¹ of N, decreasing for higher rates. Poultry litter rates equivalent to 120 to 300 kg ha⁻¹ of N, economically exceeded all the mineral fertilization strategies that were evaluated. Among all sources and rates, the highest net return was obtained for a rate of 210 kg ha⁻¹ of N as poultry litter. Higher rates provided a lower net return and increased the likelihood of nitrate leaching.

Keywords: Poultry litter; Crop modeling; DSSAT; Fertilizer management; *Zea mays* L.; Economic analysis.

Introduction

Smallholder farmers in Brazil are diverse in their cultural, social and economic profiles, ranging from traditional low input production systems to modern high technology production systems. The majority of smallholder farmers are characterized as less dependent of external inputs and that their production is primarily to meet the needs of the family (Cruz et al., 2006). Smallholder producers represent 84% of the total Brazilian farms, occupy 24% of the agricultural land and are responsible for 38% of the gross national agricultural production (IBGE, 2006). The participation of smallholder farmers in the gross domestic product (GDP) of Brazil ranged from 8.8 to 10.1% between the years 1995-2005. Maize (*Zea mays* L.) accounted for 4 to 5.9% of the smallholders GDP in the same period; in 2005 it accounted for only 4%. Lately, however, smallholder farmers have been experiencing a reduction in their income, mainly due to the increasing cost of inputs (Guilhoto et al., 2007).

In most of the Brazilian cultivated land and specifically in the Cerrado (Savannah) region, soil-nitrogen availability is a limiting factor for maize production (Escosteguy et al., 1997). It has been found that N use efficiency in the Cerrado region is around 50% (Ceretta, 2002; Pöttker and Wiethölter, 2004; Silva et al., 2005; Gomes et al., 2007; Hurtado et al., 2009). Overall, the major causes of low maize yield in the region are the inappropriate sowing dates with a risk of water stress, low N use and poor control of weeds (Affholder et al., 2003); among those limiting factors, N and water are of major relevance. The former, due to its direct impact on yield (Amado et al., 2002) and on the production cost (Silva et al., 2001) and the latter because of dry spells (dry periods within the rainy season). In the region maize is grown predominantly under rainfed conditions during which dry spells are common. For instance, there is 50% chance of 7-day long dry spells in January (Assad and Castro, 1991). For maize sown late in October the dry spells during January may coincide with anthesis and grain filling growth stages, two critical periods regarding water stress, leading to a considerable reduction in yield (Bergamaschi et al., 2006). Previous studies have determined that rainfall distribution suitable for maize production with dry spells shorter than 8 days occurs once every 13 years and that there is a 50% chance of dry spells 14 days or longer in December and January (Wolf, 1975). These results demonstrate that maize production in this region has a high risk of dry spells at any time during the growing season, therefore directly affecting yield (Barbosa et al., 1986).

The inability to control and manipulate environmental factors under field conditions makes it difficult to study the effects and interactions of inputs with weather and with different management practices. Crop simulation models are highly efficient tools to study this type of constraints and have been widely used to estimate the effects of environmental restrictions on crops yield as well as to evaluate appropriate management practices. The Cropping System Model (CSM)-CERES-Maize is one of the maize models that have been used extensively worldwide (Soler et al., 2004). The CERES (Crop Environment Resource Synthesis) consists of group of models developed by the Grassland Soil and Water Research Laboratory (Jones and Kiniry, 1986). Among the CERES models, CERES-Maize was developed for the maize crop and allows simulations of the growth and development of maize, water balance, N levels and also enables economic evaluations based on four input variables: soil, climate, crop management and genotypes (Soler, 2000). The cropping season of maize in the CERES-Maize is divided into various phases (germination, emergence, end of juvenile phase, floral induction, silking, beginning of grain filling and harvest maturity), while development is influenced by the thermal sum or thermal time, expressed in degree-days (DD), which is calculated based on the minimum and maximum daily temperatures. The thermal time required to progress from one stage of development to another is a user input and can be defined as: P_1 - Thermal time from seedling emergence to the end of the juvenile phase (expressed in DD above a base temperature of 8 °C), during which the plant is not responsive to changes in photoperiod; P_2 - Extent to which development (expressed the days) is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate (which is considered to be 12.5 hours); P_5 - Thermal time from silking to physiological maturity (expressed in DD above a base temperature of 8 °C); G_2 - Maximum possible number of kernels per plant; G_3 - Kernel filling rate during the linear grain filling stage and under optimum conditions (mg day^{-1}); PHINT - Phylochron interval, the interval in DD between successive leaf tip appearances (Ritchie et al., 1998; Jones et al., 2003). The CSM-CERES-Maize is part of the Decision Support System for Agrotechnology Transfer, DSSAT (Jones et al., 2003; Hoogenboom et al., 2011), a software that includes models for 28 different crops. The CSM-CERES-Maize has shown to be a suitable tool for technical and economic evaluation of management practices. For example, it was used to predict quality and rate of organic materials required to combine

with mineral fertilizers for profitable maize production in Thailand (Pinitpaitoon et al., 2011). In Rwanda, Bidogeza et al. (2012) used DSSAT to predict yield under combined use of organic and inorganic fertilizers and to determine best fertilization strategies. Andrade et al. (2012) used the CSM-CERES-Maize to evaluate yield and profitability of a smallholder rainfed maize production system using cattle manure as a source of N. More recently, a study conducted by Silva et al. (2013) used the CSM-CERES-Maize to assess the sustainability of the long-term use of swine manure for rainfed maize production and to derive a management strategy that will allow for minimum nitrate leaching.

Long-term studies are suitable to assess the impact of management practices in crop production. However, long-term studies are limited by inherent costs and time needed to maintain such studies; dynamic crop simulation models coupled to decision support systems may help reducing that gap. As such, DSSAT can be a suitable tool to evaluate the efficiency of using poultry litter on maize production, especially when considering the combined effects of weather uncertainties and fertilization strategies on yield and profitability.

The main goal of this study was to determine yield and net return of maize production fertilized with both mineral fertilizer and poultry litter. Specific objectives were to: a) use a dynamic crop simulation model to explore different management practices and b) determine the potential of nitrate leaching from the different fertilization strategies.

Materials and Methods

The study was conducted for conditions representing the region of Sete Lagoas, Minas Gerais State, Brazil. The representative soil of the region is a typical Haplustox (Panoso et al., 2002), characterized as clayey, structured, low bulk density and with porosity of almost 60%. A detailed description of the soil profile can be found in Amaral et al. (2015). The CSM-CERES-Maize model version 4.5.0.036 (Jones et al., 2003; Hoogenboom et al., 2011) was used to simulate scenarios of fertilizer management, including different rates of mineral fertilizer and poultry litter. The model was previously calibrated for conditions in Sete Lagoas and the cultivar coefficients for the single-cross hybrid BRS 1030 were obtained (Amaral et al., 2015).

The climate of the region is described in Amaral et al. (2015). Daily weather data, including rainfall, minimum and maximum air temperature and sunlight hours, for a period of 49 years (1960-2009) (Figure 1A, B and C), were obtained from a weather station of the National Institute of Meteorology, INMET, located at the Embrapa Maize and Sorghum experimental station in Sete Lagoas, Brazil. The daily solar radiation was estimated from sunlight hours data by using WeatherMan (Pickering et al., 1994), a utility program that is part of DSSAT (Jones et al., 2003; Hoogenboom et al., 2011). The average maximum air temperature ranged from 29.7 °C in February to 26.2 °C in July; the average minimum air temperature ranged from 18.5 °C in January to 11.5 °C in July and the average air temperature ranged from 24.1 °C in February to 18.8 °C in July (Figure 1A). The rainy season is from October to March, with an average monthly rainfall ranging from 102 mm to 293 mm (Assad and Castro, 1991); the dry season extends from April to September, with an average monthly rainfall ranging from 9 mm to 55 mm. The average annual total rainfall is 1384 mm (Figure 1B). The highest monthly average solar radiation, ranging from 19.7 to 21.8 MJ m⁻² day⁻¹ was observed from September to March, while the lowest average of 16.2 to 19.3 MJ m⁻² day⁻¹, was observed from April to August (Figure 1C).

In order to assess the inter-annual and seasonal weather variability effect on maize growth and yield, the seasonal mode of DSSAT (Thornton and Hoogenboom, 1994) was used to simulate grain yield for the period of 1960 to 2009. The CSM-CERES-Maize model was set to sow maize on October 24, a sowing date considered to be the best for rainfed production in Sete Lagoas, MG, Brazil (Amaral et al., 2009). The simulations were set to start on June 24, of each year for a more consistent simulated soil-water balance at the sowing time. Because the sowing date occurs within the dry season, it was assumed that the initial soil-water content was at the lower limit of available water. The initial nitrate and ammonium content in the soil profile were estimated by the model assuming that the soil was capable of supplying the crop with 50 kg ha⁻¹ of N (Souza and Lobato, 2004). The row spacing was set to 0.8 m and the plant population to 6.8 plants m⁻². Other management practices were obtained from recommendations generated by Embrapa (Cruz et al., 2006).

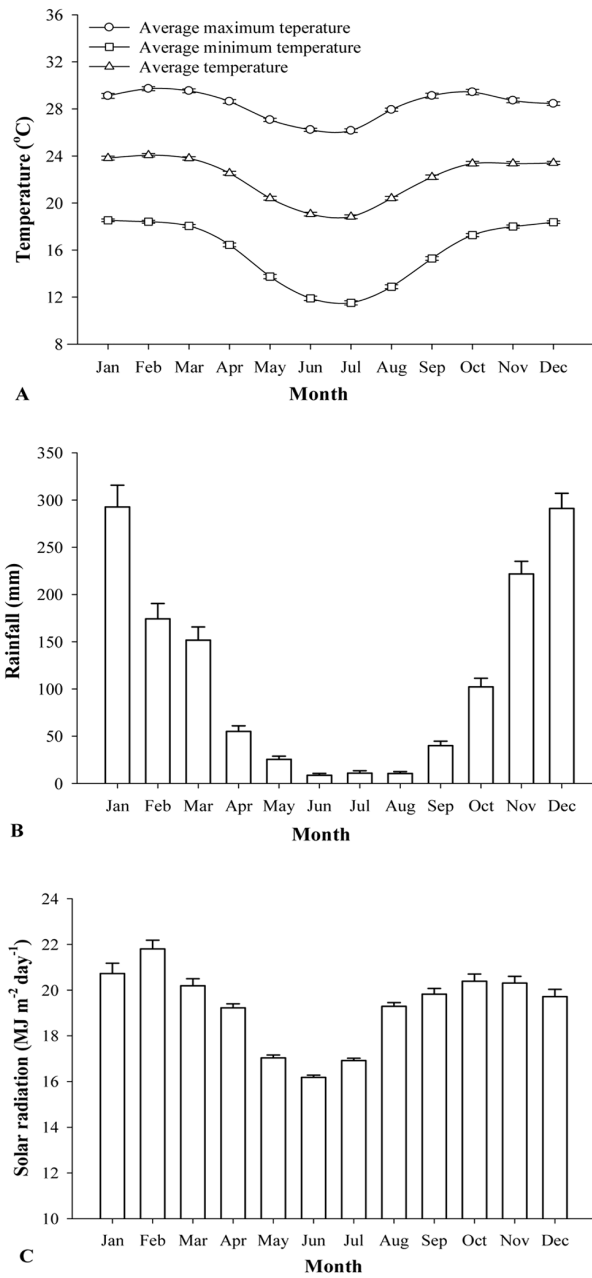


Figure 1. Long-term (1960-2009) monthly average of air temperature (A), rainfall (B) and solar radiation (C), for Sete Lagoas, Brazil.

In order to assess the crop response to mineral fertilizer and poultry litter, 13 different fertilization management strategies were set (Table 1). These strategies consisted of three mineral fertilizer rates and ten rates of air-dry poultry litter enriched with 250 kg ha⁻¹ of single super phosphate. The average content of N in the poultry litter was 30 kg t⁻¹ (Konzen, 2003). For the net return analysis, a production cost spreadsheet, developed by the Minas Gerais State Extension Service (Emater-MG), Brazil, was used. The inputs used in the simulations and in the cost analysis are described in Table 2. Our rationale considered an improved smallholder production system that considered the use of dolomitic lime every three years, the cost of adding 250 kg ha⁻¹ of single super phosphate (SSP) to each poultry litter treatment and the cost of the technical assistance to farmers in the implementation and monitoring of production system.

The cost of inputs, services and poultry litter were obtained from the Secretariat of Agriculture and Supply of Paraná State (SEAB), Brazil for the period from February 2005 to May 2010 (Paraná, 2013). The price for maize grain (Table 3) was obtained from a series of 79 weekly values from January 2009 to June 2010 at Uberlândia, Brazil, the nearest maize market place (Agrolink, 2011). All cost and price data were converted from the Brazilian currency Reais (R\$) to US dollar (US\$) by using an average conversion factor of R\$1.76:1US\$ for 2010 (Banco Central do Brasil, 2013) and were organized as a triangular probability distribution with minimum, mode and maximum values. The production costs and the poultry litter costs were combined to generate the final production costs for maize (Tables 2 and 3), computed as minimum, mode and maximum, for each treatment (Table 4). Cost results were then entered as input in the economic module of the seasonal analysis module of DSSAT.

Following the simulation of the scenarios using the historical series of weather data, one could produce stochastic net return values. For each fertilizer treatment the simulations of scenarios generated 49 yield and 147 (49×3) net return scenarios, which were plotted as frequency distribution and mean-variance. These results were analyzed in terms of the technical and economic feasibility of using mineral fertilizer and poultry litter as sources of nitrogen for maize production in the region. Additionally, the equilibrium point was calculated for the minimum, mode and maximum costs obtained for the different fertilization strategies. The equilibrium point is the yield value at which the farmer has neither profit nor loss.

Table 1. Fertilization strategies used in this study.

Description	Treatments												
	T ₁	T ₂	T ₃	T ₄	T ₅	T ₆	T ₇	T ₈	T ₉	T ₁₀	T ₁₁	T ₁₂	T ₁₃
Mineral fertilizer													
04-14-08 (N, P ₂ O ₅ , K ₂ O)	260	370	500	0	0	0	0	0	0	0	0	0	0
N formulation	10	15	20	0	0	0	0	0	0	0	0	0	0
Phosphorus formulation	36	52	70	0	0	0	0	0	0	0	0	0	0
Potash formulation	21	30	40	0	0	0	0	0	0	0	0	0	0
Single superphosphate (SSP)	0	0	0	250	250	250	250	250	250	250	250	250	250
N Side-dressed at 30 DAS	40	58	70	0	0	0	0	0	0	0	0	0	0
N side-dressed at 45 DAS	40	57	70	0	0	0	0	0	0	0	0	0	0
Air-dried poultry litter	0	0	0	1,000	2,000	3,000	4,000	5,000	6,000	7,000	8,000	9,000	10,000
N from poultry litter ⁽¹⁾	0	0	0	30	60	90	120	150	180	210	240	270	300
Total N applied	90	130	160	30	60	90	120	150	180	210	240	270	300
------(kg ha ⁻¹)-----													
------(US\$ ton ⁻¹)-----													
Cost of poultry litter	Minimum	31	62	92	123	154	185	216	247	277	308	347	386
	Mode	36	69	104	139	173	208	243	277	312	347	386	
	Maximum	39	77	116	154	193	232	270	309	347	386		

⁽¹⁾ Average of 30 kg t⁻¹ of N in the poultry litter (Konzen, 2003).

Table 2. Rates and minimum, mode and maximum values of crop inputs and services used in this study.

Description ⁽¹⁾	Unit	Amount per ha	Market price ⁽²⁾ (US\$)		
			Minimum	Mode	Maximum
			------(US\$)-----		
Seeds, single-cross hybrid BRS 1030	kg	20	71	81	98
Herbicide nicosulfuron	L	1	32	39	73
Insecticide decis 200 SC	L	0.2	4	5	11
Ploughing	Tractor hour	1	30	38	45
Harrowing	Tractor hour	1	30	38	45
Herbicide application	Tractor hour	0.3	9	11	13
Sowing	Tractor hour	0.8	24	30	36
N side dressing	Tractor hour	1	30	38	45
Insecticide application	Tractor hour	0.3	9	11	13
Helper	Man-day	1.5	11	16	20
Hand harvest	Man-day	10	97	136	171
Internal transportation	Tractor hour	0.5	15	19	22
Dolomitic lime	ton	2	19	21	24
Lime transportation	ton	2	4	6	6
Lime distribution	Tractor hour	1	10	12	15
Technical assistance	%	2	8	10	13
Total			402	511	649

⁽¹⁾ Rates and costs of poultry litter were described in the Table 1; rates and costs of mineral fertilizer were described in Tables 1 and 3.

⁽²⁾ Source: Paraná, 2013. R\$ 1.76: US\$ 1.00 for year 2010 (Banco Central do Brasil, 2013).

Table 3. Minimum, mode and maximum market price of maize grain and nitrogen, phosphorus and potash fertilizers.

Description	Maize grain ⁽¹⁾	Nitrogen ⁽²⁾ -N	Phosphorus ⁽²⁾ -P ₂ O ₅	Potash ⁽²⁾ -K ₂ O
	(US\$ per 60 kg bag)	(US\$ kg ⁻¹)	(US\$ kg ⁻¹)	(US\$ kg ⁻¹)
Minimum	8.81	1.11	1.11	1.11
Mode	9.38	1.42	1.42	1.42
Maximum	11.65	2.77	2.77	2.77

⁽¹⁾ Source: AGROLINK. Preço de milho em Uberlândia, MG, Brasil. Available: <<http://www.agrolink.com.br/cotacoes/Cotacoes.aspx>>. Last access: November 21, 2013.

⁽²⁾ Costs of nitrogen, phosphorus and potash are proportional to their concentration in the formulation 04-14-08. Source: Paraná. Secretaria de Estado da Agricultura e do Abastecimento do Paraná. Departamento de Economia Rural. Planilha de custo de insumos e serviços. Available: <http://www.seab.pr.gov.br>. Last access: October 29, 2013.

Table 4. Minimum, maximum and mode of maize production cost, for different fertilization strategies.

Description	Treatment ⁽¹⁾												
	T ₁	T ₂	T ₃	T ₄	T ₅	T ₆	T ₇	T ₈	T ₉	T ₁₀	T ₁₁	T ₁₂	T ₁₃
Minimum	565	637	701	482	514	544	575	606	637	668	698	729	760
Mode	720	813	895	610	644	679	714	748	783	818	852	887	922
Maximum	1057	1237	1398	813	851	890	928	967	1006	1044	1083	1122	1160

⁽¹⁾Treatment identification and description can be found in Table 3; combination of tables 1, 2 and 3.

Results

Crop response to fertilizer rates

Yield of maize fertilized with mineral N was 4,812 kg ha⁻¹; 5,318 kg ha⁻¹ and 5,768 kg ha⁻¹ for treatments T₁, T₂ and T₃, which correspond to N rates of 90, 130 and 160 kg ha⁻¹, respectively (Figure 2). The higher the N rate, the higher the yield. The highest yield of 5,768 kg ha⁻¹ was obtained with a rate of 160 kg ha⁻¹ of N (T₃). On the other hand, the rate of 90 kg ha⁻¹ of N (T₁) resulted in a yield of 4,812 kg ha⁻¹ that is 17% lower than the yield obtained with a N rate of 160 kg ha⁻¹ (T₃), which is 44% higher than the 90 kg ha⁻¹ of T₁ (Figure 2).

Among the treatments fertilized with poultry litter, the yield increased almost linearly up to a rate of 7 t ha⁻¹ (T₁₀) equivalent to 210 kg ha⁻¹ of N. The yield increment for poultry litter rates higher than 7 t ha⁻¹ was small, although a slightly higher yield was obtained with a rate of 8 t ha⁻¹ (T₁₁). The rate of 5 t ha⁻¹ (T₈) of poultry litter, equivalent to an N rate of 150 kg ha⁻¹, provided a yield of 5,235 kg ha⁻¹, which is lower than the 5,768 kg ha⁻¹ obtained with the treatment T₃ that used 160 kg ha⁻¹ of N as mineral fertilizer. On the other hand, for the rate of 3 t ha⁻¹ (T₆) of poultry litter, equivalent to an N application rate of 90 kg ha⁻¹, the yield was 3,878 kg ha⁻¹, which is lower than the 4,812 kg ha⁻¹ obtained with the treatment T₁ that used the same N rate as mineral fertilizer (Figure 2). Therefore, the use of poultry litter provided yields slightly lower than the equivalent rates of mineral fertilizer. This may be due to the fact that N from organic fertilizer sources is released to the crop at a slower rate as compared to mineral fertilizers (Sampaio et al., 2007).

For all fertilization treatments, high yield variability was observed as a consequence of interactions between the crop, N rates and weather conditions (Figures 2 and 3). Environmental conditions drastically affect N fertilization strategies. A combination of low rainfall, low solar radiation and high day and night temperature, an unfavorable condition for the crop grow and development, leads to low N uptake and very low yield. On the other hand, a combination of high rainfall, bright days and low minimum temperature, a favorable condition, tends to provide high maize yield. The least yield variability was obtained for treatment T₄ and the highest one for treatment T₁₃ (Figure 3). Due to unfavorable weather conditions in 25% of the years, yield from the mineral fertilizer rate of 160 kg ha⁻¹ (T₃), which provided the highest yield, ranged from 1,486 to 4,948 kg ha⁻¹. Likewise, for

25% of the years, due to favorable weather conditions, the yield of maize ranged from 6,523 to 7,638 kg ha⁻¹. In other words, there is a 50% chance for a farmer to obtain either the lowest or the highest yield for any given year as yield varied from 4,948 to 6,523 kg ha⁻¹ every other year. For a poultry litter rate of 8 t ha⁻¹ (T₁₁), equivalent to an N rate of 240 kg ha⁻¹, in 25% of the years yield ranged from 1,340 to 5,282 kg ha⁻¹ during years of unfavorable weather conditions and ranged from 6,996 to 9,015 kg ha⁻¹ during years with favorable weather conditions (Figure 2). In years with favorable weather conditions the crop responded to the higher N rates producing higher yield. On the other hand, in years with unfavorable weather conditions, even with high N rates, low yields were obtained. As a result, yield variability was high among the different fertilization strategies (Figures 2 and 3).

Within mineral fertilizer strategies, the rate of 160 kg ha⁻¹ (T₃) provided the highest average yield with a variance only slightly higher than the rate of 130 kg ha⁻¹ (T₂). Within poultry litter fertilization strategies, a rate of 7 t ha⁻¹, equivalent to 210 kg ha⁻¹ of N (T₁₀), resulted on the second highest average yield (Figure 3).

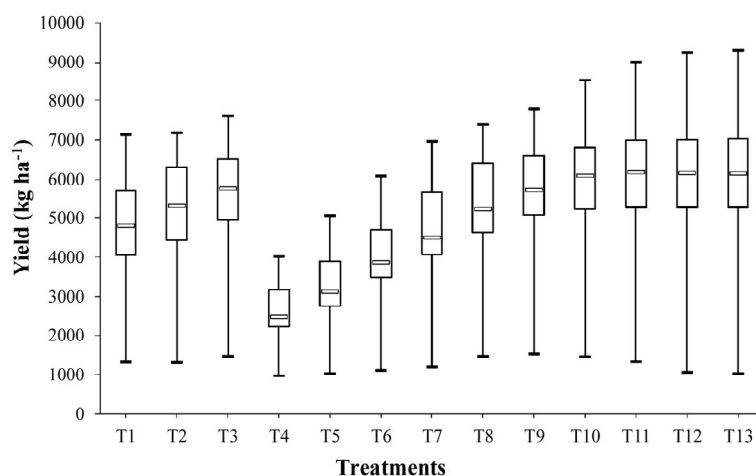


Figure 2. Variation in maize yield for the different fertilization strategies. The bottom of the box indicates the lower 25 percentile, the line in the box indicates the median or the 50 percentile and the upper limit of the box indicates the 75 percentile. T₁, T₂ and T₃ are mineral N rates of 90, 130 and 160 kg ha⁻¹, respectively and T₄ to T₁₃ are poultry litter rates equivalent to N rates of 30, 60, 90, 120, 150, 180, 210, 240, 270 and 300 kg ha⁻¹ plus 250 kg ha⁻¹ of single superphosphate, respectively.

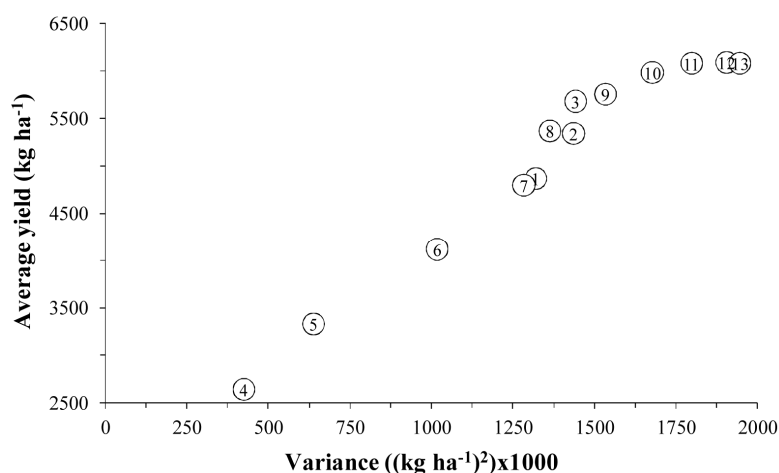


Figure 3. Variance of the average yield for the different fertilization strategies. Circles 1-3 correspond to T₁, T₂ and T₃ or mineral N rates of 90, 130 and 160 kg ha⁻¹, respectively. Circles 4-13 correspond to T₄ to T₁₃ or poultry litter rates at equivalent N rates of 30, 60, 90, 120, 150, 180, 210, 240, 270 and 300 kg ha⁻¹ plus 250 kg ha⁻¹ of single superphosphate, respectively.

Cost of production and yield economic net return

Considerable variation was observed in the cost of production as a consequence of the variability in the historic market prices of crop inputs (Table 4). The higher the N rate, the higher the minimum, mode and maximum cost of production and the larger the difference between the maximum and the minimum cost of production for each treatment. For the rate of 90 kg ha⁻¹ (T₁) of mineral fertilizer, the minimum, mode and maximum cost of production were US\$ 565, US\$ 720 and US\$ 1,057 ha⁻¹, against US\$ 544, US\$ 679 and US\$ 890, respectively, for the same N rate as poultry litter (Table 4). For the rate of 160 kg ha⁻¹ (T₃) of mineral fertilizer the cost of production ranged from US\$ 701 to US\$ 1398 ha⁻¹, while the N rate of 150 kg ha⁻¹ (T₈) of poultry litter resulted in a cost of production ranging from US\$ 606 to US\$ 967 ha⁻¹. For the rate of 8 t ha⁻¹ of poultry litter (T₁₁), which provided the best yield (Figure 2), the minimum, mode and maximum cost of production were, respectively, US\$ 698, US\$ 852 and US\$ 1083 ha⁻¹, while the rate of 7 t ha⁻¹ of poultry litter (T₁₀) provided a minimum, mode and

maximum cost of production of US\$ 668, US\$ 818 and US\$ 1,044 ha⁻¹, respectively (Table 4).

The optimum median economic results (Figures 4 and 5) were different from those that provided the highest median yield (Figures 2 and 3). The trend of the net return for the different rates of mineral fertilizers was in the opposite direction of the trend in yield, i.e., the higher the rate of mineral fertilizer, the lower the economic return. The net return for the rates of 90 kg ha⁻¹ to 160 kg ha⁻¹ of mineral fertilizer ranged from a profit of US\$ 31 ha⁻¹ to a loss of US\$ 42 ha⁻¹. Among the poultry litter strategies, the net return ranged from a loss of US\$ 183 ha⁻¹ for a rate of 30 kg ha⁻¹ of N (T₄), to a profit of US\$ 78 ha⁻¹ for a rate of 300 kg ha⁻¹ of N (T₁₃). The highest profit of US\$ 163 ha⁻¹ was achieved for the rate of 7 kg ha⁻¹ of poultry litter, equivalent to 210 kg ha⁻¹ of N (T₁₀). The net return decreased for poultry litter rates higher than 7 t ha⁻¹ while rates of 4 t ha⁻¹ or higher economically exceeded all the mineral fertilization treatments (Figure 4).

For a rate of 90 kg ha⁻¹ of N as mineral fertilizer (T₁), the economic losses ranged from US\$ 862 to US\$ 123 ha⁻¹; this was due mainly to adverse weather conditions. Likewise, in one out of four years, under favorable weather conditions, the net economic return ranged from US\$ 200 to US\$ 824 ha⁻¹. In 50% of the years the net economic return ranged from a loss of US\$ 123 to a profit of US\$ 200 ha⁻¹. For the poultry litter rate of 7 t ha⁻¹ (T₁₀), the treatment that provided the highest net return, economic losses from US\$ 5 to US\$ 829 ha⁻¹ and profits from US\$ 335 to US\$ 990 ha⁻¹ are expected. In 50% of the years, net economic returns are expected to range from a loss of US\$ 5 to a profit of US\$ 335 ha⁻¹ (Figure 4).

A more profitable scenario of the different fertilization strategies was derived when net return and its inter-annual variance were analyzed (Figure 5). Among the different mineral fertilization strategies, the N rate of 90 kg ha⁻¹ resulted in the highest net return of US\$ 36 ha⁻¹ with the lowest variance. The poultry litter rate of 7 t ha⁻¹ (T₁₀) provided the highest average profit of US\$ 158 ha⁻¹ but with a high variance (Figure 5). Although it did provide a profit higher than all the mineral fertilizer rates evaluated, poultry litter rates higher than 7 t ha⁻¹ caused a decrease in the average net return.

An approach used by farmers to make decisions is the economic equilibrium, which refers to the product market price in which neither profit nor loss occurs. For the mineral fertilization strategy of 90 kg ha⁻¹ of N (T₁) that resulted in the highest net return among the mineral fertilizer treatments, the minimum, mode and maximum equilibrium point were US\$ 116, US\$ 148 and US\$ 217 per ton, respectively. On the other hand, for a poultry litter rate of 7 t ha⁻¹, equivalent to 210 kg ha⁻¹ of N (T₁₀), the minimum, mode and maximum equilibrium point were US\$ 112, US\$ 137 and US\$ 175, respectively. With that information the farmer can look at market price forecast and make a decision on whether to grow maize or not. For instance, if the forecasted maize market price is US\$ 140 per ton or lower it may not be worth growing maize. In this case an adjustment on the production system has to be made by changing to another crop, variety, fertilization rates and so on.

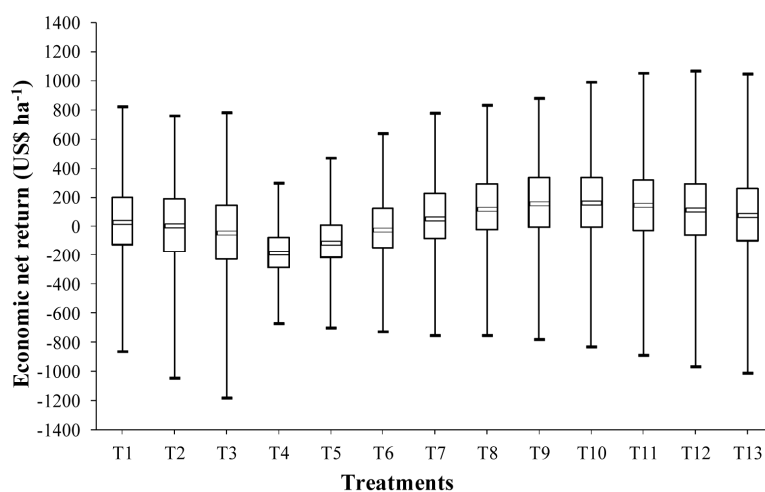


Figure 4. Variation of economic net returns for the different fertilization strategies. The bottom of the box indicates the lower 25 percentile, the line in the box indicates the median or the 50 percentile and the upper limit of the box indicates the 75 percentile. T₁, T₂ and T₃ are mineral N rates of 90, 130 and 160 kg ha⁻¹, respectively and T₄ to T₁₃ are poultry litter rates at equivalent N rates of 30, 60, 90, 120, 150, 180, 210, 240, 270 and 300 kg ha⁻¹, plus 250 kg ha⁻¹ of single superphosphate, respectively.

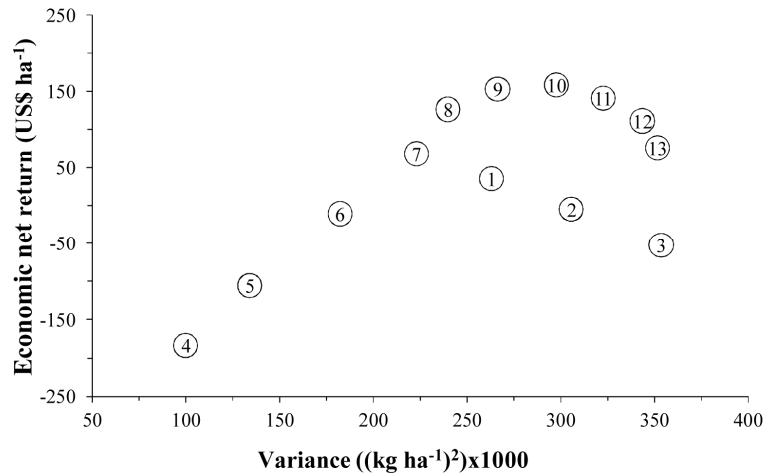


Figure 5. Variance of average economic net return for the different fertilization strategies. Circles 1-3 correspond to T₁, T₂ and T₃ or mineral N rates of 90, 130 and 160 kg ha⁻¹, respectively. Circles 4-13 correspond to T₄ to T₁₃ or poultry litter rates at equivalent N rates of 30, 60, 90, 120, 150, 180, 210, 240, 270 and 300 kg ha⁻¹, plus 250 kg ha⁻¹ of single superphosphate, respectively.

Nitrate leaching potential

From a sustainability perspective the amount of simulated leached N ranged from 9 kg ha⁻¹ to 18 kg ha⁻¹ (Figure 6). The poultry litter rate of 7 t ha⁻¹ (T₁₀) that resulted in the highest average net return had an amount of leached N of 10 kg ha⁻¹, which was very similar to the 9 kg ha⁻¹ simulated for the mineral fertilization rates of 90 to 160 kg ha⁻¹ (T₁ to T₃) (Figure 6). Due to weather conditions, the high N rate evaluated provided a high variability of N leached; this was especially true when using poultry litter. For poultry litter rates from 8 t ha⁻¹ to 10 t ha⁻¹ (T₁₁ to T₁₃) the range between the minimum and maximum leached N was very large due to the interactions between crop response, management, weather conditions. In years with favorable weather conditions for maize (high incident solar radiation, no water deficit and low minimum temperature), the simulated nitrate leaching was low, even when high N rates were applied. On the other hand, in years with adverse weather conditions (water deficit in key phases of maize and high minimum temperature) the nitrate leaching was as high as 92 kg ha⁻¹ for high N rate (Figure 6). This is due to the fact that under favorable weather conditions the maize crop absorbs the soil nitrate which is prone to be leached.

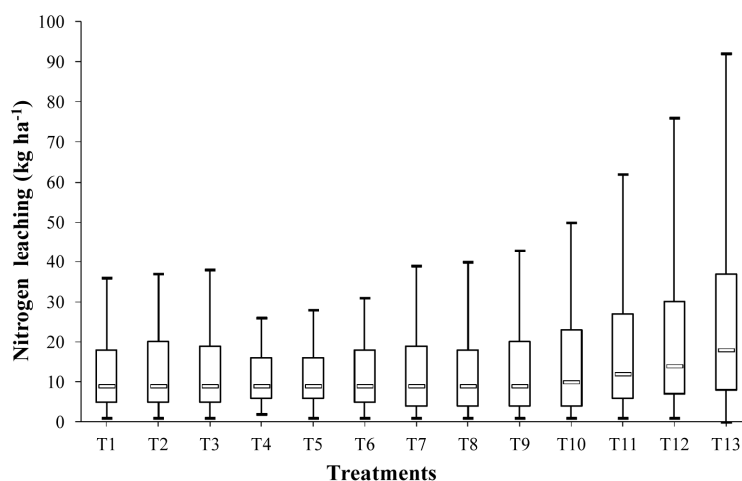


Figure 6. Variation of leached nitrate rates for the different fertilization strategies. The bottom of the box indicates the lower 25 percentile, the line in the box indicates the median or the 50 percentile and the upper limit of the box indicates the 75 percentile. T₁, T₂ and T₃ are mineral N rates of 90, 130 and 160 kg ha⁻¹, respectively and T₄ to T₁₃ are poultry litter rates at equivalent N rates of 30, 60, 90, 120, 150, 180, 210, 240, 270 and 300 kg ha⁻¹, plus 250 kg ha⁻¹ of single superphosphate, respectively.

Discussion

This study showed that the single-cross hybrid BRS 1030 had potential to produce high yield. However, the weather conditions in Sete Lagoas for the October sowing date limits maize rainfed production, especially due to the occurrence of dry spells (Assad and Castro, 1991), high night temperatures and reduced availability of incident radiation, as a consequence of cloudy days (Figure 1). For instance, Alves et al. (2011) found that for conditions in Janaúba, Brazil, even if the crop is kept under appropriate soil moisture conditions through the use of supplemental irrigation, factors such as temperature and radiation are the major cause of low yield in the region. In another study conducted by Wu et al. (2008) using modeling, they observed that solar radiation and temperature are the major factor affecting potential yield and rainfall distribution affecting rainfed yield of maize in China.

Our results indicate that the crop responded positively to both different rates of mineral fertilizer and different rates of poultry litter. A rate of 160 kg ha⁻¹ of mineral N fertilizer provided the highest average yield of 5,680

kg ha⁻¹ (Figure 3). Regarding poultry litter, the crop responded almost linearly to rates up to 7 t ha⁻¹, while for higher application rates of poultry litter slight increases in yield were obtained. These higher poultry litter rates should not be recommended because of increased cost (Figures 4 and 5) and greater risk of pollution due to nitrate leaching (Figure 6). The simulated yield obtained with the poultry litter treatments (Figure 2) were in agreement with those obtained by Konzen (2003), who reported a yield of 8,450 kg ha⁻¹ for a poultry litter rate of 7.5 t ha⁻¹, for conditions in Rio Verde, Brazil. When comparing simulated yield obtained by using the two types of fertilizers our simulations indicated that the poultry litter treatments resulted in less yield, as compared to mineral fertilizer. This is due to the fact that the model considers the poultry litter transformation into the soil (Godwin and Singh, 1998), in which the N is available to plants at a slower release rate as compared to the conventional mineral fertilizer (Sampaio et al., 2007).

In a variety trial conducted in Sete Lagoas, Brazil, the average yield of the single-cross hybrid BRS 1030 was 7,534 kg ha⁻¹ and 6,358 kg ha⁻¹, with 13% humidity, for the 2003/2004 and 2004/2005 seasons, respectively (Cruz et al., 2005). In another field trial conducted in Selvíria, MS, Brazil, Kaneko et al. (2010) obtained an average yield of 7,518 kg ha⁻¹ for an N rate of 120 kg ha⁻¹. Those results are in the range of from 1,486 to 7,638 kg ha⁻¹ (Figure 2) simulated yield obtained for the same maize variety fertilized with 130 kg ha⁻¹ of mineral N (Figure 2), indicating that the model satisfactorily simulates crop yield.

Survey results from the Brazilian Geography and Statistic Institute (IBGE), for the period from 2003 to 2012, found that rainfed maize yield in the Sete Lagoas region ranged from 4,000 to 6,050 kg ha⁻¹ (IBGE, 2013), which is in the range of 1,330 to 7,151 kg ha⁻¹ obtained in this study for a scenario of 90 kg ha⁻¹ of N as mineral fertilizer. Another study conducted by the State Extension Service (Avaliação de sistemas de produção na região central de Minas Gerais, 2010), during the 2009/2010 cropping season, indicated that the average rainfed maize yield in the region was 2,527 kg ha⁻¹. This figure is lower than the 4,812 kg ha⁻¹ average simulated yield obtained in this study with a mineral N rate of 90 kg ha⁻¹ (T₁) (Figure 2) evidencing that the yield gap, commonly observed among Brazilian smallholders, can be improved with the adoption of appropriate management practices.

Regardless of the source of N used, a high yield variability was observed among fertilization treatments (Figures 2 and 3). This is an indication of the strong effect of weather on rainfed maize production in the region. In

addition, the higher the N rate used, the higher the variance on yield (Figure 3), indicating that adequate weather conditions favor the crop response to N fertilization. Higher yield is an indicative of higher extraction of nutrients; as a consequence, less nitrate are leached (Figure 6). On the other hand, in years with adverse weather conditions the crop does not respond to high N rates and greater nitrate leaching occurs. Similar findings were reported by Jagtap et al. (1999) based on simulations with CSM-CERES-Maize in Africa. They found that the effect of weather may mask the positive effect of fertilizer applications on maize yield. More recently, for conditions in China (Zhong et al., 2010), a high variability in the response of maize to N fertilization was observed in long-term field trials that tested different combinations and rates of mineral fertilizer, manure and stover due to a variability in local weather conditions. Wu et al. (2008) also noted a high inter-annual variability of simulated rainfed maize yield in China, especially due to variability on rainfall distribution.

The comparison of the profitability obtained with the mineral fertilizer strategies showed that the net return decreased as the N rate increased (Figures 4 and 5). The highest net economic return was obtained with a mineral N rate of 90 kg ha⁻¹. Among all the poultry litter scenarios, the highest economic net return of US\$ 158 was achieved with a rate of 7 t ha⁻¹ (210 kg ha⁻¹ of N). Higher poultry litter rates provided lower economic net returns, while rates of 4 t ha⁻¹ or higher, economically exceeded all the mineral fertilization rates.

Research conducted by Silva et al. (2001) reported a maximum economic return of maize production with a rate of 126 kg ha⁻¹ of mineral N. Kaneko et al. (2010), studying the economic viability of rainfed maize production under no-till in Selvíria, Brazil, observed that for the 2007/2008 season a profit of US\$ 143 was obtained when 120 kg ha⁻¹ of N was split into 30 kg ha⁻¹, 45 kg ha⁻¹ and 45 kg ha⁻¹ when the crop presented four to eight fully developed leaves. For the 2008/2009 cropping season the highest profit of US\$ 81 was obtained with a single application of the same N rate at sowing time. When using tillage practices, regardless of the N application strategy, maize production was not profitable. The differences in the profitability obtained indicate how weather variability affects the crop response to fertilization management and can be misleading. This also exemplifies the importance of using modeling as a tool to evaluate the long-term effect of uncertainties due to weather on maize production profitability.

The high variability in the net economic return for all scenarios (Figures 4 and 5) was due to interaction between the crop, the available N in the soil, and the uncertainties due to weather. Fluctuations in price and input cost also add to this variability, making maize production in the region a risky activity. As for yield (Figures 2 and 3), regardless of the source, the higher the N rate the greater the net return variability (Figures 4 and 5). The present study also indicates that research on weather and climate forecasting could help with the development of decision support tools to reduce risks of failure in dryland production systems in the region. For instance, decision support systems that incorporate the outcomes of crop simulation models could be used by the extension service as tools to leverage the uncertainties associated to weather conditions in the region. Linking weather forecasts to crop simulation models has shown benefits in other regions (Soler et al., 2007). Given the high weather variability in the region, the simulations indicated that if no weather forecast is available, the farmers should be advised to use a low N fertilizer rate to reduce the risk of economic losses and to minimize nitrate leaching.

From sustainability perspective not only the technical and economic feasibility of maize production has to be analyzed but also the indicators of environmental pollution such as nitrate leaching. The simulated amount of nitrate leached ranged from 9 kg ha⁻¹ to 18 kg ha⁻¹ (Figure 6), which is in the range of the 10 to 20 kg ha⁻¹ reported by Coelho et al. (2003) for tropical soils of Brazil. Andrade et al. (2007), for conditions in Sete Lagoas, Brazil, using drainage lysimeters, measured a cumulative amount of 23 kg ha⁻¹ of leached nitrate in a no-till maize field. As for this study, a poultry litter rate of 7 t ha⁻¹, which provided the highest profit, had a leached nitrate amount of 10 kg ha⁻¹, close to the 9 kg ha⁻¹ simulated for the mineral fertilization rates of 90 to 160 kg ha⁻¹ (Figure 6). Considering profitability and environmental concerns, rates of poultry litter between 4 t ha⁻¹ and 7 t ha⁻¹ would be more profitable and sustainable than any rate of mineral fertilizer. Based on these results, a mineral N rate of 90 kg ha⁻¹ and a poultry litter rate of 7 t ha⁻¹ can be recommended for a sustainable production of dryland maize in the region.

Conclusions

A rate of 160 kg ha⁻¹ of mineral N fertilizer provided the highest average maize yield while the highest net return was obtained with a mineral N fertilizer rate of 90 kg ha⁻¹. Among the poultry litter treatments, the highest

yield was obtained with a rate equivalent to 240 kg ha⁻¹ of N but the best profit was obtained with a rate equivalent to 210 kg ha⁻¹ of N. Poultry litter rates equivalent to 120 kg ha⁻¹ of N or higher, economically exceeded all the mineral fertilizers rates while rates of poultry litter that provided higher than 210 kg ha⁻¹ of N increased the risk of nitrate leaching. The inter-annual weather variability combined with fluctuations on yield, prices and cost of inputs makes rainfed maize production in the region highly risky from an economic standpoint.

Acknowledgements

This study was conducted under the auspices of the National Council for Scientific and Technological Development (CNPq) through the project "Profitability Analysis of Alternative Fertilizer Sources for Smallholder", process 574975/2008-0. We would like to thank Emater-MG, for mediating the contact with the farmer and Ariel Pereira Oliveira and Karina Conceição da Silva Moura, for their support with the economic data collection and Antônio Cláudio Barros for the text translation.

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