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Nitrogen management strategies for maize production systems: Experimental data and crop modeling

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Abstract

Maize (*Zea mays* L.) is an important crop among Brazilian smallholder farmers, who are also responsible for 40% of the poultry and egg production in the country. Although poultry litter is considered a potential pollutant, if properly stabilized and distributed in the field it can be used as a source of nitrogen for maize production. In this study, the response of maize to mineral fertilizer and poultry litter as source of nitrogen was evaluated and the results were then used to parameterize a process-based model. For both sources of nitrogen used in the second trial the average observed yield was higher than the average yield obtained by farmers during the preceding years, indicating that there is a potential for improvement of maize yield in the region. A rate of 195 kg ha^{-1} of nitrogen as poultry litter provided a slightly higher yield than a rate of 145 kg ha^{-1} of nitrogen as mineral fertilizer. After adjustments in the CSM-CERES-Maize cultivar-specific coefficients the model satisfactorily simulated maize anthesis, physiological maturity and yield. Poultry litter has the potential to be an alternative source of nitrogen for maize production in smallholder farms. The CSM-CERES-Maize model properly simulated maize growth, development and yield for both, mineral fertilizer and poultry litter sources of nitrogen.

Keywords: Family-farming; Organic fertilizer; Crop modeling; DSSAT; *Zea mays* L.

Introduction

Smallholder farmers are important contributors to agricultural production in Brazil and in neighboring countries. Their contribution to the sector has been recognized by the Brazilian Government with the implementation of the National Program for Strengthening Family Farming (PRONAF), which is based on credit and technology transfer support (Lemes, 2009). Globally, Brazil ranks 3rd on maize (*Zea mays* L.) production; about 55% of smallholder farmers contribute to 49% of the total production in the country. Also, maize is used as feed in the major Brazilian animal production chains. For instance, smallholder farmers account for 40% of the poultry and egg production nationwide (Guanziroli and Cardim, 2000), evidencing its importance in the economy of smallholder farmers (Cruz et al., 2006). A poultry and egg production operation generates about four tons of manure per year per 1,000 animals with an average concentration of 30 kg t^{-1} of nitrogen, 36.5 kg t^{-1} of potassium, 23.0 kg t^{-1} of calcium, 7.3 kg t^{-1} of magnesium and 65.5% of organic matter (Konzen, 2003). According to Cassol et al. (1994) the total phosphorus content is generally between 4 and 24 kg t^{-1} in dry weight basis.

The amount of P fertilizer required for maize production is not as large as nitrogen. Also, a part of the phosphorous in the manure is not mineralized and thus, is unavailable to crops (Gunary, 1968; Fordhan and Schwertmann, 1977). Therefore, phosphorous is necessary when manure is used as a part of composting or directly as fertilizer for crops (Konzen, 2003).

Nitrogen is required in large quantities (Escosteguy et al., 1997; Freire et al., 2001) and is the macronutrient that most influences maize yield (Sabata and Mason, 1992; Zhang et al., 1994; Silva et al., 2001; Amado et al., 2002). The cost of nitrogen fertilizer directly affects the profitability of the farm (Silva et al., 2001; Kaneko et al., 2010). Due to price fluctuations of mineral fertilizers the adoption of poultry litter as an alternative source of nutrients has increased among farmers. This is especially true if the farm is close to a poultry and egg facility. The practice also reduces environmental concerns and provides other benefits, such as the improvement of soil fertility and soil conservation (Galvão et al., 1999; De Ridder et al., 2004; Meng et al., 2005; Souza et al., 2005).

Crop growth and development are a function of the interaction between environmental conditions and management practices. Crop simulation models coupled to decision support systems can be useful tools for understanding those interactions (Tsuji et al., 1998; Alexandrov and Hoogenboom, 2000; Soler et al., 2008; Porter et al., 2009). Simulation models can help determining the impact of limiting factors in crop production and evaluating different management scenarios (Amaral et al., 2009; Andrade et al., 2009; Amaral et al., 2011; Andrade et al., 2011). For example, the crop simulation models of the Decision Support System for Agro-technology Transfer, DSSAT (Jones et al., 2003; Hoogenboom et al., 2011) simulate detailed soil water and nitrogen balances (Ritchie et al., 1989; Godwin et al., 1989). They can, therefore, be used to assess different scenarios that involve nitrogen fertilizer management and farm profitability.

In Brazil, few studies have been conducted to analyze the long-term response of crops to alternative management practices, mainly because of time and cost. An option to this limitation is the use of modeling, which has been adopted in manure management studies. For instance, Bowen et al. (1993) evaluated the CERES-Maize model of DSSAT to simulate the use of green manure in maize production for conditions in Brazil, concluding that the model provided a realistic simulation of legume N release. An adsorption coefficient has to be set for subsoil layers in order to properly simulate nitrate leaching. Shayya et al. (1993) developed the Animal Waste Management Program (AWMP) to assess the economic and environmental impact of animal manure use in crop production. Hoffman and Ritchie (1993) coupled a manure management model to the CERES-Maize model to evaluate the long-term use of manure in maize crop in Germany and US.

The objectives of this study were to: (1) evaluate the response of maize to mineral fertilizer and to poultry litter as a source of nitrogen; (2) parameterize the CSM-CERES-Maize model for nutrient management applications; (3) evaluate the performance of the model for simulating growth, development and yield of maize grown with mineral fertilizer and poultry litter.

Materials and Methods

The field studies were conducted at the experimental station of Embrapa Maize and Sorghum in Sete Lagoas, State of Minas Gerais, Brazil. Results from two field trials were used for model parameterization and evaluation. The experimental fields were located at 19° 27' S, 44° 10' W, with elevation of 729 m above sea level and 19° 27' S, 44° 10' W, with elevation of 738 m.

The climate of the region is classified according to Köppen as Aw, ie, Savannah climate with a dry winter and average air temperature of the coldest month above 18 ^{o}C (Sans and Avelar, 1994). The dry and wet seasons are well-defined and the wet season is too short to allow a second cropping season, a common practice in the main grain production area of Central-South Brazil. The soil is representative of the Brazilian Cerrado (Savannah) biome and the local vegetation is a transition between the Atlantic Forest and the Cerrado.

Weather data

Daily weather data were collected from a conventional weather station, located at 19° 29' S, 44° 10' W, with elevation of 732 m. The weather station was 3.3 and 2.1 km apart from the two experimental fields. For both trials, solar radiation was estimated using the Angströn-Prescott (Angströn, 1924; Prescott, 1940) procedure build in the WeatherMan (Pickering et al., 1994), a DSSAT tool for weather data management, using observed daily sunshine hours.

Daily weather data was plotted for the cropping season of the two field trials. For the first trial the cropping season started on February 21, 2009 and ended on July 16, 2009 (Figures 1A, B and C). The air temperature varied from 7.9 to 35.1 °C (Figure 1A). The average maximum and minimum air temperatures were 28.5 and 15.8 °C, respectively; solar radiation varied from 8.5 to 27.2 MJ m^{-2} day^{-1} with the largest daily values observed at the beginning of the cropping season. As expected in the region, solar radiation reduces considerably during rainy days (Figures 1A and B). The average air temperature during the cropping season of the first trial was 22.1 °C and the average solar radiation was 18.1 MJ m^{-2} day^{-1}. The total rainfall was 286 mm and the number of rainy days was 33.

For the second trial the cropping season was from March 12, 2009 to August 11, 2009. The average maximum and minimum air temperature were 28.3 and 15.0 °C, respectively, the maximum and minimum solar radiation, were 25.5 and 8.5 MJ m^{-2} day^{-1}, respectively. The average air temperature was 21.7 °C and the average solar radiation was 17.4 MJ m^{-2} day^{-1}. The total precipitation of the period was 232 mm with 27 rainy days.

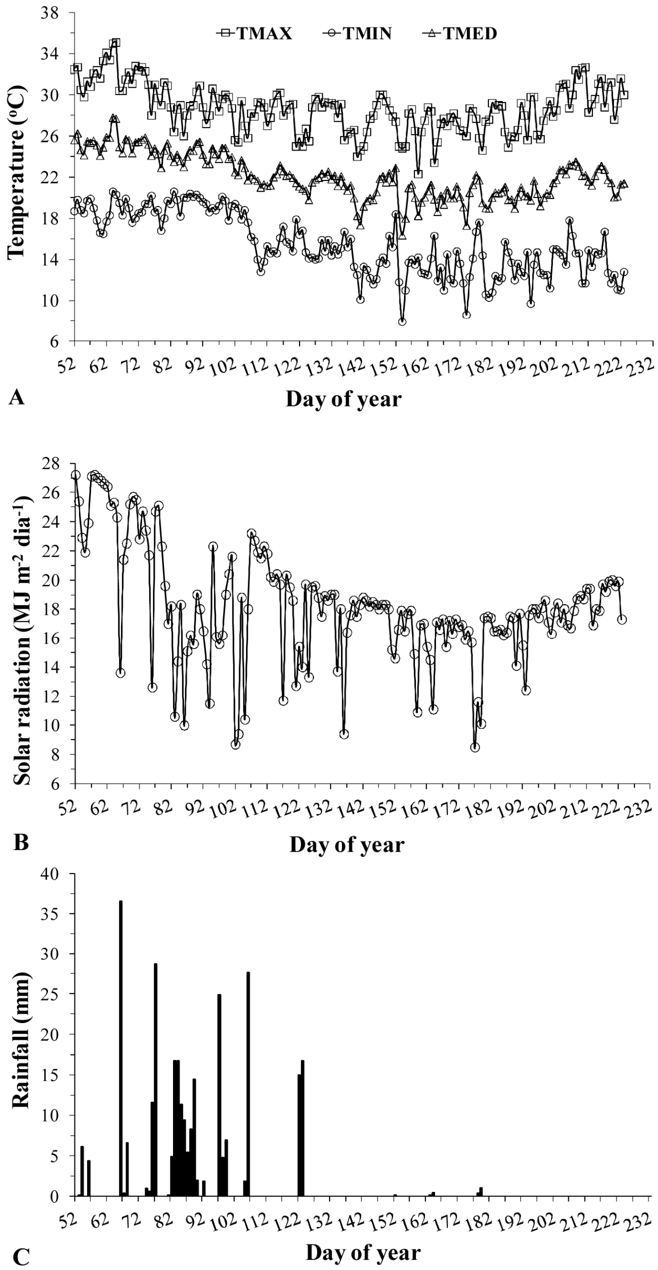


Figure 1. Daily maximum, minimum and average air temperature (A), solar radiation (B) and rainfall (C) during the cropping season.

Soil characterization

The soil at the two experimental sites was a typical Haplustox (Panoso et al., 2002), characterized as clayey, structured, low bulk density and with porosity of about 60%. Samples were collected in the first trial for physical and fertility analyses (Table 1). The total soil available water was less than 10%; the top 50 cm of soil hold less than 50 mm of available water.

Trials setup and crop management

First trial – for model parameterization

The first trial was set to collect data for parameterization of the CSM-CERES-Maize model. The crop was grown under optimum management practices conditions. The trial was setup as only one treatment with three replications and for this reason no statistical analysis were performed. Prior to sowing, the soil was prepared using a subsoiler, disc plow and harrow. The single-cross hybrid BRS 1030 was sown manually on February 21, 2009 with a row spacing of 0.8 m and a final plant population of 66,370 plants ha^{-1}. At sowing, 32 kg ha^{-1} of nitrogen were applied as 8-28-16 (N, P_2O_5, K_2O) + 0.4% Zn at 10 cm depth. Additionally, 60 (20-02-20; N, P_2O_5, K_2O) and 112 kg ha^{-1} of nitrogen (as urea) were side-dressed at 20 and 28 days after sowing (DAS), respectively (Table 2). Pests, diseases and weed were controlled following local agronomic recommendations (Cruz, 2012). Supplemental irrigation was calculated by running the daily water balance approach suggested by Allen et al. (1998) using a spreadsheet (Albuquerque and Andrade, 2001). The irrigation was applied using a solid-set sprinkler system. Irrigation depths were measured using catch cans installed inside the plots (Figure 2). The total amount of irrigation applied during the cropping season was 328 and 331 mm for the parameterization and evaluation trials, respectively.

Table 1. Soil profile characteristics at the two experimental site.

Layer base depth (m)	Lower limit[1] ($m^3\ m^{-3}$)	Upper limit[2] ($m^3\ m^{-3}$)	Saturation ($m^3\ m^{-3}$)	Root growth factor	Saturated hydraulic conductivity ($m\ h^{-1}$)	Bulk density ($kg\ m^{-3}$)	Organic carbon (%)	Clay (%)	Silt (%)	Total nitrogen (%)	PH in water
0.05	0.284	0.378	0.568	0.9	0.0523	1050	2.18	63	19	0.12	5.7
0.10	0.270	0.366	0.577	1.0	0.0977	1020	2.10	63	22	0.12	5.8
0.30	0.278	0.374	0.561	1.0	0.0786	1070	1.90	68	20	0.10	5.7
0.50	0.268	0.362	0.599	0.6	0.0645	960	1.68	71	13	0.08	5.2
0.70	0.262	0.352	0.611	0.3	0.2302	930	1.62	72	13	0.06	5.0
0.90	0.253	0.340	0.627	0.1	0.3719	890	1.45	72	14	0.06	5.0
1.10	0.250	0.329	0.631	0.1	0.3730	870	1.41	72	14	0.05	5.0

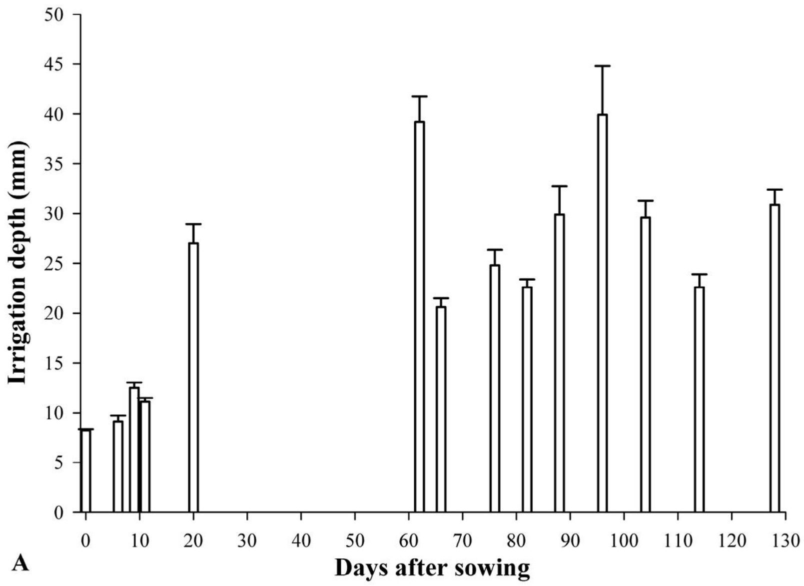
(1) Soil lower limit of available water or permanent wilting point; soil water content in equilibrium with a tension of 1500 kPa.

(2) Soil upper limit of available water or field capacity; soil water content in equilibrium with a tension of 10 kPa.

Table 2. Fertilizer types and application rates used in this study.

Description	Unit	Trial 1 – Model parameterization mineral fertilizer	Trial 2 – Model evaluation poultry litter and mineral fertilizer: Treatment identification[(1)]				
			T_1	T_2	T_3	T_4	T_5
08-28-16 (N, P_2O_5, K_2O) applied at sowing	kg ha^{-1}	400	0	0	0	0	400
Nitrogen from formula		32	0	0	0	0	32
Phosphorus from formula		112	0	0	0	0	112
Potash from formula		64	0	0	0	0	64
20-02-20 (N, P_2O_5, K_2O) applied at 17 DAS		300	0	0	0	0	0
Nitrogen from formula		60	0	0	0	0	0
Phosphorus from formula		6	0	0	0	0	0
Potash from formula		60	0	0	0	0	0
Single superphosphate (SSP)		0	250	0	0	250	0
Nitrogen side-dressed at 26 DAS		112	0	0	0	0	112
Air-dry poultry litter (PL)		0	6,500	6,500	6,500	6,500	0
Nitrogen from poultry litter[(2)]		0	195	195	195	195	0
Total applied nitrogen		204	195	195	195	195	144

[(1)] T_1=6.5 t ha^{-1} of poultry litter (PL) + 250 kg ha^{-1} of single superphosphate (SSP), both broadcasted; T_2=6.5 t ha^{-1} of PL broadcasted; T_3=6.5 t ha^{-1} of PL applied in the surface along the sowing row; T_4=6.5 t ha^{-1} of PL applied in the surface along the sowing row + 250 kg ha^{-1} of SSP in the sowing row; T_5=mineral fertilizer. [(2)] Nitrogen concentration in the poultry litter: 3% (Konzen, 2003).



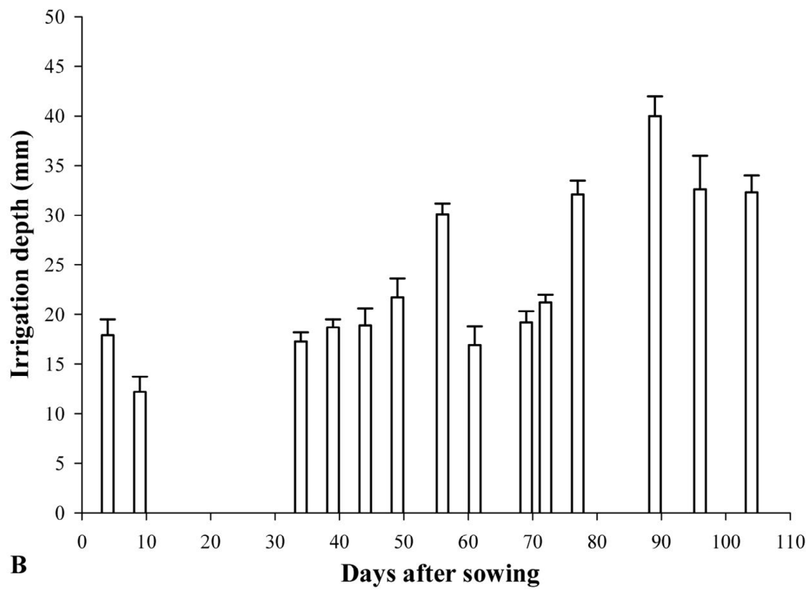


Figure 2. Average irrigation depths applied in the trial 1 (A) and in the trial 2 (B). Vertical bars indicate the standard error.

Second trial – for model evaluation

The second trial was conducted to obtain data to assess the performance of the model and was set in a location with soil characteristics similar to the first trial (Table 1). The soil was prepared using a disc plow and harrow. The experiment consisted in a randomized complete block design with five poultry litter (PL) fertilization strategies, each supplemented with phosphorous as single super phosphate (SSP) and a check treatment using mineral fertilizer, with four replications of 7 m^{-2} each. The treatments were: 6.5 t ha^{-1} of PL (195 kg ha^{-1} of N) broadcasted over soil surface + 250 kg ha^{-1} of (SSP) (T_1); 6.5 t ha^{-1} of PL broadcasted over soil surface + 0 kg ha^{-1} of SSP (T_2); 6.5 t ha^{-1} of PL side-dressed in the sowing row + 0 kg ha^{-1} of SSP (T_3); 6.5 t ha^{-1} of PL side-dressed in the sowing row and supplemented with 250 kg ha^{-1} of SSP (T_4); and a check treatments consisting of mineral fertilizer at a rate of 32 kg ha^{-1} of nitrogen at sowing and 115 kg ha^{-1} of nitrogen as urea side-dressed 27 DAS (T_5). All poultry litter applications were conducted prior to planting. It was assumed that each ton of poultry litter can provide an average of 30 kg ha^{-1} of nitrogen (Konzen, 2003). A summary of the amount of fertilizer that was applied in this second trial can be seen in Table 2. The single-cross hybrid BRS 1030 was sown on March 12, 2009 with 0.8 m row spacing and 65,000 plants ha^{-1}. Supplemental irrigation was applied using a solid-set sprinkler system following the same procedure as in the first trial. The irrigation depths measured with catch cans are presented in Figure 2.

Data collection

First trial – model parameterization

Soil samples of layers 0-15; 15-30; 30-45; 45-60; 60-90; 90-120 cm were obtained at sowing time for water content determinations. Some key maize crop phenological phases were monitored following the recommendations described in Jones et al. (2003). The number of plants emerged in each plot was counted in a 1-meter long row three times a week. The emergence date was set when 50% of the plants had emerged. Ten plants in each plot were then tagged to monitor the number of leaves, anthesis and physiological maturity. The number of leaf tips and of leaf with ligule was recorded three times a week. The 6^{th} leaf was tagged to avoid missing abscised leaves. The total number of leaves per plant was recorded in the three tagged plants of each plot. Anthesis was recorded when hair of ears was 2-cm long in 50% of the plants in the plot. The physiological maturity was established when 50% of the 60 kernels sampled in the middle of three ears presented the black layer.

Samples for growth analysis were collected twelve times during the cropping season. Five representative plants of each plot were sampled for leaf area and for dry mass determinations. Leaves + sheath were separated from stem + tassel. Ears were shelled and separated into grain, husk and cob. The leaf area of green leaves was obtained with a LI-3100C area meter (www.licor.com/). Samples were oven-dry at 65 ^{o}C for dry mass determination.

The experiment was ended on August 5, 2009 by removing all plants in a 15 m^2 area. Grain yield, aboveground biomass, number of plants (plants m^{-2}), number of ears (ears m^{-2}), ears per plant (ears $plant^{-1}$), number of grains per plant (grains $plant^{-1}$), number of grains per unit area (grains m^{-2}), unit grain weight and harvest index were determined at each replication. Dry matter of the plant and its components were obtained after oven-drying the samples at 65 ^{o}C.

Second trial – model evaluation

Initial soil moisture was assumed to be at field capacity since no soil sample was collected and the trial was sowed at the end of the rainy season. Crop development phases required by the CSM-CERES-Maize model were monitored following the same procedure as in the first trial. Samples for growth analysis were obtained seven times during the growing season by sampling five representative plants in all five treatments. Due to the small size of the plots, no replications were obtained in this trial.

For harvest, all plants in two 4-m length central rows were removed in each plot. Plants were processed, weighted and oven-dried at 65 °C, for dry mass determination. Observed data were the same as in the first trial. Since there were treatments being tested and replications data from this second trial were subjected to analysis of variance. The average values of crop traits, obtained for the different fertilization treatments were compared using the t-test (LSD), at 5% probability.

Considering that the soil of the two trials presents a concentration of more than 3% of organic matter (% organic matter = % organic carbon x

1,724) in the rooting zone (Table 1) and that each 1% of organic matter in the soil provides an average of 50 kg N ha^{-1} (Sousa et al., 2002), we assumed that the soil could supply to the crop in the first year, 50 kg ha^{-1} of mineral nitrogen.

Model parameterization

The CSM-CERES-Maize model of DSSAT version 4.5.0.036 (Jones et al., 2003; Hoogenboom et al., 2011) has six cultivar-specific coefficients that need to be derived for a new variety as described in Table 3. Data from the first field trial were used with the CSM-CERES-Maize model to adjust the cultivar-specific coefficients by using a trial and error procedure as was described in Tsuji et al. (1998). The coefficients from a similar maize genotype were used as starting point. The model was run once and then simulated and observed data were compared. The RMSE (Loague and Green, 1991) and the Willmott index of agreement *d* (Willmott et al., 1985) were obtained and used to evaluate how close were simulated and observed data. The anthesis date was fixed first by adjusting P_1 (thermal time from seedling emergence to the end of the juvenile phase, expressed in degree days above a base temperature of 8 ^oC); then the number of leaves was set by adjusting PHINT (phylochron interval; the interval in thermal time between successive leaf tip appearances). Then, P_5 (thermal time from silking to physiological maturity, expressed in degree days above a base temperature of 8 ^oC) was adjusted. Finally, the coefficients G_2 (maximum possible number of kernels per plant) and G_3 (kernel filling rate during the linear grain filling stage and under optimum conditions in mg/day) were adjusted. The set of cultivar-specific coefficients that resulted in the highest *d* and in the lowest RMSE were chosen to create the new cultivar.

Model evaluation

Data from T_2, T_3 and T_5 of the second trial (Table 2) were used to assess the performance of the model. The poultry litter was considered in the model as organic amendment. Treatments T_1 and T_4 were not considered because the CSM-CERES-Maize model, version 4.5.0.036, was not evaluated locally for phosphorus simulation. Simulated and measured data were compared based on the *d* and RMSE indices.

Table 3. Cultivar-specific coefficients derived for the single-cross maize hybrid BRS 1030.

Coefficient identification and description	Value
P_1 - Thermal time from seedling emergence to the end of the juvenile phase (expressed in degree days above a base temperature of 8 °C) during which the plant is not responsive to changes in photoperiod.	263.8
P_2 - Extent to which development (expressed as 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).	0.5
P_5 - Thermal time from silking to physiological maturity (expressed in degree days above a base temperature of 8 °C).	1,034
G_2 - Maximum possible number of kernels per plant.	648
G_3 - Kernel filling rate during the linear grain filling stage and under optimum conditions (mg/day).	5.14
PHINT - Phylochron interval; the interval in thermal time (degree days) between successive leaf tip appearances.	44.22

Results

Model parameterization

Anthesis occurred at 63 DAS and physiological maturity at 145 DAS. Observed harvested yield was 8,098 kg ha^{-1} (Figure 3A) and the aboveground biomass at harvest was 17,867 kg ha^{-1} (Figure 3B). The average observed final number of leaves was 20 (Figure 3D). The maximum leaf area index (LAI) of 4.6 m^2 m^{-2} was recorded at 45 DAS (Figure 3C). Except for LAI, the variability observed in the measured data, expressed by the standard error of the mean (vertical bars in the charts) was small, indicating that the field space variability was small (Figures 3A, B, C and D). Regarding the LAI data, it seems that the largest standard error of the mean was due to the large variability of the area of green part of the leaves (Figure 3C); such a large variation was not observed in the aboveground biomass data (Figure 3B). The adjusted cultivar-specific coefficients P_1, P_2, G_2, G_3 and PHINT are presented in Table 3.

After adjusting the cultivar-specific coefficients it was observed that the CSM-CERES-Maize model simulated yield, aboveground dry biomass, LAI and the appearance of leaves well (Figure 2). A RMSE of 823 kg ha^{-1} and a *d* index of agreement of 0.96 were computed for the grain weight measured along the crop cycle. For the aboveground biomass the RMSE was 1,362 kg ha^{-1} and *d* was 0.99, while for the LAI, the RMSE was 0.66 and *d* was 0.92. A RMSE of 1.43 and a *d* of 0.96 were obtained for the number of leaf tips. At harvest, measured yield was 8,098 kg ha^{-1} as compared to a simulated yield of 8,089 kg ha^{-1}, while measured aboveground biomass was 17,867 kg ha^{-1}, against a simulated biomass of 19,147 kg ha^{-1} (Figures 3A and B).

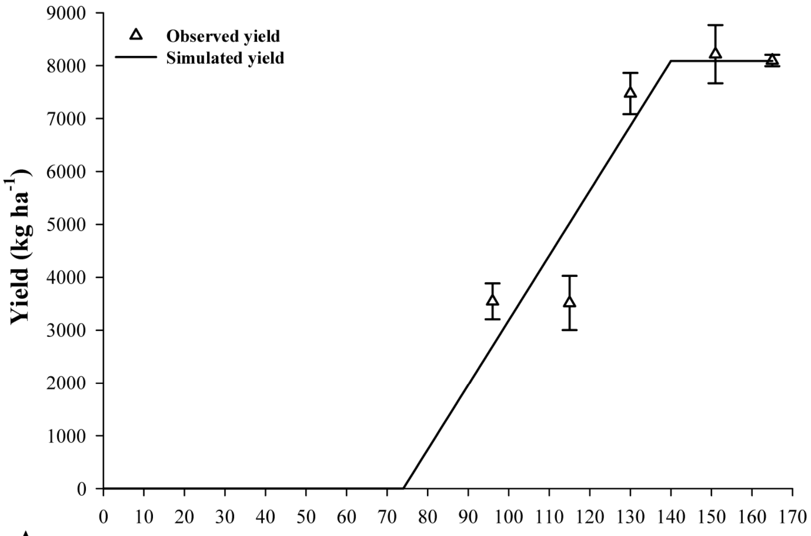
Model evaluation and response to mineral and organic nitrogen fertilizer

The highest observed grain yield was obtained in treatment T_1 followed by T_5, T_3, T_4 and T_2. The highest yield was directly related to larger number of ears per plant and to higher number of kernels per unit of surface area of T_1 as compared to the other treatments. Yield from T_1 and T_5 was significantly different ($P<0.05$) from that of T_2, T_3 and T_4. Yield from T_2, T_3 and T_4, on the other hand, were not statistically different (Table 4). The aboveground biomass from T_4 and T_5 was 18,102 and 18,840 kg ha^{-1}, respectively (Table 4). The treatment T_1 had the highest number of ears m^{-2} and T_1 and T_5 had the highest number of ears plant^{-1} and the highest number of grains m^{-2}, which is in agreement with the highest yields obtained in these treatments (Table 4).

Table 4. Number of plants, cobs, grains per square meter, number of cobs per plant, unit grain weight and total aboveground biomass of the single-cross hybrid BRS 1030, for different fertilization strategies.

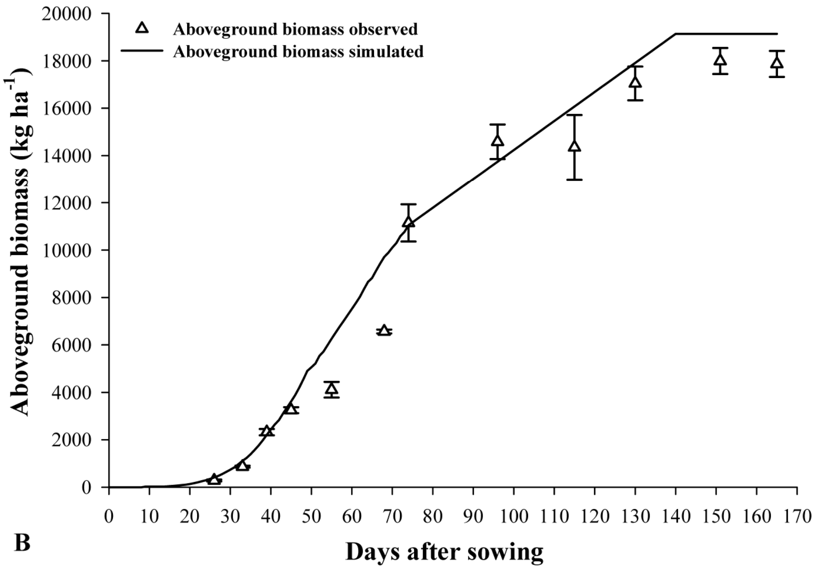
Treatment[(1)]	Plants m^{-2}	Ears m^{-2}	Ears plant^{-1}	Kernels m^{-2}	Kernel unit weight	Total biomass	Grain yield dry mass[(2)]
					mg grain^{-1}	---------kg ha^{-1}----------	
T_1	6.66^{a}	6.05^{a}	0.93^{a}	2,854^{a}	324.1^{ab}	14,442^{b}	8,157^{a}
T_2	5.08^{c}	4.06^{c}	0.77^{bc}	2,189^{b}	328.7^{ab}	12,053^{c}	7,080^{b}
T_3	6.39^{ab}	5.03^{b}	0.75^{bc}	2,435^{b}	315.6^{b}	13,691^{b}	7,086^{b}
T_4	6.45^{ab}	4.33^{bc}	0.72^{c}	2,392^{b}	326.2^{ab}	18,102^{a}	6,711^{b}
T_5	5.96^{b}	4.88^{b}	0.84^{ab}	2,765^{a}	331.5^{a}	18,840^{a}	7,549^{a}

[(1)] T_1 - 6.5 t ha^{-1} of poultry litter plus 250 kg ha^{-1} of single super phosphate (SSP), broadcasted; T_2 - 6.5 t ha^{-1} of poultry litter, broadcasted; T_3 - 6.5 t ha^{-1} of poultry litter, side-dressed; T_4 - 6.5 t ha^{-1} of poultry litter side-dressed, plus 250 kg ha^{-1} of SSP and T_5 - mineral fertilizer; all fertilizations were applied at sowing.
[(2)] Within column, values with the same letter are not different by t-test (LSD) at 5% probability.



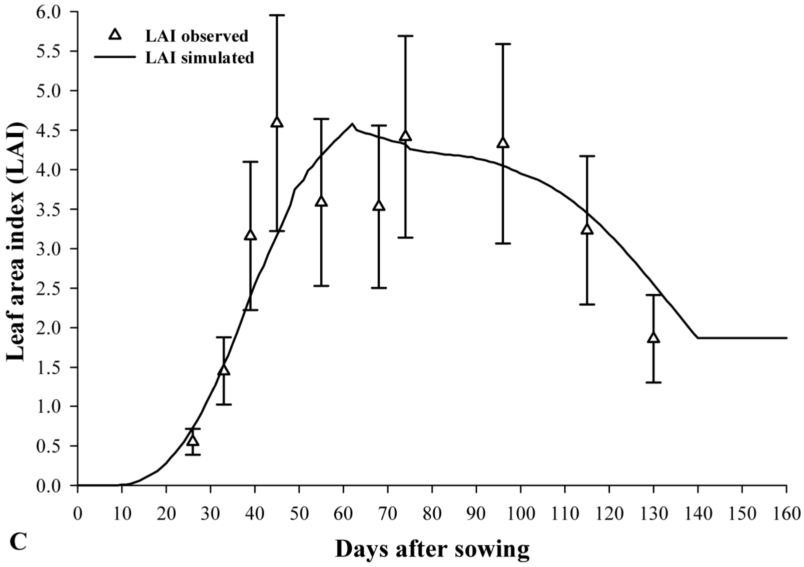
Observed yield
Simulated yield
Yield (kg ha-1)
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170
Days after sowing

A

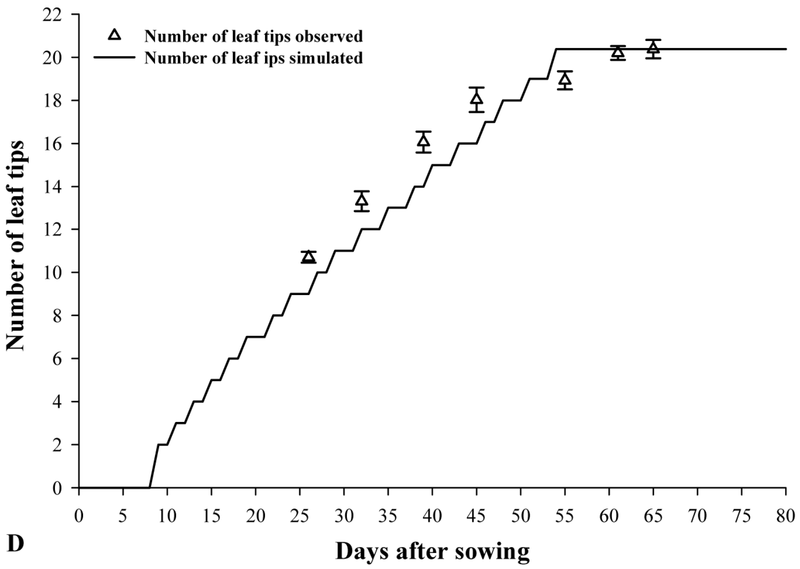


Aboveground biomass observed
Aboveground biomass simulated
Aboveground biomass (kg ha-1)
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170
Days after sowing

B



C



D

Figure 3. Simulated and observed yield (A) and aboveground biomass (B), expressed in dry mass basis, leaf area index (C) and leaf tip number (D), after the parameterization of the model. Vertical bars indicate the standard error.

The model successfully simulated days to anthesis and to physiological maturity for T_2 and underestimated both phenological stages by one day in T_3. For T_5 the model underestimated anthesis by three days and physiological maturity by one day (Table 5). The model simulated the appearance of leaves during the growing season for T_2, T_3 and T_5 well (Figure 4A). The RMSE was 0.61, 0.64 and 0.98 leaves per plant, while *d* was 0.99, 0.99 and 0.98, respectively. The average observed total number of fully developed leaves was 20, 21 and 20, as compared to 22 simulated for T_2, T_3 and T_5, respectively. Although the air temperature is the major driven force on maize development rate and leaf emission, other factors such as water, nutrients, salinity, light intensity and seed size can also affect them. The observed total number of leaves of maize cultivars varied with the sowing date in southeastern Brazil (Gadioli et al., 2000). In another study Soler et al. (2005) found that the phyllochron, which is the thermal interval between the appearances of successive leaf tips, is not constant along the maize cycle as assumed in the CSM-CERES-Maize model. This can be the reason why the model sometimes does not perfectly simulate the maize phenological stages and development.

Table 5. Observed and simulated anthesis and physiological maturity dates.

Treatment[1]	Anthesis date		Physiological maturity date	
	Simulated	Observed	Simulated	Observed
	Days after sowing (DAS)			
T_2	69	69	151	151
T_3	69	70	151	152
T_5	69	72	151	152

[1] T_2 - 6.5 t ha^{-1} of poultry litter broadcasted; T_3 - 6.5 t ha^{-1} of poultry side-dressed; and T_5 - mineral fertilizer.

The observed grain yield was 7,080 and 7,086 kg ha^{-1}, while simulated values were 7,170 and 7,254 kg ha^{-1}, respectively, for T_2 and T_3 (Figure 4B). The RMSE for comparing observed and simulated yield along the crop cycle for these treatments was 693 and 971 kg ha^{-1} and *d* was 0.98 and 0.97, respectively. For T_5, the mineral fertilizer check treatment, observed yield was 7,549 kg ha^{-1} and the simulated yield was 7,205 kg ha^{-1}, with a RMSE of 961 kg ha^{-1} and a *d* of 0.97 (Figure 4B).

The model simulated reasonably well the temporal variation on aboveground biomass (Figure 4C). The RMSE of 3,192 kg ha^{-1}, 3,761 kg ha^{-1} and 3,244 kg ha^{-1} and *d* of 0.92, 0.90 and 0.94, for T_2, T_3 and T_5, respectively. The final aboveground biomass was overestimated in all three treatments (Figure 4C); however, the final aboveground biomass for T_5 was reasonably estimated.

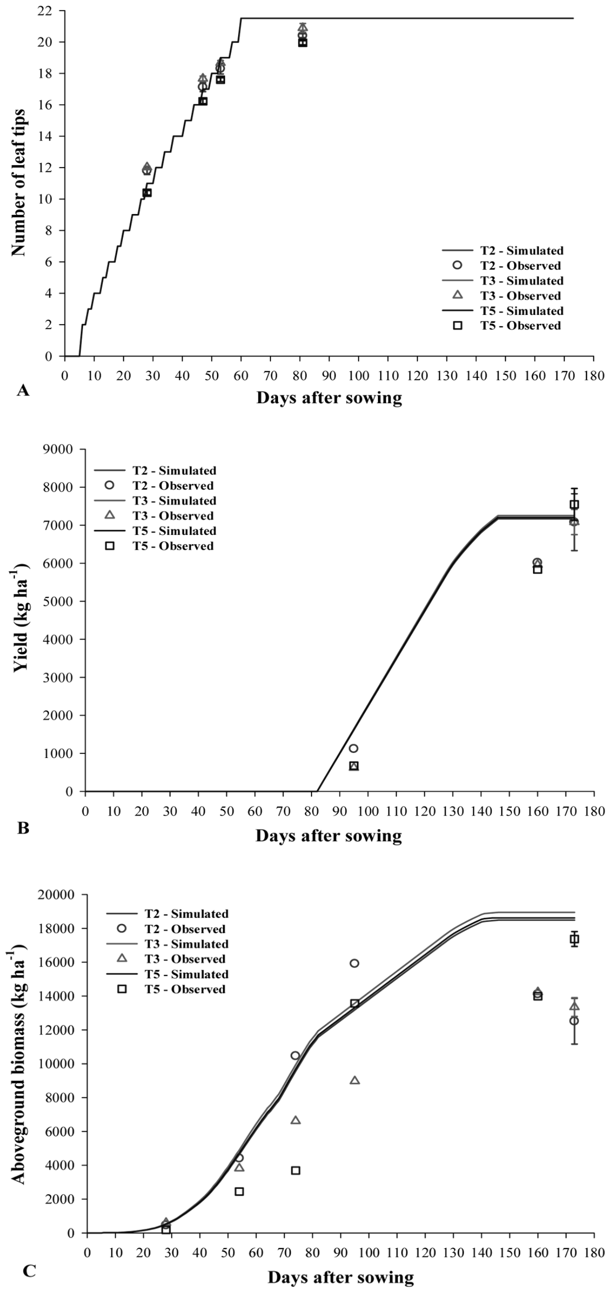


Figure 4. Observed and simulated number of leaves (A), yield (B) and aboveground biomass (C) for treatments T_2, T_3 and T_5.

Discussion

Weather conditions

The weather conditions observed during the course of the two field trials were adequate for off-season maize production in the region with the use of supplemental irrigation. Average maximum, minimum and average day air temperature, precipitation and solar radiation observed during the trials were close to the normal values expected for the region (Sans and Avelar, 1994).

Model parameterization

The harvested yield of 8,098 kg ha^{-1} obtained in the first trial was higher than the 5,753 kg ha^{-1} observed for the same hybrid in a variety trial conducted throughout the State of Minas Gerais, Brazil (Embrapa, 2010). In another trial, carried out for parameterization and evaluation of the predictive capability of the CSM-CERES-Maize model, in Piracicaba, São Paulo, Brazil, with sowing on March 13, 2002, under irrigated conditions, Soler et al. (2007) obtained yields as 4,986; 5,139; 5,047 and 5,306 kg ha^{-1} for hybrids AG9010, DKB 333B, DAS CO32 and Exceler, respectively. The higher yield obtained in this first trial indicates that field conditions were of sufficient quality to use the data for model parameterization.

The cultivar-specific coefficients P_1, P_2, G_3 and PHINT (Table 3) adjusted for the single-cross hybrid BRS 1030 using data from the first trial were in the range of the values obtained by Soler et al. (2007) for the hybrids AG 910, DKB 333B, DAS CO32, Exceller. The coefficient P_5 was larger than those obtained for the four hybrids, since that hybrid has longer crop cycle. On the other hand, the coefficient G_2 for the single-cross hybrid BRS 1030 was smaller than the figures obtained for the hybrids, indicating that it produces fewer kernels per plant.

Crop response to mineral and organic nitrogen fertilizer

In the second trial, since only one third of the average 1% phosphorus provided by the poultry litter is in organic form (Cassol et al., 1994), the use of 250 kg ha^{-1} of SSP at sowing was essential to supply maize needs. The crop response to manure was more pronounced when the poultry litter was broadcast over the soil surface as compared to side-dressed. The average yield from all treatments (Table 4) was considerably higher than the national average yield of 3,880 kg ha^{-1} for year 2011 and higher than the state average yield of 4,823 kg ha^{-1} (IBGE, 2013). As compared to the state variety trials (Embrapa, 2010), yield from the second trial was also higher. In a study conducted by Konzen (2003), the use of 3.6, 5.0 and 7.5 t ha^{-1} of poultry litter (108; 150 and 225 kg ha^{-1} of N, respectively) provided maize grain yield of 6,690; 7,508 and 7,352 kg ha^{-1}, respectively, which is close to the yield obtained in the second trial for a rate of 6.5 t ha^{-1} of poultry litter that correspond to 195 kg ha^{-1} of N (Table 4). Choudhary et al. (2013), comparing alternative sources of fertilization for maize in India recorded a yield of 4.130 kg ha^{-1} when 1.25 t ha^{-1} of chicken manure at a concentration of 4% N was used. Additionally Alizadeh et al. (2012) observed that the application of 11 t ha^{-1} of poultry manure at 3% N in combination with urea-N (217 kg ha^{-1}) improves maize growth and production, with subsequent enhanced N uptake in arid soils with low soil organic matter (SOM), soil moisture and N availability.

Although treatments T_4 and T_5 produced a large amount of aboveground biomass, the high nitrogen rate in T_4 provided by the poultry litter, was not directly converted into grain production. A high vegetative growth may have occurred under these conditions, with low translocation of photo-assimilates to the kernels, resulting in low harvest index. The results from the second trial confirm that poultry litter can be an alternative source of nitrogen for maize production.

Model evaluation

When comparing the observed data of the second trial with those simulated by the model, one could note that leaf appearance (Figure 4A), anthesis and physiological maturity (Table 5) were properly simulated. The yield simulated by the model was only 1.25% and 2.31% higher than the observed yield for T_2 and T_3, respectively and 4.77% lower than the observed yield for the mineral fertilizer check, T_5 (Figure 4B).

Considering the complexity of the processes involved in the nitrogen dynamics in the soil and the absorption by the plants, when using organic fertilizer, we can state that the CSM-CERES-Maize model adequately simulated growth, development and yield of maize fertilized with poultry litter as alternative source of nitrogen. These results may allow to further use the model as a tool to analyze different management scenarios with the use of poultry litter and other types of organic fertilizer. These scenarios may include, but are not limited to, technical and economic feasibility of using different rates of PL and the sustainability of such production system.

Conclusions

Poultry litter had the potential to be an alternative source of nitrogen for smallholder farmers. When complemented with mineral phosphorus fertilizer, it provides satisfactory maize yield. The CSM-CERES-Maize model satisfactorily simulated growth, development and yield of maize grown with different fertilizer sources, including poultry litter.

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