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Model-based approach for maize yield gap analysis related to climate variability and nitrogen management

Maria Carolina da Silva Andrea

Thesis presented to obtain the degree of Doctor in Science. Area: Agricultural Systems Engineering

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RESUMO

Abordagem baseada em simulações para análise de *yield gaps* da cultura do milho relacionados à variabilidade climática e manejo de nitrogênio

Para alcançar a segurança alimentar e atender necessidades ambientais, os índices médios de produtividade de importantes culturas na alimentação como a do milho devem aumentar em detrimento da expansão de áreas cultivadas. A cultura do milho possui como principais fatores responsáveis pelos baixos indices de produtividade no Brasil os deficits hídrico e de nitrogênio (N). O conceito de quebra de produtividade (*yield gaps*) é a diferença entre a máxima produtividade que pode ser atingida em dado local, seja ela limitada pela água (Yw) ou não (Yp), e a produtividade média observada em condições práticas (Ya). Esse conceitoé de grande importância para caracterização de limites de alcance de máximas produtividades e definição de estratégias de manejo para mitigação dos mesmos. A produtividade potencial (Yp) é aquela determinada pelas condições de temperatura, radiação solar, fotoperíodo e potencial genético; à produtividade limitada pela água (Yw) adiciona-se a limitação hídrica imposta por cultivos em sequeiro. Nesse estudo buscou-se caracterizara variabilidade das quebras de produtividade referentes às condições ambientais e de manejo; bem como avaliar o retorno econômico e energético do manejo dessas quebras por meio da aplicação mecanizada de fertilizantenitrogenado em seis municípios localizados na região Centro-Sul do país nas duas épocas de cultivo da cultura do milho (safra e safrinha).Quebras de produtividade referentes à restrição hídrica (CYg = Yp - Yw) e impostos pelas condições de manejo (MYg =Yw - Ya) foram determinadas com auxílio da utilização do sistema de modelos integrados DSSAT (*Decision Suport System for Agrotechnology Transfer*).O modelo da cultura do milho (CSM CERES-MAIZE) foi calibrado com dados de ensaio de cultivares, obtidos para os últimos anos em todas as regiões avaliadas. Na 1ª safra, os indices de Yp foram mais altos e os indices de Yw foram mais altos e variáveis devido à variabilidade climática.A quebra de produtividade relativa ao manejo foi mais limitante do que a quebra relativa ao deficit hídrico em quase todos os municípios avaliados. Em ambas as safras de cultivo, maiores e menores MYg foram encontrados em dois municípios das regiões Sul e Centro-Oeste do país, respectivamente. Apesar de ambas as regiões apresentarem altas produtividades medias (Ya), diferentes condições ambientais determinaram as maiores diferenças absolutas entre seus indices de Yp, Yw e MYg. Ao avaliar a rentabilidade (R$ kg^{-1}; MJ kg^{-1}; R$ ha^{-1}; MJ ha^{-1}) da aplicação de N como estratégia de redução de MYg, observou-se o comportamento da variação dos rendimentos de produtividade com o aumento das doses de N. Em termos gerais, os rendimentos decrescentes apresentaram maior eficiência de uso do insumo (por massa colhida e por unidade de área) nas menores doses de N (20-80 kg ha^{-1}). Lucros econômicos e energéticos (sem considerar sua taxa de variação com relação ao aumento do custo de aplicação) foram encontrados até doses mais altas de N (90-400 kg ha^{-1}), sendo que esse limite é diretamente influenciado pelas condições climáticas locais. O manejo local dos MYg pode ser mais ou menos viável em função da combinação das condições ambientais e de manejo usual locais. Em termos gerais, o custo de aplicação de N é maior na 2ª safra devido às condições climáticas mais limitantes, porém municípios com manejo eficiente da quebra de produtividade foram encontrados mesmo nas condições de cultivo do milho safrinha.

Palavras-chave: *Zea mays*; Intensificação de produtividade; Manejo rentável; rendimentos decrescentes; Simulação de produtividades

ABSTRACT

Model-based approach for maize yield gap analysis related to climate variability and nitrogen management

To achieve food security and meet environmental requirements, the average rates of major crop yields in crops such as maize are expected to increase instead of expansion of cultivated areas. Maize crop has as main factors responsible for the low yields in Brazil the water and nitrogen (N) deficits. The concept of yield gaps is the difference between the maximum yield that can be achieved in a given place, limited by water (Yw) or not (Yp), and the average yields, observed under practical conditions (Ya). This concept is of great importance for characterizing the range of maximum yields and definemanagement strategies to its mitigation. Yield potential (Yp) is determined by conditions of temperature, solar radiation, photoperiod and genetic potential; to Water-limited yield (Yw) is added the water limitation imposed by crops on rainfed condition. In this study we aimed to characterize the variability of yield gaps related to environmental and management conditions; and to evaluate the economic and energy returns related to management of these yield gaps through the mechanical application of nitrogen fertilizer in six regions located in the South Central portion of the country in two periods of maize cultivation (1st and 2nd maize growing seasons). Yield gaps related to water restriction (CYg = Yp - Yw) and imposed by management conditions (MYg = Yw - Ya) were determined through aid of integrated models DSSAT system (Decision Suport System for Agrotechnology Transfer). The maize model (CSM CERES-MAIZE) was calibrated with cultivars trial data obtained for the last few years in all evaluated regions. In the 1st growing season, Yp was higher and Yw was higher and more variable than on 2nd growing season due to climate variability. The yield gaps relative to management were more limiting than the gaps relative to water deficit in almost all the evaluated regions. In both crops' growing seasons, higher and lower MYg were found in two regions of Southern and Midwestern portion of the country, respectively. Although both regions presented high average yields (Ya), different environmental conditions determined the largest absolute differences between their rates of Yp, Yw and MYg. When assessing the profitability (R$ kg^{-1}, MJ kg^{-1}, R $ ha^{-1}; MJ ha^{-1}) of N application as MYg reduction strategy, the behavior of the variation in yields with increasing rate of N was observed. In general, the diminishing returns showed higher use efficiency (per harvested yield and per unit area) at lower N rates (20-80 kg ha^{-1}). Economic and energy profits (regardless of their rate of change related to the increased application of cost) were found at higher N rates (90-400 kg ha^{-1}), and this limit is directly influenced by local climate conditions. Local management of MYg can be more or less viable depending on the combination of environmental conditions and usual management conditions. In general, the cost of N application is higher in 2nd growing season due to most limiting climatic conditions, but regions with efficient management of yield gapswere alsofound in 2nd growing season

.

Keywords: *Zea mays*; Yield intensification; Profitable management; Diminishing incomes; Yield simulations

LIST OF ABBREVIATIONS

C - Carbon

Ca - Calcium

Cos - Cosine

CYg – Yield gap related to water deficit

CV – Coefficient of variation

DUL – Drained upper limit

DSSAT – Decision Support System for Agrotechnology Transfer

ET - Evapotranspiration

ETP –Potential evapotranspiration

K - Potassium

LL - Drained lower limit

MFMF – Maize – fallow cropping sequence

Mg - magnesium

MYg – Yield gap related to crop management

MWMW – Maize – wheat cropping sequence

N – Nitrogen

OM – Organic matter

SAT – Saturation limit

SMSM – Soybean – maize cropping sequence

P - Phosphorus

PTF – Pedotransfer function

Ya – Farmer's average yields

Ybf – Cultivar trials yields

YG – Yield gap

Yp – Potential yield

Yw – Water-limited yield

1 INTRODUCTION

Ensuring global food security in the face of global current and forthcoming conditions, such as climate change and its impacts on agriculture and vice-versa; competition between food and biofuel; and conservation of natural ecosystems are examples of some of the most important issues current agricultural activity faces and will continue to face in the upcoming years. To all of these issues, the most probable mitigationmeasure depends on the rate of gain in crop yields on already existing farmland, which means reducing the yield gaps between the local attainable yields (maximum yieldsthat can be obtained from combination of environment and genetics) and actual yields (FOLEY et al., 2011). Achieving food security by gains in average crop yields or closing these yield gaps imposes challenges, such as ensuring adequate food accessibility (common situation in developing countries) and sustainably maximizing yields per unit of cultivated area (situation of developed countries) (CIAMPITTY; VYN, 2014).

Maize is one of the most important crops produced in Brazil and also at world level (third most produced crop in both areas). Brazilian maize production is only behind United States and China (FAO, 2016). In Brazil, its importance is mostly indirectly linked to human food, since almost 55% of its total production is allocated for animal consumption (BRAZILIAN ASSOCIATION OF MAIZE INDUSTRIES - ABIMILHO, 2014). In Figure 1, past decade’s relationship between area, production and average yields of maize in Brazil are compared with South American and world situation. On the past few years cultivated area of maize of the presented regions showed an increase, although less accentuated when compared to average yields. Cultivated area of Brazil, South America and World showed increases of 30, 40 and 40% from 1961-2014, respectively. According to Grassini, Eskridge and Cassman (2013), nearly all of world’s cultivated area expansion of major cereal crops (maize, wheat and rice) occurred in South America, Asia and Africa in the past years (since 2000). The increase in arable land will probably continuing to happen, and specifically in Brazil it is partly associated with expansion of agriculture in Cerrado(Brazilian savannah).In the Cerrado, by use of research and development (e.g. no tillage practices), agricultural production became possible on its typical acidic soils (BRUINSMA, 2009); currently representingthe major share of national agricultural total production. Total production increases were 166, 172 and 114%, respectively (FAO, 2015). However, despite current expansions of farmland, increases in staple crops production are preferably going to happen due to the intensification of its production (BRUINSMA, 2009). Yield increases have been more pronounced (Figure 1) in the past decades, with 104; 92 and 54% of increase for Brazil, South America and world, respectively.

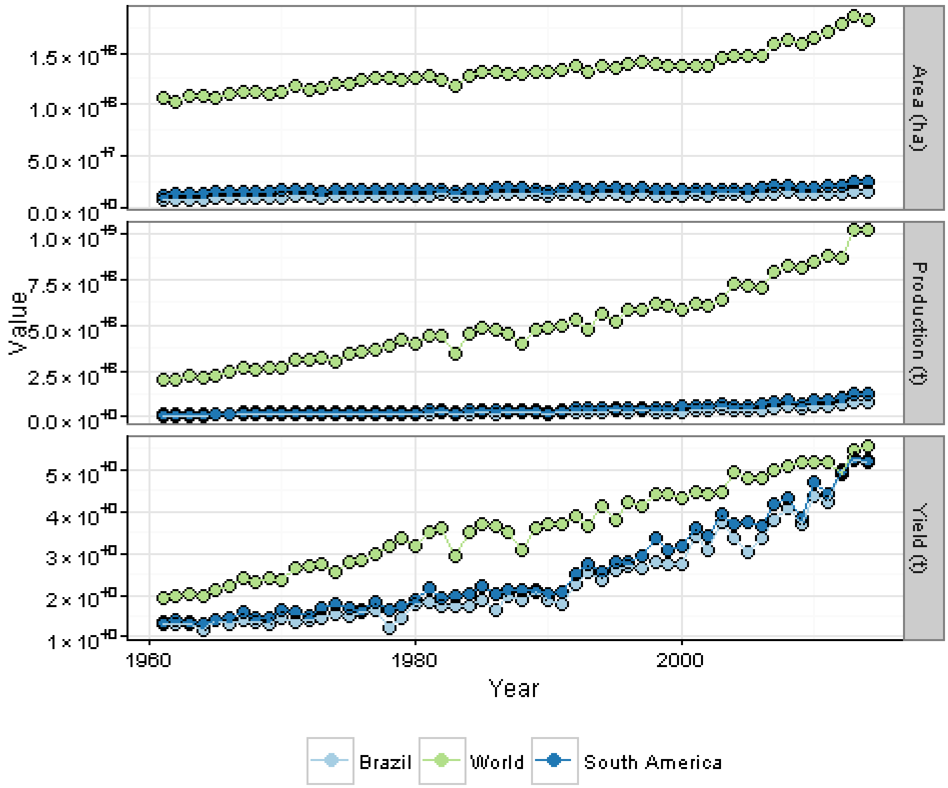

Figure 1 -Time course of relationship between Brazilian, South American and World maize harvested area, total production and average yields.

Source: FAO(2015).

Although intensification of crop production is a real necessity for many countries, quantification of the increases and limits of such achievement should be clearer. Increasing yields is possible only up to a biophysical limit, imposed by environment characteristics and potential of the genetic material (LOBELL; CASSMAN; FIELD, 2009). Grassini, Eskridge and Cassman(2013) point as questionable studies that account for undetermined linear rates of yield increases in the future (such as studies of food security projections) and that do not consider a biophysical limit to crop yields (i.e., annual rates of yield increase or use of “record” crop yields as reference). This can be alleviated by making realistic estimations of those maximum levels of yields. Those estimations usually rely on environment and management data, which should comprise the maximum quantity of years with climate, yield, soil and management information, as well as the use of crop models to simulate those optimum conditions (GYGA, 2015).

When analyzing Brazilian reality, although close to world and South American values, the country's average yields are still well below potential, since the national average is lower than several locations in the country with more intensive production (Figure 2). In historical terms, all main five Brazilian regions presented increases of average yields greater than 200% (1976-2014 for 1st growing season and variable period for 2nd growing season), except for 2nd growing season on Northern region.

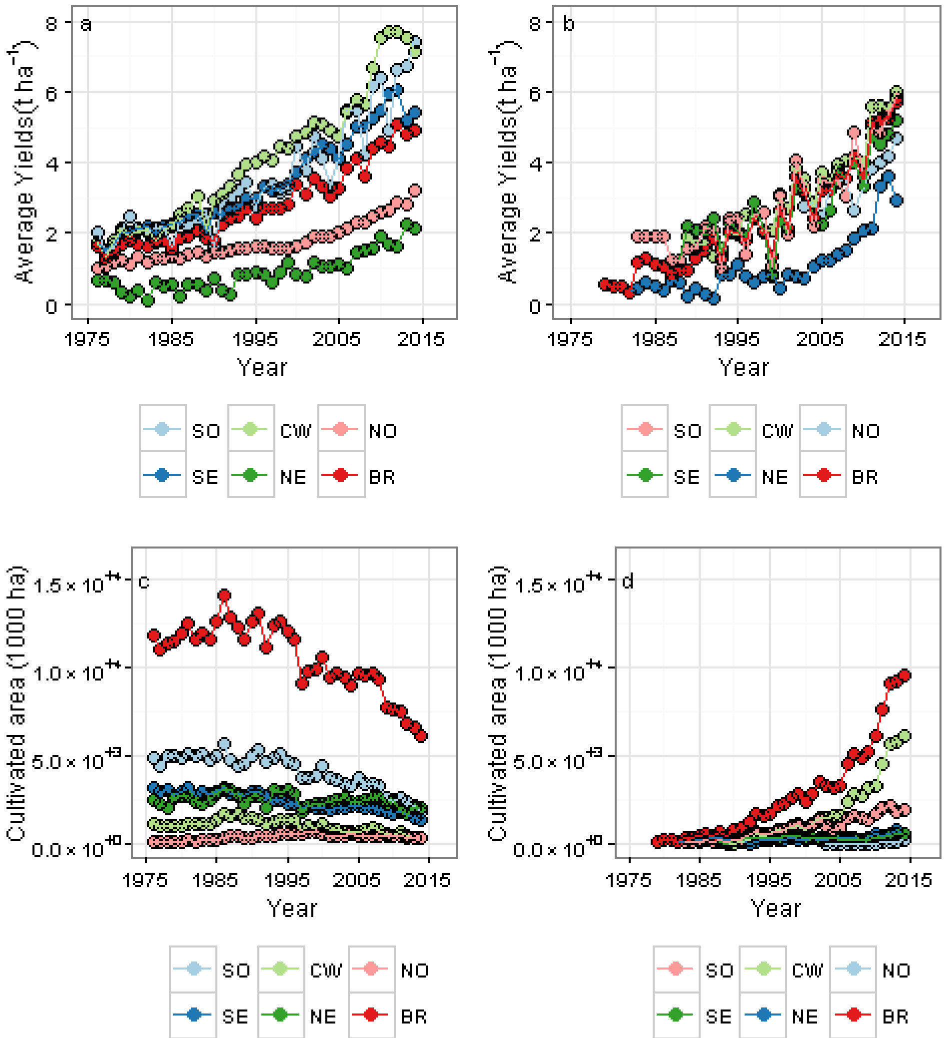

Figure 2–Time course of maize average yields on 1st (a) and 2nd (b) growing seasons and cultivated area on 1st (c) and 2nd (d) growing seasons in Brazilian main regions and national level. SO: Southern; SE: Southeastern; CW: Mid-Western; NE: Northeastern; NO: North regions and BR: Brazil.

Source: Companhia Nacional de Abastecimento - CONAB (2015).

The Southern and Mid-Western regions are responsible for the majority of national maize production (together, both regions account for 56% and 89% of national production in both growing seasons, that were 30.2 and 54.5 million tons in 2014, respectively), as well as the highest average yields, which are also above the national level. In terms of cultivated area, the whole country and both Southern and Mid-Western regions had decreases of 1st season cultivated area in the period presented in Figure 2 (-49; -61 and -66%, respectively). For 2nd growing season the opposite tendency was observed, with increase of cultivated area for all regions, especially for Mid-Western regions. However, since yield increases are being observed in a more accentuated manner only in the past years, it is difficult to determine if they are close to stabilization without performing a detailed local analysis. That stability is indicated by a plateau of average yields, which is observed when average yields get near yield potential (LOBELL; CASSMAN; FIELD, 2009). This statement confirms the necessity of making clear the possible limits of intensification of production.

The existence of significant yield gaps and consequently opportunity for their improvement in Latin America is attributed mainlyto nutrient and water limitation (FOLEY et al., 2011), for all main staple crops production. Specifically for maize, proper nutrient management, particularly related to nitrogen, is of great importance for increasing its average yields (COELHO, 2007; DOBERMANN, 2005).Although not specific for maize, Figure 3 shows the time course of total national consumption of nitrogenous fertilizer and urea in the past decades. At national level, urea represents the major source of nitrogenous fertilizers and its total consumption is the 3rd largest, only behind potassium chloride and superphosphate. Urea's share of consumption represented 14% of all consumed fertilizers (29.7 metric tons) in 2015. Central-Southern Brazil (comprising Southern, Southeastern and Mid-Western regions) consumed 25.9 thousand metric tons of fertilizers (all types) in 2015, which represents 86% of the country's total consumption. In terms of consumption of nutrients by the main crops (that may not be fully provided by fertilizers), maize is the crop that most consumes nitrogen, with an estimate of 34% of the element's consumption among nine main crops in 2008 (INTERNATIONAL PLANT NUTRITION INSTITUTE -IPNI, 2016).

Even though nutrient management, especially nitrogen for maize, in Brazil seems a plausible measure to increase yields and reduce gaps given current situation and projections; there are several issues that should be carefully analyzed. Foley et al.(2011) indicate that despite the key role of fertilizers on increasing average yields, there are impacts regarding their overutilization on energy use (i.e., the energy used for manufacturing nitrogenous and phosphate fertilizers); environment conditions (such as water pollution) and economic limits of the system (high prices of those inputs). The latter authors still indicate that the most common situation is to find excess or lack of nutrient use on agriculture at global level; and suggests that targeting those locations with low efficiency of use of nutrients and water is the first step in planning yield improvements. Added to that, the difficulty in analyzing many management scenarios due to time and money constraints combined with the increasing need for agronomic decision making have intensified the use of crop models and other simulation approaches to assess feasibility of management improvements (JONES et al., 2003).

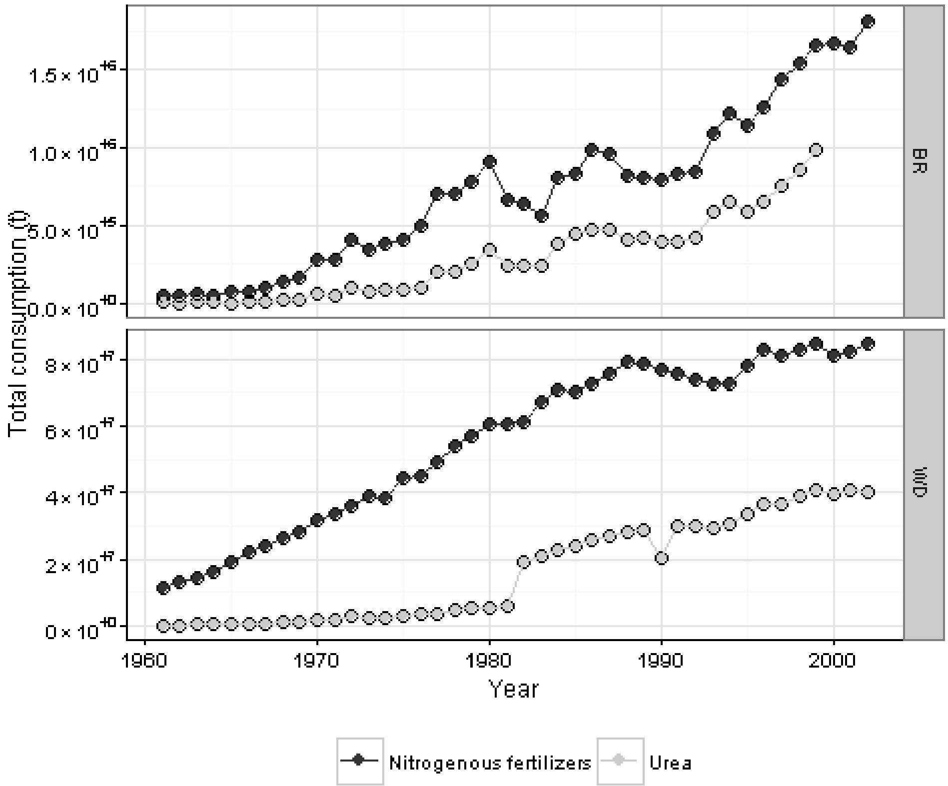

Figure 3–Time course of national and world level total consumption of nitrogenous fertilizers (including urea) and urea. BR = Brazil; WD = World.
Source: FAO (2015).

Considering the prior presented issues, the main objective of this study was to determine rainfed maize yield gaps related to climate conditions and management; and evaluate the profitability of mechanized nitrogen management as a strategy for closing the gaps.

This study contains two parts: (i) local characterization, model calibration, determination of yield reference levels (potential and water-limited) and determination of yield gaps, related to climate conditions and crop management, (ii) simulation of yields under different nitrogen fertilization and simulation of mechanized nitrogen application, all used to determine the economic and energy profitability of managing yield gaps through this nutrient management.

The framework and results are able to help decision makers on important real conditions decisions, such as managing profitability from fertilizer use. Practical and necessary results can be obtained from a combined simulation approach by using local data and knowledge.

Methods and results in this study can assist finding the most economical use of an important, but energy and economically expensive, input on maize production.

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2 MODEL-BASED APPROACH FOR MAIZE YIELD GAP ANALYSIS RELATED TO CLIMATE VARIABILITY AND NITROGEN MANAGEMENT: I - POTENTIAL YIELD, WATER-LIMITED YIELD AND YIELD GAPS

Abstract

Maize is one of the main crops in the world and in Brazilian agriculture; however Brazilian average actual yields are usually low and far from attainable yields. Yield gap (Yg) quantifies the differences between potential, attainable and actual yields, wherein climate variability represents an important role as also directly influences on crop management of rainfed systems. Yield gap studies are numerous worldwide, but are still scarce in Brazil. A study based on a simulation approach was carried out using the crop simulation model CSM CERES-Maize, part of the *Decision Suport System for Agro-Technology Transfer* (DSSAT). The model was utilized to assess climate-induced variability and yield gap of rainfed maize for the crop's yearly two growing seasons, during a period of 10-30 years, in six regions with economic importance on crop productionin Central-Southern Brazil. The model was calibrated using local hybrid trials (Ybf) for an early maturing hybrid. Reference yield levels, namely potential (Yp) and water-limited (Yw) yields were simulated for 30 growing seasons (1983-2013) using daily historical weather data and average crop management information. Using local farmers' average yields (Ya) from series of 10 to 20 years and reference yield levels, yield gaps (water-related yield gap –Cyg; and management yield gap – MYg were determined).The simulated experiments provided average Yp of 11.4-21.0 t ha^{-1} for 1^{st} season; 9.2-12.6 t ha^{-1} for 2^{nd} season and Yw of 10.7-18.6 t ha^{-1} for 1^{st} season; 7.7-9.9 t ha^{-1} for 2^{nd} season. Average yield gap due to water deficit (CYg) varied between3-51 % of total (0.2-4.9 t ha^{-1}) for 1^{st} season and between 9-42 % of total (0.4-2.6 t ha^{-1}) for 2^{nd} growing season. Average yield gap due to management (MYg) varied between49-94% of total (4.5-7.9 t ha^{-1}) for 1^{st} season and between 58-91 % of total (2.0-3.8 t ha^{-1}) for 2^{nd}growing season. These results indicate the importance of crop management to increase yields toward the maximum attainable in all studied regions. There is opportunity for increasing yields in almost all scenarios (regions vs. season). Opportunities for increasing yields to its biophysical limit imply that crop management performed with proper weather forecast will be indispensable for closing yield gaps.

Keywords: *Zea mays*; Crop simulation model; Ceres-Maize; DSSAT; Crop management

2.1 Introduction

Maize is a major crop for both global and Brazilian agriculture production systems. Brazil is the third largest producer in the world (behind USA and China) and was responsible for 80 million tons of total production in 2013 (FAO, 2015). However, average actual yields (4.9 and 5.7 t ha^{-1}in the 1^{st} and 2^{nd}growing seasons, respectively) (CONAB, 2015) are still below their local potential, representing conditions for yield improvements. This improvement, however, is preferably related to intensification of crop yields rather than expansion of arable land (FOLEY et al., 2011; LOBELL; CASSMAN; FIELD, 2009), mainly due to environmental reasons, such as deforestation.

When analyzing crop yield increases and yield gaps, it is necessary to define the physical limit of the maximum attainable yields in that particular condition. A few decades those limits were estimated and evaluated by means of highest local detected yields, as in contest yields worldwide (COELHO et al., 2003). Posteriorly, the use of tools such as crop models has facilitated those analyses, and currently they are indispensable in this type of study. However, one must first acknowledge that there are local environmental characteristics operating together with the plant influencing the ability to achieve those yield limits. Soil, climate and plant factors must present a favorable combination for such achievement (COELHO et al., 2003). Thus, it is possible to understand the importance of plant-environment relationship, determinant for the occurrence of periodic phenomena characteristic of the plant, known as phenology.

Regarding this interaction between genetic material and environment, some particularities concerning maize can be observed. The understanding of phenological events allows the correlation of plant development with environmental conditions, especially the weather. This can be particularly important when analyzing potential crop development in an environment; e.g., water deficit, high temperatures, low solar radiation or reduction in leaf area may undermine the development of grain formation by contributing to the reduction of supply of photosynthates (BERGAMASCHI; MATZENAUER, 2014). In terms of solar radiation, maize is a crop that does not present saturation due to this climate factor. Maize is a C4 crop, thus efficient when it comes to radiation utilization. Photoperiod is a climate factor of greater seasonal than interannual variation. The increase of photoperiod causes longer period of crop’s vegetative development; in contrast, shortening of photoperiod may cause, in some genotypes, responses represented by reduction of its thermal needs. In general terms, maize gentic materials are considered neutral or of low photoperiodic response, thus having little sensitivity to photoperiod variation. In Brazilian conditions and for practical purposes, photoperiod is considered little significant, wherein thermal conditions are main responsibe for the crop development (BERGAMASCHI; MATZENAUER, 2014; CRUZ et al., 2010). Temperature is identified as main factor regulating maize phenology (BERGAMASCHI; MATZENAUER, 2014; CRUZ et al., 2010). Maize genotypes basically need to accumulate certain energy amount to get through development phases. For certain maturation group, it is possible to estimate phenology based on air temperature. Linear models associating maize phenology and thermal sum have been utilized (TOJO SOLER, SENTELHAS; HOOGENBOOM, 2005). Altitude is also important since it is directly related to temperature. In general terms, in Brazilian conditions, maize planted on higher altitude may achieve higher yields since it basically presents longer period to compled its cycle and lower nocturnal respiration rate due to a wider range of daily temperatures (CRUZ et al., 2010).

Potential yield (Yp) and water-limited yield (Yw) (Figure 1) are concepts or reference levels of these maximum achievable yields in irrigated and rainfed systems, respectively. Yp depends only onthe interaction between the genotype, solar radiation, temperature, photoperiod, and plant population. Yw depends on the same factors as Yp, in addition to water deficit, typical of rainfed systems (FOLEY et al., 2011; LOBELL; CASSMAN; FIELD, 2009). These are considered theoretical concepts due to the impossibility of determining their exact values in practice, since general management conditions (affected by fertilization, pests and diseases) are not considered for their determination. Thus, the most common way of determining Yp and Yw for a given crop system is by using crop simulation models, although field experiments with the best management practices can also be used for auxiliating their determination (AFFHOLDER et al., 2013; GRASSINI et al., 2015; KASSIE et al., 2014; LOBELL; CASSMAN; FIELD, 2009; SENTELHAS et al., 2015; VAN WART et al., 2013).

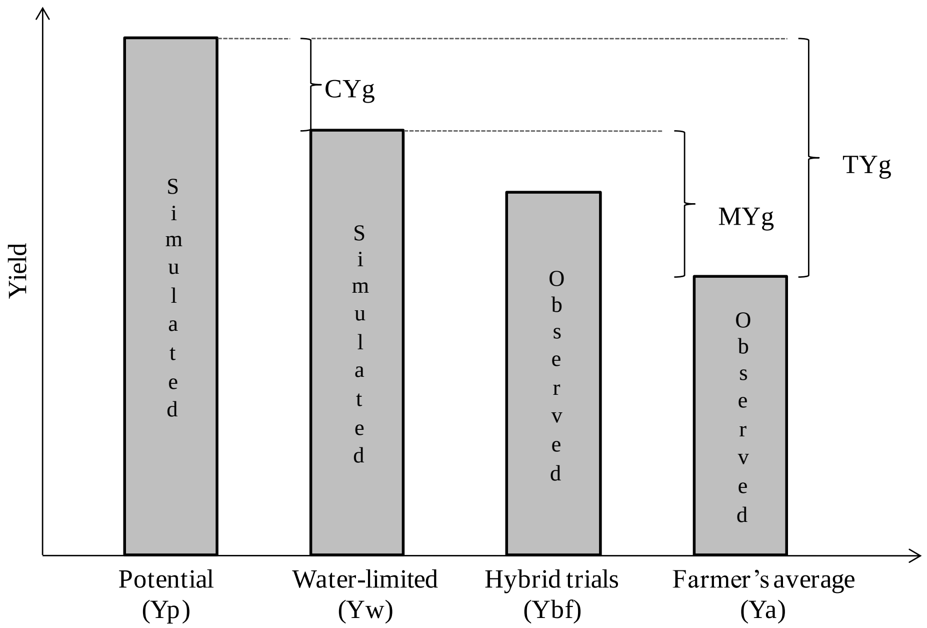

Figure 1 –Yield reference levels and yield gaps used in the present study.
Adapted from Lobell et al. (2009).

Being Yp and Yw nothing but concepts, some considerations on their determination can be performed. Management practices to achieve those potential reference yield levels, besides hardly feasible in practice, also suffers from intereannual variability due to weather conditions. Thus, Yp and Yw may be also determined for local typical management conditions (van WART et al., 2013). However it is important for one to understand that different arrangements of measures such as spacing, plant density, sowing date and choice of genetic material may provide variation on Yp and Yw levels.

Yp and Yw can be simulated using a minimum set of input data, including climate, soil and usual crop management (sowing window, row spacing, plant population and cultivar). With quality data, practical and low cost estimation of Yp and Yw can be done in a robust manner (GRASSINI et al., 2015; LOBELL; CASSMAN; FIELD, 2009). Models can be calibrated (i.e., adjusted to local conditions) by using experimental data come from good management practices, such as hybrid trials (Ybf) (KASSIE et al., 2014). By using the local farmer’s average yields (Ya), it is then possible to estimate the size of the gap between what is being produced and the maximum attainable for local conditions. Different yield gaps can be determined, such as the difference between Yp and Yw, representing the gap caused by water deficit (CYg), or the difference between Yw and Ya, representing the gap due to crop management (MYg).

Currently there are a wide variety of crop models that basically vary in the approaches used for estimating processes related to soil-plant-atmosphere interactions (BOUMAN et al., 1996). Decision Support System for Agrotechnology Transfer (DSSAT)(JONES et al., 2003) is a system that incorporates several crop simulation models, and has been used under Brazilian conditions (MARIN; JONES, 2014; SOLER; SENTELHAS; HOOGENBOOM, 2007). The main components in DSSAT are the crop models, which can be manipulated by using different databases that describe a typical system (soil, weather, genetics, experiments, pests and economics) and model applications (crop rotation; sensitivity, spatial, validation, sequence and seasonal analysis). Such diversity allows one to simulate the crop performance under a great variety of scenarios (JONES et al., 2003).

Affholder et al. (2013) evaluated the magnitude and causes of staple crops’ yield gaps (maize, millet and rice) in Brazil, Senegal and Vietnam. The authors used experimental data and crop model to determine local yield reference levels and yield gaps. Yield gaps was found to be equally or greatly caused by crop management than climate conditions in most of the assessed regions. van Wart et al. (2013) evaluated yield gaps of rice, maize and wheat in China, United States and Germany. The authors also developed a protocol to help obtaining robust and reproducible yield reference levels at diverse scale of study. The protocol indicates the importance of procedures related mainly to period and detailment of weather and crop management information to obtain robus estimated o Yp and Yw data.

In summary, diverse studies has been developed at world level to characterize local production and yield gaps situation (LOBELL; CASSMAN; FIELD, 2009). Most of these studies highlight the importance of such subject on current and upcoming climate change an global food security conditions.

Thus, simulation approaches are useful in synthesizing knowledge, allowing one to understand the whole system and providing information on how to better manage it. Based on that,this study aimed: (i) to utilize a crop simulation model to determine and quantify maize yield reference levels (potential and water-limited yields) and yield gaps of typical rainfed production systems in six Brazilian regions; (ii) evaluate the influence of climate variability and management on yield variability of an early season maize cultivar in each region.

2.2 Materials and Methods

2.2.1 Assessed regions

Six regions represented by counties with economic importance in national maize production and having availability of soil, weather and management data were selected for this study (Figure 2). Three municipalities (RSPF, PRGU, PRPA) located in the Southern (Passo Fundo, in Rio Grande do Sul state: 28°15'S, 52°24'W; Guarapuava, in Paraná state: 25°23'S, 51°27'W; and Palotina, in Paraná state: 24°16'S, 53°20'W, respectively) and other three (MSMJ, MTDI, GOJA) locatedin the Mid-Western portion of the country (Maracaju, in Mato Grosso do Sul state: 21°37'S, 55°10'W; Diamantino, in Mato Grosso state: 14°24'S, 56°25'W and Jataí, in Goiás state: 17°52'S, 51°41'W, respectively). Due to the location of the regions across the country, differences in main environmental characteristics such as soil and climate conditions are observed (Figure 3 and Annexes A and B).

In climatic terms, climatic classification systems were utilized to define those differences. Köppen, a more broad classification due to the utilizing only the amount and distribution of rainfall and average temperatures, and Thornthwaite classification, more specific in terms of agrometerological purposes due to the utilization of atmosphere and water balance components information (see Annex B for climate classifications and climatological water balance).

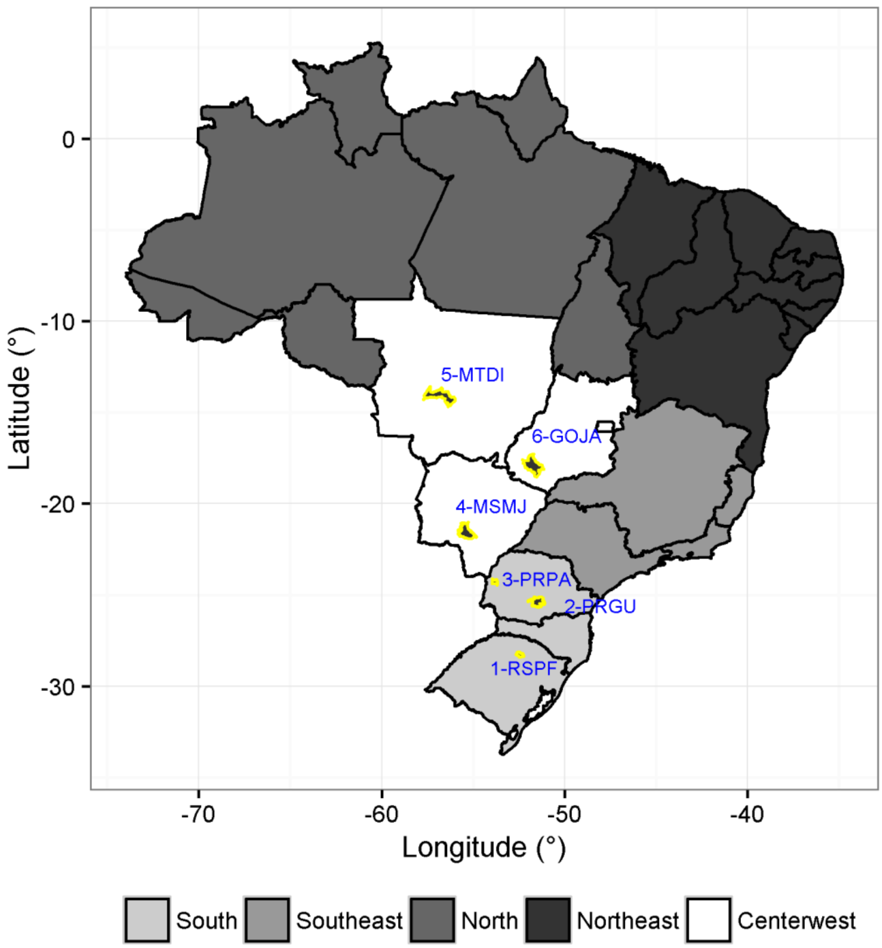

Figure 2 -Localization of the regions selected for this study. Shapes of the studied regions are highlighted. RSPF, PRGU, PRPA, MSMJ MTDI and GOJA indicate, respectively, the counties of Passo Fundo, Guarapuava, Palotina, Maracaju, Diamantino and Jataí

High resolution (1 ha) Köppen´s climate classification (ALVARES et al., 2013) shows that Southernmost regions present a humid subtropical climate, differing in summer temperatures (hot: Cfa and temperate: Cfb), and central regions present tropical climate, differing on winter humidity (monsoon: Am and dry winter: Aw). Thornthwaite climate classification (THORNTHWAITE, 1948) allows the determination of periods that are most likely to present water deficit or surplus due to an estimated evapotranspiration (ETP). Thornthwaite classification presents types and subtypes of climate conditions according to moisture and thermal efficiency. Most regions present humid climate type, with little or no water stress, except for MTDI, which may present deficit in summer, and MSMJ, in which water surplus hardly exists (Figure 3). Also, almost all regions present the megathermal climate type, due to high ETP, except for RSPF and PRGU, which present the mesothermal climate type.

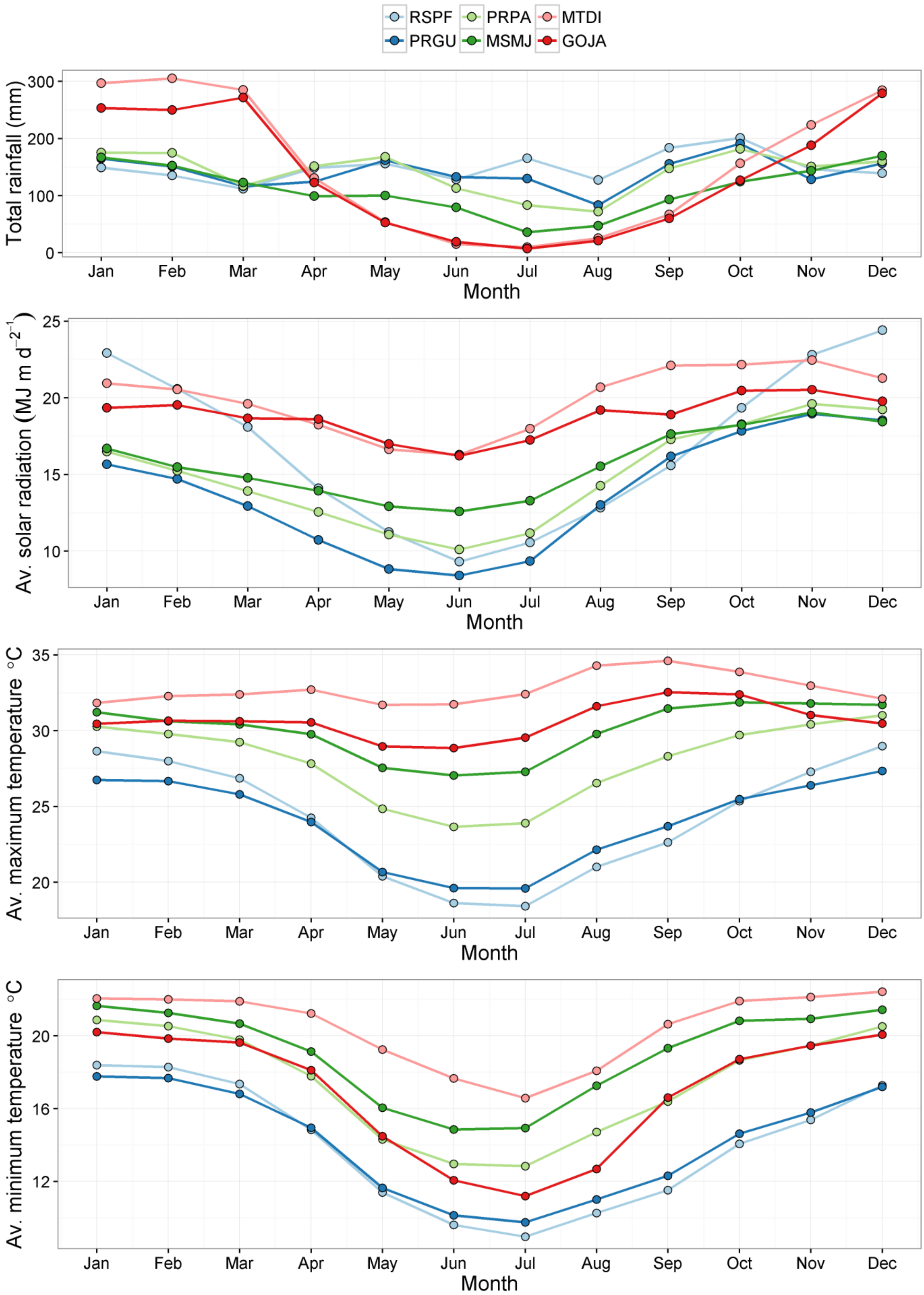

Figure 3 - Monthly total rainfall (a), average solar radiation (b), average maximum (c) and minimum (d) temperatures of the studied regions, based on a 30-year (1983-2013) daily weather record.

The two most central regions (MTDI and GOJA) have the average highest solar radiation and maximum temperature; and the two southernmost regions (RSPF and PRGU) have average lowest temperatures. Average maximum temperatures show variability and it generally tends to increase with latitude. For average minimum temperature, GOJA is an exception since it has the 2nd highest latitude and 3rd lowest minimum temperature, probably related to its altitude (> 700 m).

Except for the two Southernmost regions, besides the historically traditional 1st growing season for the crop (usually starting in September/October), there is also a 2nd growing season (Annex A), which is when the crop is cultivated right after the 1st or humid season, both referred in this study as "1st maize growing season" and "2nd maize growing season". The 2nd growing season, which usually starts in January-February, is drier than the 1stone, especially for Central Brazil, in which there is an accentuated drier period from April-September (Figure 3). Regions that produce maize on2ndgrowing season have been growingin its economic importance in recent years, wherein it has become even more important than 1st growing season, represented by either larger planted area or total production. This study was developed at average county level, over both maize growing seasons (1st and 2nd, according to regional predominance), wherein average (or usual) crop management was considered homogeneous.

2.2.2 Main steps

In this study, four main steps were taken: (i) determination of soil initial conditions; (ii) model calibration; (iii) simulation of yield reference levels (Yp and Yw); and (vi) determination of yield gaps (CYg and MYg). Simulation approaches were performed for steps i, ii and iii, and will be following detailed directions. For all steps historical weather data, predominant soil profile characteristics and average crop management were utilized.

2.2.3 Model

The DSSAT package system (DSSAT v. 4.6.0.18) (JONES et al., 2003) was used in this study. DSSAT comprises models for diverse crops, such as cereals, legumes, oil, vegetable, fiber, forage, sugar, fruit and others. DSSAT is basically a set of independent programs that are compatible for operatig together. The crop simulation models (CSM) occupy the main position, while counting on databases comprising weather, soil, genetics, management and experiments information.

For model calibration and simulation of yield reference levels, the maize model (CSM CERES-MAIZE) and CENTURY organic matter model coupled with DSSAT (GIJSMAN et al., 2002) were utilized. For the determination of soil initial conditions, wheat, soybean and maize crop simulation models (CERES-WHEAT, CROPGRO-SOYBEAN and CERES-MAIZE) were utilized, also coupled with CENTURY model to simulate prior crops in rotation. The DSSAT's Sequence and Seasonal analysis tools were used for performing the simulations. Sequence analysis is a tool that is used mainly for crop rotations, since it does simulate the carry over effect of nutrients in soil through years. This tool was used only for the determination of soil initial conditions, in which a local characterization of some attributes of soil organic matter was intended. For all other simulations, Seasonal analysis was utilized. This tool, unlike Sequence analysis, does not account for carry over effect of organic matter, thus enabling the analysis of individual management measures under given weather conditions, using the same soil initial conditions for each year of simulation. Model's input data are described as follows.

2.2.4 Weather data

Historical weather data (daily maximum and minimum air temperature, sunshine hours and rainfall) from 1983 to 2013 were utilized for climate characterization (Figure 3). Most data was observed(NATIONAL INSTITUTE OF METEOROLOGY -INMET, 2014) and data gaps were filled by using global database(NATIONAL AERONAUTICS AND SPACE ADMINISTRATION PREDICTION OF WORLDWIDE ENERGY RESOURCE -NASA, 2015). Daily solar radiation was obtained using Angström-Prescott model with "a" and "b" coefficients (a = 0.29 * cos latitude; b = 0.52) proposed by Glover & McCulloch (GLOVER; McCULLOCH, 1958), when sunshine hours were available, or by Bristow and Campbell model (BRISTOW; CAMPBELL, 1984), when only temperature data were available. Daily rainfall data for all regions was obtained from national database (NATIONAL WATER AGENCY -ANA, 2014) for the same period.

Climate information presents great importance on crop models since their use is related to most of plant-soil-atmosphere interactions. In general terms, the model integrates several informations on environment, management and crops' physiological processes to determine processes of the hydrological cycle (e.g., water input and output, water use by the plant). The ETP is computed and partitioned between potential plant transpiration and potential soil evaporation. Limited soil evaporation is also determined, thus actual soil evaporation is considered as the minimum among the latter (soil evaporation rates). Then, the model computes a soil-root system limitation to root water uptake and again actual plant transpiration is considered as the minimum among both computed rates. Water deficit is based on the ratio between root water uptake and atmospheric demand for water. If the atmospheric demand for water exceeds capacity of the soil-root system to supply water, then processes such as photosynthesis, phenology, expansion and growth processes are affected by the water stress.

2.2.5 Soil data

Soil profile data (0 to 100 cm) were obtained from global database (FAO/INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS/ISRIC - WORLD SOIL INFORMATION/INSTITUTE OF SOIL SCIENCE - CHINESE ACADEMY OF SCIENCES/JOINT RESEARCH CENTRE OF THE EUROPEAN COMMISSION - FAO/IIASA/ISRIC/ISS-CAS/JRC, 2012), which is basically a combination of regional and national soil data, harmonized in order to fill gaps and considered to have high reliability for Latin America. The utilized data refer mainly to soil texture, bulk density, soil organic C and acidity in water. For each region, two predominant soil profiles were identified and saved in DSSAT soil file, although only the most predominant was used for analysis (Annex A) due to their similarity. Specific soil water parameters (lower limit, LL; drained upper limit, DUL; and saturation, SAT) were estimated through two pedotransfer functions (PTF) (Annex A) (ASSAD et al., 2001; REICHERT et al., 2009) better suited for the study regions when compared with DSSAT's PTF developed for temperate environments. The adopted PTF used as input soil texture values (clay, silt and sand). Drainage coefficients and runoff curve were estimated by DSSAT, by means of its specific soil data module (SBuild). Maximum soil depth for crop root development was set to 1.2 m (MONSANTO, 2015).

Dominant soil group of the study regions are Ferralsols, but Cambisols, Nitisols and one Arenosol profile were also found. Ferralsols, a major (first level) soil grouping according to FAO classification (IUSS WORKING GROUP WRB, 2014), indicates a high content of sesquioxides. Within the second level of soil classification (FAO, 2014), the Rhodic grouping was predominant in the study regions, indicating that the formative elements are representative of red-coloured soils. In Mid-Western region, there is a predominance of deep, well drained soils, with good physical characteristics and low fertility, which is easily corrected by fertilization and liming. Its slope also facilitates intensive mechanization. In

Southern region, slopes are more diverse, with the presence of predominantly fertile soils. The Brazilian soil classification (EMBRAPA, 2009), regarding the distribution of main soil classes, establishes that in the Midwestern and Southern regions the most frequent is Latosol (Oxisoil) class, although in Southern region the Neosol (Entisol) class is also present (COELHO; CRUZ; PEREIRA FILHO, 2003).

2.2.6 Crop data

Average crop management, related to plant density, row spacing, sowing window and nutrient management were adopted from national databasesand were utilized in the simulations. Management information utilized for performing the simulations of soil initial conditions are presented in Table 1. Management information for performing maize simulations) are presented in AnnexA.

Table 1 - Average management information utilized in determination of soil initial conditions

Crop	Spacing (m)	Plant density (pl m^{-2})	Nitrogen management (kg ha^{-1})	Sowing Window (dd/MM)
Soybean	[1]0.45	[1]30	-	[4]1-15/10
Wheat	[2]0.17	[2]25	[3]40	[4]1-10/06

[1](EMBRAPA, 2004); [2](CAIRES et al., 1999); [3] (FNP CONSULTORIA & COMÉRCIO, 2015); [4](BRASIL, 2014).For soybean and wheat cultivars, a calibration performed for a Brazilian region (DALLACORT et al. 2006) and the default cultivar from DSSAT, respectively, were utilized in the simulations.

2.2.7 Simulation of soil initial conditions

Due to a common difficulty in using crop models related to information of organic matter (OM) pools at the beginning of simulations, a previous simulation approach was carried out to determine mineral N and stable C pools. The simulation approach usually performed on those cases of lack of information on organic matter fractions (named “spin-up” simulations) aim to set the conditions prior to the start of main simulations and relies on some kind of equilibrium state of organic matter, requiring precise local historical information (BASSO et al., 2011; LUGATO; JONES, 2014; OGLE et al., 2007). Stable C in particular is rarely measured routinely, and it can represent a major fraction of soil organic matter in tropical oxidic clayey soils, as found in many parts of Brazil (FERNANDES, 2002; LEITE; MENDONÇA; MACHADO, 2004) and ultimately impact on crop’s nutrient availability.In practical terms, organic matters' stable fraction, which is intimately connected with nutrient availability through mineralization (e.g., added crop residues can increase short term nutrient mineralization, but decrease the stable fraction if no nutrient is added to soil), is also connected with OM quality, nutrient addition and microbial activity, through complex and even not fully understood processes (KIRKBY et al., 2014; MOLINA-HERRERA; ROMANYÀ, 2015). Mineral N, although highly unstable, is strongly influenced by local conditions (environment and management). Thus, a more specific determination of this fraction was considered necessary in order to estimate initial nutrient availability within each scenario (region and growing season). Considering the lack of precise historical management information for a whole region and impossibility of measuring organic matter nutrient pools, especially for defining a region's condition, an adapted simulation approach was taken. A representative cropping sequence including maize was chosen to characterize each simulation scenario. For 1st maize season, in the three southernmost regions a winter grass (in the present study represented by wheat) + maize (MWMW) was chosen; in the other three Central regions fallow + maize was chosen (MFMF). For 2nd maize season, a soybean+ maize cropping sequence was adopted (SMSM), since this is a very common practice for Mid-Western and Southern Brazil with warmer winters. Each scenario was run for 150 years using the environmental and average crop management data (see Table 1) and the crop models for maize, wheat, soybean and soil organic matter coupled with DSSAT. Results of mineral N and stable C pools from these simulations were compared with literature values (Annexes C and D), which were chosen for presenting similar conditions to those of the present study; predominantly clayey soils with annual cropping systems in Central-South Brazil. The output from simulations of soil initial conditions, mineral N and stable C pools were utilized as additional input data in maize yield simulations.

2.2.8 Model calibration and evaluation

Calibration of genetic coefficients was performed to adjust phenological phases and yields to observed data, as recommended by previous studies (GRASSINI et al., 2015; KASSIE et al., 2014; PAGLIS; PINHO, 2009). Data from field experiments, known as cultivar trials, were considered as the highest actual yields (Ybf) (they are usually above farmer's average yields) and used for model calibration. These trials mostly comprised the Network of National Trials of maize cultivars (created in 1962), currently coordinated by the Brazilian Company of Agricultural Research (Embrapa). Due to their relevance on national production, all regions had at least one season of available cultivar trials, although it was scarcer for 1st maize season in Mid-Western due to its declining economic relevance at this region. The Ybf had above-average management, yet was limited by biotic and non-biotic factors due to the impossibility of perfect management as provided by models. Ybf of trials in each region (or nearby region, depending on its availability) of 2 to 4 years was used for model calibration (set I) and validation (set II) (Annex E). Use of Ybf was also due to physical impossibility of experimental data that could represent Yp or Yw. Genetic coefficients of maize model P1, P5, G2 and G3 were adjusted. Calibrations were focused first on phenology (P1 and P5 coefficients) and then on yield (G2 and G3 coefficients) (see Annex F for coefficients description). A range of up to 15% of absolute deviation was considered acceptable regarding the differences between observed (Ybf) and simulated (Yw) (GRASSINI et al., 2015), although the 15% of deviation was not necessarily the observed difference in all locations. Model performance was evaluated by means of statistical indices of root mean square error (RMSE); mean absolute error (MAE); and coefficient of determination (R^2).

2.2.9 Simulations of potential and rainfed potential yields

The reference yield levels Yp and Yw were simulated using the thirty years of weather data and described environment characteristics in conditions of no limitation of water and nitrogen (for Yp); and in conditions of no limitation of nitrogen, with water limitation (for Yw). In simulation terms, very high levels of nitrogen fertilization were utilized for both Yp and Yw determination; automatic irrigation (i.e., unlimited water supply) was utilized for Yp simulation. In N fertilization terms, all high N levels were compared in order to determine the N scenario that represented the highest average among thirty years of simulation.

2.2.10 Farmers average yields (Ya)

From 1990 to 2013, historical regional farmers' average yields (Ya) were used for determining the yield gaps. Ya data were adopted from IBGE (INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA - IBGE, 2015), which is obtained at the county level, through annual field surveys by technicians. A detrending process (HEINEMANN; SENTELHAS, 2011) was conducted to extract the upward tendency that is normallyobserved in historical yield series due to technological advances. This procedure was performed to be able to analyze the influence of climate variability on local average yields isolated from the technology effects. In general terms, the last year of the data series is used as reference, a trend line (local regression) is considered as the techonolgical effect and the deviations are considered as the climate effect (Equations 1 and 2) (HEINEMANN; SENTELHAS, 2011).

$$D_1^n = x - \bar{y}/\bar{y} \quad (1)$$

$$YA_1^n = (D_1^n + 1) * \bar{y}_n \quad (2)$$

Where D_1^n is the relative deviation from the first (1) to the last year (or reference year, n) in the data series; x is the observed yield (kg ha^{-1}); $\bar{y}$ is the predicted yield (kg ha^{-1}); YA is the adjusted yield (kg ha^{-1}).

2.2.11 Yield gaps and result analysis

Yield gaps were determined as the difference between different yield levels (LOBELL; CASSMAN; FIELD, 2009). The water deficit yield gap (CYg) was obtained by the difference between Yp and Yw (CYg = Yp – Yw). The management gap (MYg) was obtained by the difference between Yw and Ya (MYg = Yw – Ya). Thus, the total gap (TYg) was obtained by the difference between Yp and Ya (TYg = Yp – Ya) or the sum of CYg and MYg (TYg = CYg + MYg). The CYg was used to understand how much of the gap is caused by water deficit throughout the crop season and MYg to indicate losses due to crop management, referred to a maximum achievable in rainfed systems. TYg represents a non-feasible concept for rainfed environments, given the difference between average management and ideal management with no water deficit.

Weather data (seasonal rainfall, solar radiation, maximum and minimum temperature and evapotranspiration) were analyzed and correlated with simulated yields (Yw) to subsidize the discussion of the crop-climate relationship (Annex G). Correlation was determined through Pearson’s coefficient (strength of the linear association, ranging from -1 to 1) and t-test.

Yp and Yw simulated values and climate variability were analyzed for a 30-year series of experiments. Yield gaps (CYg, MYg and TYg) were evaluated for the same number of years of Ya (10-20 years, depending on the availability of the region). Basic statistical analysis was performed for all yield levels and yield gaps. Yield reference levels were compared by contrast tests (Annex H).

2.3 Results

2.3.1 Soil initial conditions

Representative cropping sequences of each location were used to provide initial values of stable C and mineral N pools. In terms of mineral N pools, the SMSM cropping sequence (predominant of 2nd maize season), represented the greatest availability of mineral N in the upper layer (0-20 cm). MFMF presented similar values to SMSM, although the former may not truly represent the majority of production systems of those locations. Maize production on 1st season on Mid-Western regions is becoming smaller due to the predominant soybean-maize succession on that portion of the country. The lowest mineral N availability found for WMWM was attributed to the fact that a grain grass crop represents a high demand of N, along with a high C:N in its composition, as widely reported by the literature (AITA et al., 2001; AMADO; SANTI; ACOSTA, 2003; BORTOLON et al., 2009; CERETTA et al., 2002; HEINZMANN, 1985; SILVA et al., 2006). For stable C, in all simulated scenarios, the majority of total C was found as being in OM more stable portion (50 to 90% of stable C in no-till cultivated crop systems). The different cropping sequences did not show variation in simulated stable C values, an expected result due to the high stability and long turnover rate of this fraction of OM, which has already been reported for Brazilian conditions by Leite; Mendonça and Machado (2004). Stable C presented an increase with soil depth for all locations. Simulated values of mineral N pools and stable C related to a representative cropping sequence of each region were considered satisfactory due to its proximity of literature values found in Brazilian regions with similar environmental and production system's characteristics (Annexes C and D).

2.3.2 Variability of farmers' average yields

Variability of farmers' average yields (Ya), after detrending adjustment is presented for the 1st (a) and 2nd (b) maize growing seasons (Figure 4). In an overall analysis, Ya on the 2nd season are more homogeneous (lower variability, general CV = 15%) than compared with the 1st season (general CV = 29%). But considering each scenario individually (region x season), the lowest and highest variability of Ya were both found, respectively, for 1st maize season, in GOJA (CV = 2.5%) and RSPF (CV = 25%).

In 1st season, despite higher Ya variability, its higher rainfall amount results in years with relatively high Ya values when compare to 2nd season. Rainfall also shows less variation during 1st season when compared to 2nd season (CV = 17 to 29% and CV = 20 to 40%, respectively) (Annex G). The greater rainfall homogeneity of 1st season Ya indicates that in general terms management considers average environment conditions (more nutrient intensive), although with different intensities among regions. In GOJA, PRGU and PRPA this average management is more intensified, which results in higher Ya values. In MSMJ and MTDI, the diminishing of 1st season importance is probably related to a less intense average management, resulting in lower Ya, with similar values for their Ya of 2nd season (see Annex A). For 2nd season, according to available average crop management data, farmers are more conservative in nutrient management, which is probably related to lower rainfall amount with higher variability. Other biophysical factors (e.g. solar radiation and temperature) have influence on maximum attainable yields, but water and nitrogen management are likely to have a prominent influence on the fact that in 2nd season Ya does not have high values as in the 1st seasonat the studied regions. It must be emphasized that overall soil properties and crop management should be considered as being indispensable for water and nitrogen benefits.

In Figure 5 is possible to observe the relationship between Ya and seasonal rainfall, one of the most influencing factor for yields in studied regions. The dashed lines shows linear trends fitted for Ya of each region in each season. A positive correlation between variables, despite the large dispersion of data, can be observed for almost all regions. Lowest correlation (Pearson's coefficient) were found for RSPF (-0.27) and MSMJ (-0.35) on 1st and 2nd seasons; while highest correlation were found for PRGU (0.30) and MTDI (0.30) on 1st and 2nd seasons, respectively.

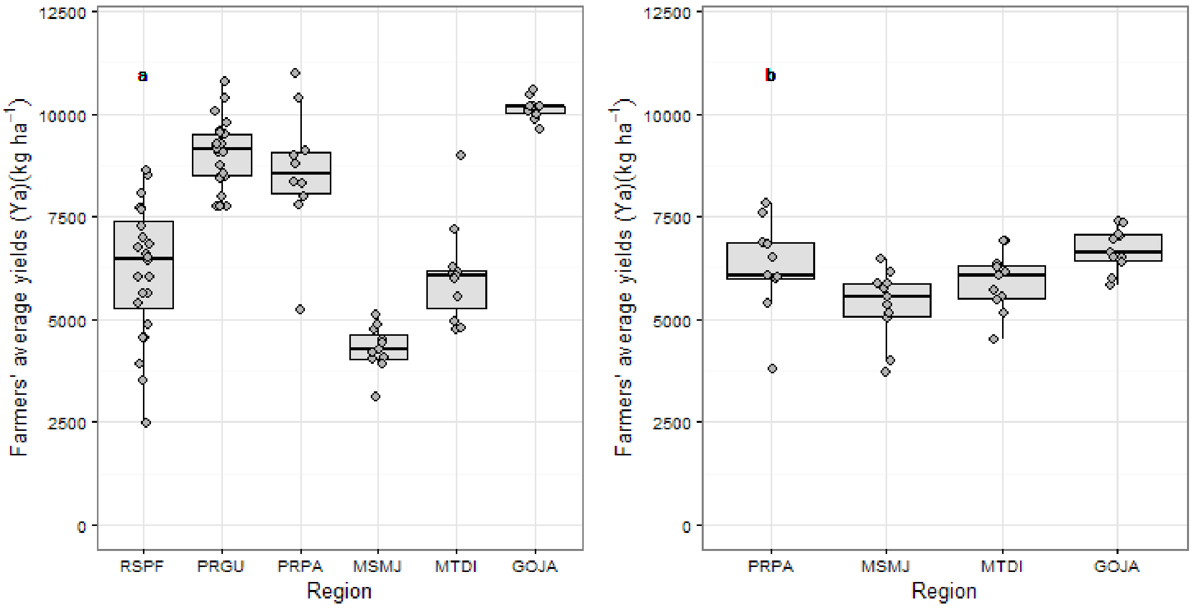

Figure 4–Variation of adjusted historical average yields (Ya) for 1st (a) and 2nd (b) maize seasonsin the studiedregions.

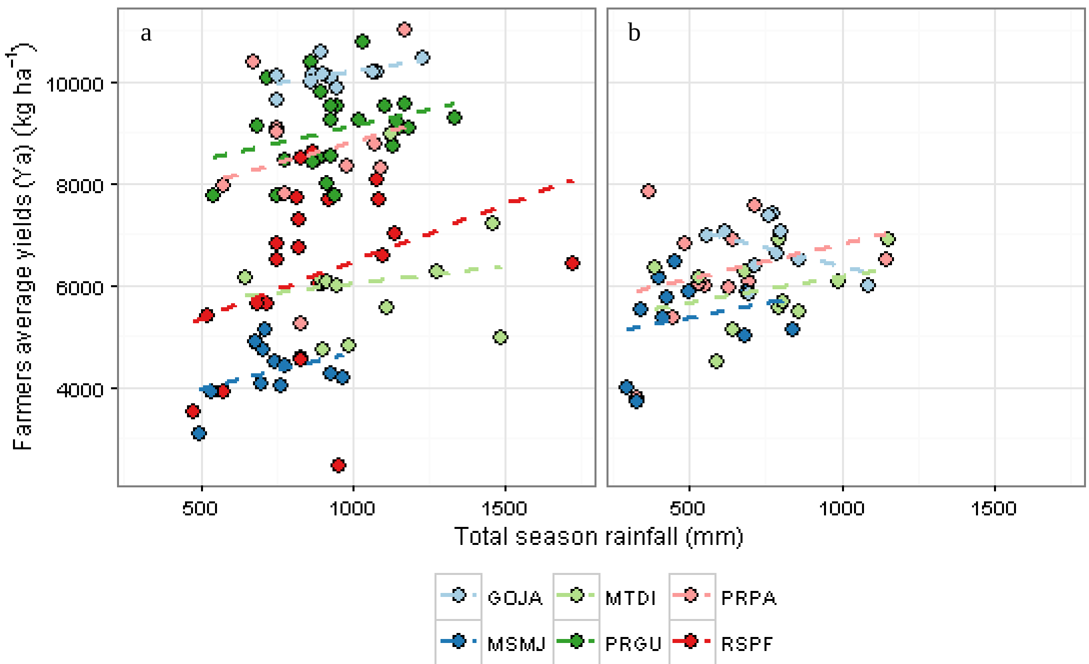

Figure 5 - Relationship between total seasonal rainfall and farmers' average yields (Ya) for 1st season (a) and 2nd season (b). The total seasonalrainfallrefers to the specific years with Ya data and considering the sowing window used in the present study (Annex A).

The dispersion of these datasuggests that other factors, considerably related to crop management (e.g., crop fertilization, protection, sowing dates), other climate variables and also factors related to highly variable rainfall distribution patterns present influence on famers' average yields variability. Thus, on these regions with lowest correlation other climate variables and average crop management may be influencing Ya in a more strong manner. As Ya refers to all farmers of each region, with different sowing dates, an average sowing date was adopted (Annex A), which could cause variation in effectiveness of reported seasonal rainfall. Also, spatial variability of rainfall between the weather stations used and farm region could represent another source of variability for yield estimation.

2.3.3 Model calibration and evaluation

The calibration and validation of the model was performed by using 2-4 seasons of hybrid trials data (Annex E). Primarily, for each specific region, trials considered more accurate (i.e., with yields higher than the Ya) were chosen. The classification between which trials were used for calibration or validation was random. Regions had two, three or four sets (seasons) of data. If the region had three or four seasons of trials, two of them were used for model validation. After the calibration and validation, simulated yields were also compared with the Ya time series to identify the concomitant presence of peaks and declines of farmer's average yields (Appendix A), since their presence was considered to a satisfactory indicator of the sensibility of the model to simulate yields in the specific environment. The overall model performance indicated by closeness to the 1:1 line (red line) (Figure 6), for hybrid trials covering all regions and seasons, was satisfactory. A linear model was fit for each process (calibration and validation) for all regions presenting a coefficient of determination (R^2) of 0.88 and 0.92, respectively. The model was able to distinguish different yield levels, according to the region and growing season, to climate conditions when compared to Ya data set (Appendix A). Simulated yields were slightly higher than the trials; which were probably caused by reducing factors, such as pests, diseases, weeds and even non-optimal nutrition, which are not considered by the crop model (KASSIE et al., 2014).

Model evaluation was also performed by indicators, such as the absolute differences between observed and simulated yields, is presented in Annex J. The agreement between estimated and observed yields was considered satisfactory, even considering the uncertainties associated with the hybrid trials data (e.g. one single harvest date for all hybrids of the same cycle length). Dates of anthesis presented a maximum deviation of 9 days, with an average of 4 days for all simulations. Dates of maturity presented a higher deviation (average of 16 days) probably due to uncertainties of considering the harvest date of the crop as the maturity date given by the model.

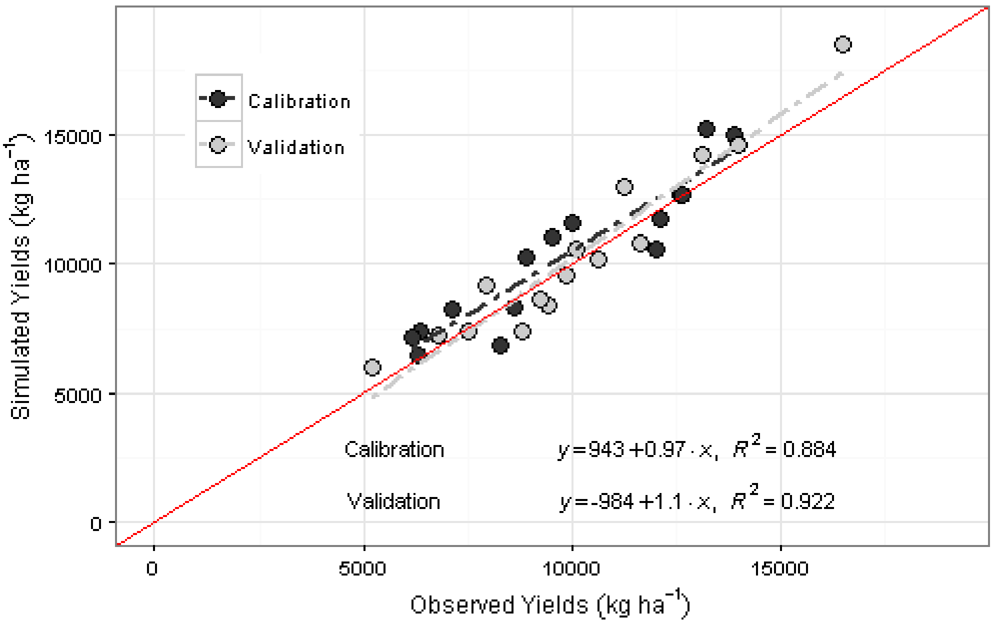

Figure 6 -Relationship between observed and simulated maize yields duringthe calibration (a) and validation (b) processes.

For some utilized trials, sowing/harvest dates were not available, thus average phenology dates for each region were adopted. Yield deviation presented a maximum of 2 t ha^{-1} (representing around 15% of difference for absolute values), which was considered acceptable. Presentation of absolute yield differences is due to the fact that given the small dataset, only the use of statistical parameters such as RMSE and MAE would not represent a robust measurement (CHAI; DRAXLER, 2014). RMSE and MAE of grain yield, days for anthesis and days for maturity (harvest) are presented in Annex J.

2.3.4 Potential yield, water-limited yield, yield gaps and climate-crop yield relationship

Figure 7 and 8 and Tables 2 and 3 shows results of Yp, Yw and yield gaps. Although results were calculated for two predominant soil types, in Figures 7 and 8, and Tables 2 and 3, data refer only to the most predominant soil type in each region, as the results were very similar for both soil types. The only exception to that was MTDI, wherein the most predominant profile is a sandyloam and the second most predominant one is mainly clayey.

Yp was higher (by statistically significant contrasts) and with lower interannual variability than Yw (Figure 7, Table 2, see Annex H for statistic comparison). First season's Yp was higher and less variable when compared to 2nd season for all regions. On 1st season, PRPA, the region with the highest average Yp presented contrasts without statistic difference only when compared to PRGU. In MTDI, with the lowest average Yp, it presented contrasts with statistic differences when compared to all other locations. On 2nd season, MTDI, the highest average Yp, presented constrasts with statistic difference compared to all other locations.

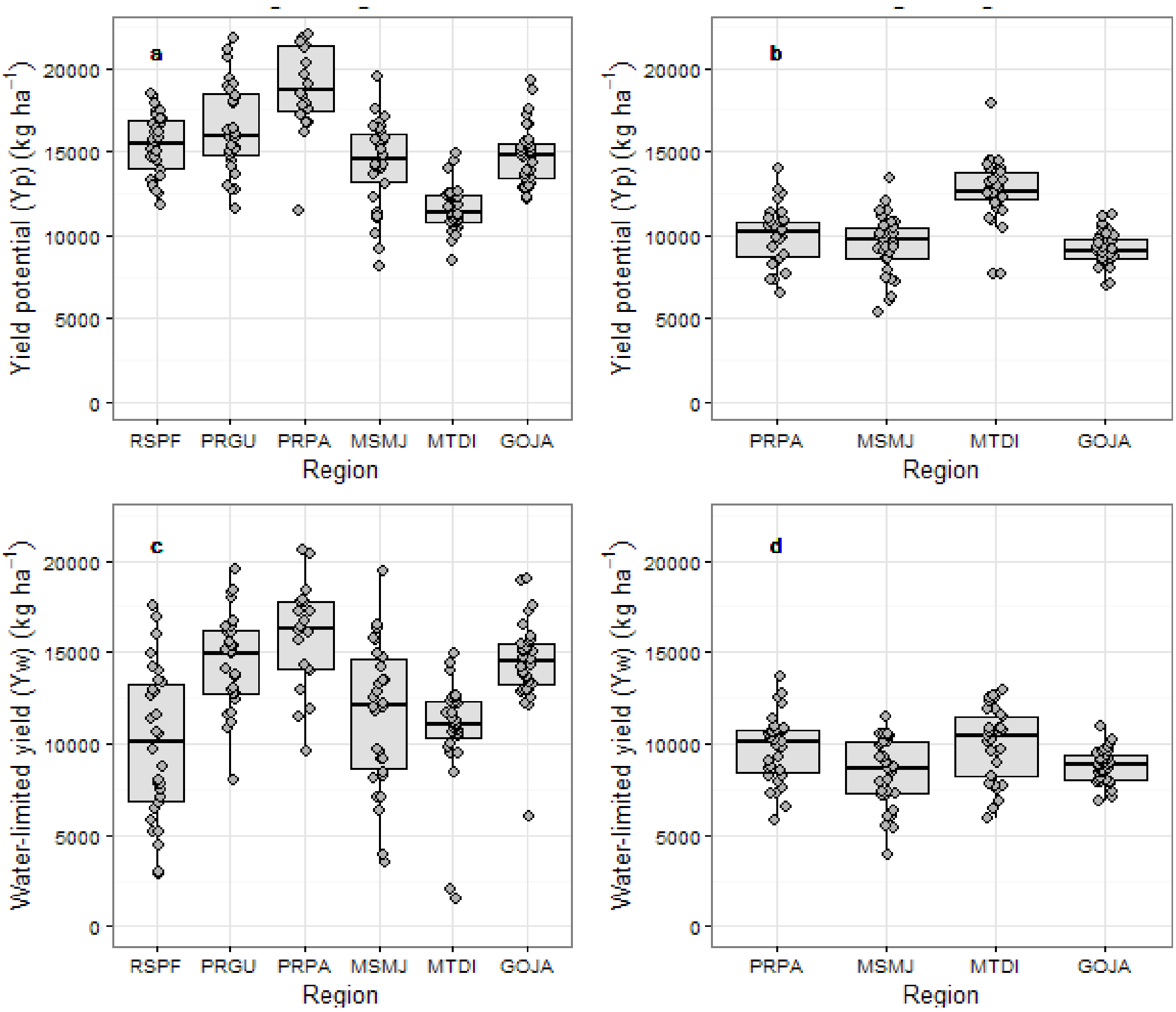

Figure 7 - Variability of simulated potential yield, Yp (a,b) and water-limited yield ,Yw, (c,d) (1983-2013). Paired plots (a,b; c,d) refer to 1st and 2nd maize growing seasons, respectively, considering the predominant soil type for each region.

Table 2 – Basic statistical description of simulated potential yield (Yp) and water-limited yield (Yw) (1983-2013); and observed average yield (Ya) (1990-2013) for each studied region.

Region	Season	-----------Yp-------------			------------Yw----------			-------------Ya-----------		
		Mean	SD	CV	Mean	SD	CV	Mean	SD	CV
		(t ha^{-1})		(%)	(t ha^{-1})		(%)	(t ha^{-1})		(%)
RSPF	1	13.3	1.1	8.8	10.8	2.7	25.2	6.2	1.6	24.9
PRGU	1	16.8	3.0	18.1	15.6	3.0	19.2	9.0	0.8	8.8
PRPA	1	21.0	3.4	16.3	18.6	4.2	22.6	8.5	1.5	17.7
PRPA	2	10.2	1.7	16.9	9.9	2.0	20.1	6.2	1.1	17.1
MSMJ	1	14.3	2.7	18.9	12.5	3.6	29.1	4.3	0.5	12.4
MSMJ	2	8.6	1.6	19.3	7.7	1.9	24.8	5.3	0.8	15.6
MTDI	1	11.4	1.4	12.3	10.7	2.8	26.0	6.1	1.2	20.4
MTDI	2	10.9	1.4	13.4	7.9	1.4	17.9	5.9	0.7	12.5
GOJA	1	14.7	1.7	12.1	14.4	2.2	15.1	10.1	0.3	2.5
GOJA	2	8.3	0.9	10.9	8.1	0.8	10.3	6.7	0.5	7.8
Mean	1	15.3	2.2	14.4	13.8	3.1	22.9	7.4	1.0	14.5
	2	9.5	1.4	15.1	8.4	1.5	18.3	6.0	0.8	13.3

Yield gaps were analyzed in terms of its absolute values and the participation of each yield gap on total (Table 3) and in terms of its relative values, associated with its reference yield level (Figure 8).

Table 3–Partitioning of water deficit and crop management maize yield gaps on total yield gap for 1st and 2nd seasons in different regions in Brazil.

Region	Season	CYg (t ha^{-1})			MYg (t ha^{-1})			CYg/TYg	Yg/TYg
		Mean	SD	CV (%)	Mean	SD	CV (%)		
RSPF	1	4.9	4.3	0.9	4.6	3.2	0.7	0.51	0.49
PRGU	1	1.4	2.0	1.4	6.0	3.1	0.5	0.19	0.81
PRPA	1	3.0	2.7	0.9	7.9	4.6	0.6	0.28	0.72
PRPA	2	0.4	0.8	2.1	3.8	2.0	0.5	0.09	0.91
MSMJ	1	3.3	4.3	1.3	5.7	3.6	0.6	0.37	0.63
MSMJ	2	1.5	2.0	1.3	3.5	1.5	0.4	0.30	0.70
MTDI	1	0.2	0.3	1.7	5.6	1.6	0.3	0.03	0.97
MTDI	2	2.6	1.9	0.8	3.5	1.9	0.5	0.42	0.58
GOJA	1	0.3	0.5	1.8	4.5	2.1	0.5	0.06	0.94
GOJA	2	0.4	0.4	0.9	2.0	0.8	0.4	0.18	0.82
Mean	1	2.2	2.3	1.3	5.7	3.0	0.5	0.2	0.8
	2	1.2	1.3	1.3	3.2	1.5	0.5	0.2	0.8

(Obs: CYg = Yp – Yw; MYg = Yw – Ya.)

In terms of gap caused by management, MYg, its average in absolute values varied between 4.5 (GOJA) and 7.9 t ha^{-1} (PRPA) for the 1st season, and between 2.0 (GOJA) and 3.8 t ha^{-1} (PRPA) for the 2nd season. The average MYg of all regions per season was higher on

1^{st} season, indicating more opportunities for yield absolute increases. MYg represented the major share of TYg, pointing its relative higher importance than gap caused by water deficit (participation greater than 50% of TYg) was stated for almost all scenarios except in RSPF (1^{st} season).

The gap caused by water deficit (CYg) varied between 0.2 t ha^{-1} (MTDI) and 4.9 t ha^{-1} (RSPF) for the 1^{st} season; and between 0.4 t ha^{-1} (GOJA, PRPA) and 2.6 t ha^{-1}(MTDI) for the 2^{nd} season. This gap achieved a maximum of 51% (RSPF) and 42% (MTDI) of TYg for 1^{st} and 2^{nd} growing seasons, respectively. The CYg was also relevant in MSMJ and MTDI (1^{st} and 2^{nd} growing seasons, respectively) with participation >30% of TYg.

In general terms, yield gap due to water deficit was higher on the regions evaluated for 1^{st} maize growing season, since Yp and Yw can achieve higher threshold values than on 2^{nd} growing season. Variability of MYg was higher than CYg, on both growing seasons (higher CV). The differences on absolute values are directly related both to the magnitude of Yw and/or efficiency of average management. The former was more intense in the Southern regions (PRGU, PRPA), while the latter was more pronounced in MSMJ (1^{st} season). Both conditions indicate the existence of more opportunities for management improvements.

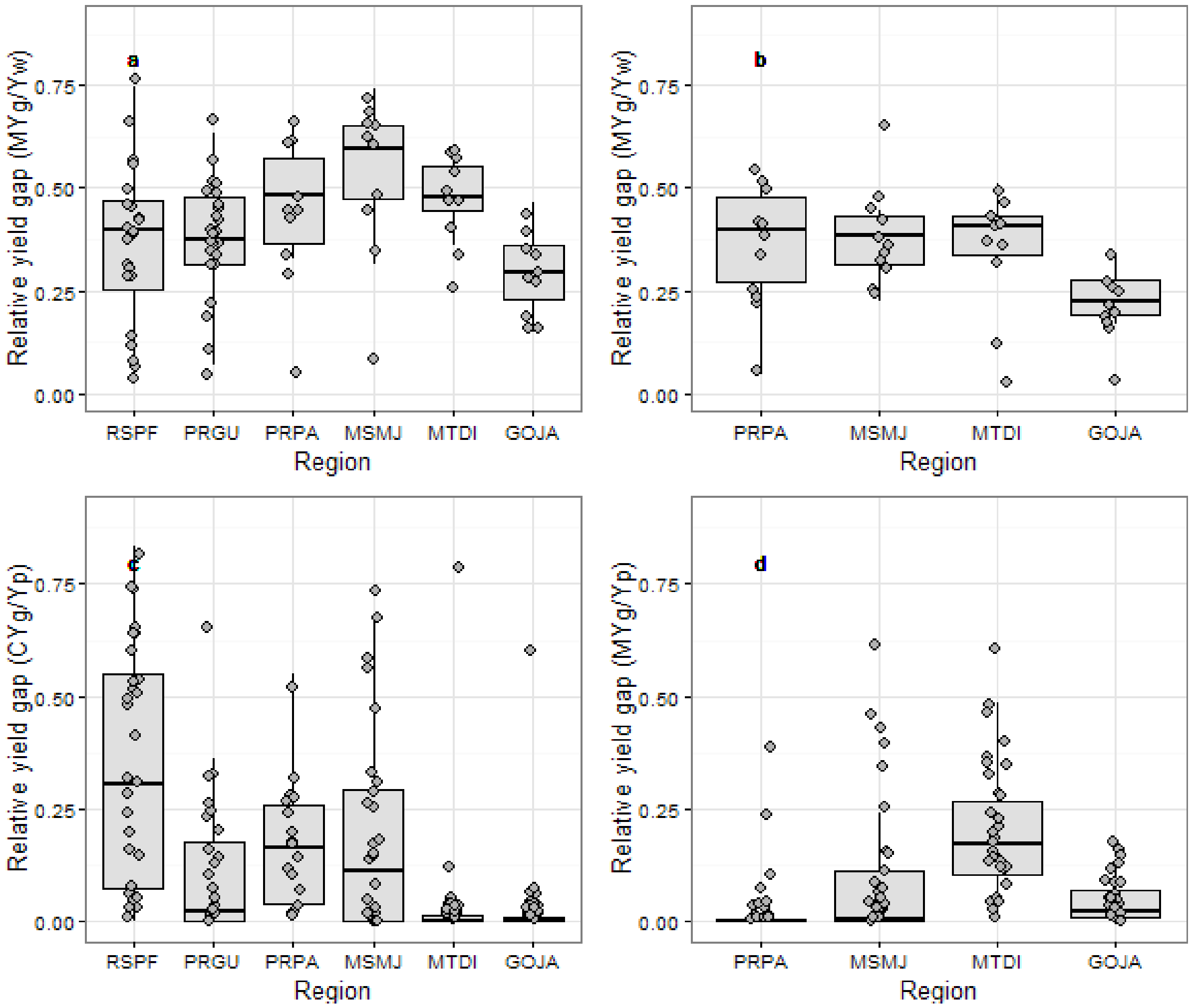

Figure 8 - Variability of relative management (a,b) and water-related yield gaps (c,d) of the studied regions. Relative yield gaps refer to its specific yield reference level (Yw for MYg and Yp for CYg). Paired plots (a,b; c,d) refer to 1st and 2nd maize growing seasons, respectively, considering the predominant soil type for each region.

When analyzing statistical parameters, it is possible to infer about the homogeneity of yield gaps existence. RSPF, besides having the highest CYg on 1st season, it has also the lowest variability (CV), thus indicating that its existence is more likely to take place across years. On 2nd growing season, the highest and least variable CYg was found for MTDI.

In terms of relative yield gap related to crop management (Figure 8a and b), the highest and the lowest values were found for the scenarios (regions and seasons) in which Ya and average crop management were less intensive (MSMJ) and where Ya and crop management were more intensive (GOJA, both growing seasons), respectively. In RSPF MYg/Yw were more variable probably influenced by climate variability, while relative high values of PRGU and PRPA are due to those regions’ highest Yw levels. On 2nd season, variability of values is lower than on 1st season, with highest and lowest average values found for MTDI and GOJA, respectively.

As for relative yield gap due to water deficit, on 1st season RSPF presented the highest average and the highest variability of results. This region, along with MSMJ also presented one of the highest seasonal rainfall variability and correlation with simulated yields (Annex G). Regions with the lowest average relative CYg also represented the lowest seasonal rainfall variability. On 2nd season this indicator also presented influence from rainfall variability, being higher for Mid-Western regions.

Results from Annex G help in understanding the importance of the required climate variables for performing the simulated crop yields. Simulated yields were used for the correlation analysis since the observed yields (Ya) may contain a lot of uncertainties related to average crop management, making it difficult to observe the climate effect on each region and cultivation season. Also, the availability of years of data from simulated yields is higher.It is clear that although not always presenting stronger correlation (coefficient >= 0.5), correlation with seasonal rainfall and minimum temperature were generally the most important among climatic variables.

2.4. Discussion

2.4.1 Soil initial conditions

The approach was considered useful to characterize each location in terms of C and N initial conditions by means of interaction of its environment and average management conditions. It is emphasized that the approach was based on average management information, due to difficulty in obtaining detailed and long-data history information of crop management, and especially attributing these to a whole municipality area. Thus, further detailing of field history should be considered for a site-specific analysis. As for the model used in the approach, CENTURY, its use in Brazilian conditions has been increasingly spread in the past years (BORTOLON et al., 2009; CERRI et al., 2007; LEITE; MENDONÇA; MACHADO, 2004; NASCIMENTO et al., 2011) and is considered a useful tool for organic matter modeling, especially related to C and N balances. In terms of mineral N, Bortolon et al. (2009) observed that CENTURY model predicted well the tendency of N fixation and fertilization in the N dynamics, despite the high variability of mineral N, strongly influenced by management and meteorological conditions (within and among years). The approach used in this study was able to show differences in N availability between cropping systems, such as the expected tendency of higher N availability in systems with legume succession (typical of

2^{nd} maize growing season systems)and lower with winter grains succession (typical of cooler climate in Southern Brazil). The mineral N results should be analyzed with caution, since they are highly variable in the soil, affected directly by soil temperature andmoisture, tillage, fertilization and residual C:N. Obtained mineral N pools were within the most frequent range of values found in literature for similar conditions (Annex D).The first day of maize sowing date was considered to obtain those optimized N and C pools, so we emphasize that few days of difference may represent high variability on mineral N pools. In terms of stable C, the estimated values did not change between the simulated scenarios of cropping systems, as expected due to the high stability of this organic matter fraction (as well as the duration of simulations). Stable C's results were also similar to those found for similar Brazilian conditions of literature references (Annex C), where it represents a large share of soil OM (AnnexD). This high share of stable C in soil organic carbon is reported and attributed to the clayey and oxidic composition of several Brazilian soils (FERNANDES, 2002; LEITE; MENDONÇA; MACHADO, 2004; NUNES et al., 2011).

2.4.2 Farmer's average yields

In general, farmers' average yields in the 1^{st} season arehigher than in the 2^{nd}growing season, which is mainly attributed to the higher and better distribution of rainfall during the months of November to January, despite 1^{st} growing season's interanual variability of rainfall levels. Historical rainfall variability is pointed as an influence on crop management (KASSIE et al., 2014). In the regions where maize is cultivated in both growing seasons, N topdress application (predominantly via urea) are lower in the 2^{nd}season when compared to 1^{st}season (20% less than 1^{st} season fertilization according to FNP CONSULTORIA & COMÉRCIO (2015). Among studied regions, GOJA (1^{st} season) has higher N consumption compared to other regions, due to ammonium sulfate application, in addition to topdress urea application (FNP CONSULTORIA & COMÉRCIO, 2015). This more intense nutrient use as one of the management responses to climate conditions (high average seasonal rainfall) that resulted in the highest farmers' average yields at GOJA among studied regions.Discussion of Ya constraints was performed using as reference the average nutrient management from a national database, although the reader is referred to the probable variability of values, especially when considering one single production system.

2.4.3 Model calibration and evaluation

The use of hybrid trial yields (Ybf) was considered sufficient for model calibration. When the model was validated with independent data, the errors (absolute deviation) were below 15%, which is acceptable for studies of yield determination influenced by climate variability. The yield data used for calibration (Yw) represents an optimum management, thus it was related to above-average management of trials. The model does not consider any biotic stress, such as pests and diseases, which may occur in the hybrid trials. Thus, these constraints and all possible available information on crop development should be considered when using experimental data for calibrating the model. In this study, most simulated yields for calibration and validation were slightly higher than Ybf, indicating the differences between simulated and experimental yields. It is emphasized that more specific data on physiological maturity of cultivars instead of harvest date could provide more accurate results. The use of actual yields for estimating Yw and/or Yp is a common practice, and has been performed by many authors (ERNST et al., 2016; HALL et al., 2013; LOBELL; CASSMAN; FIELD, 2009; VAN ITTERSUM et al., 2013). The use of publicly available data is also acknowledged (GRASSINI et al., 2015), as it is related to dissemination of the proposed assessment method. However, it must be emphasized that a greater availability of trial data, comprising spatial variability within regions, would decrease the level of uncertainties on model calibration and evaluation (HALL et al., 2013).

Justino et al. (2013) calibrated CERES-Maize model for the 1st season under Brazilian conditions. These authors used one year of experimental data for calibration and another for validation, also focusing on dates of anthesis and maturity and grain yields. They found small absolute differences between simulated and observed yields (0.1 to 0.4 t ha^{-1}) over experiments. Experiments performed within one region (county in Mato Grosso state) were utilized for calibration, and later experiments were simulated for several regions across Mato Grosso and Pará state. Soler et al. (2007) calibrated and evaluated CERES-Maize model also with two years of experimental data: one year with irrigated and other with irrigated and rainfed treatments. The authors used several pieces of information for calibrating and validating the model, such as dates for emergence, anthesis, maturity, yield and yield components. They studied four cultivars for 2nd maize season in the state of São Paulo. Model performance was considered accurate, with a maximum of 11% deviation in grain yields.

Regarding the model genetic coefficients (Annex F), its comparison with other studies is a difficult task, since they may vary with the region and environmental conditions. Soler, Sentelhas and Hoogenboom(2007), for example, found the lowest (196) and highest (263) P1 value for a very early season and for a normal season maize hybrid, respectively, in Southeastern Brazil. Justino et al. (2013) found a higher value of P1 (319) for an early season cultivar on 2nd maize season for Central Brazil. Thus, in the present study it was performed one calibration per location and season.

2.4.4 Yield reference levels, yield gaps and climate-crop yield relationship

Simulated Yp showed lower variability than Yw (AFFHOLDER et al., 2003; LOBELL; CASSMAN; FIELD, 2009; VAN ITTERSUM et al., 2013), indicating that the water deficitis the main factor responsible for Yw interannual variability (average CV% of Yp was similar to both growing seasons). For the 1st growing season, rainfall variability ranged considerably (higher in RSPF and lower in GOJA) although it was even more accentuated for 2nd maize season (higher on MTDI and lower in GOJA and PRPA). Small differences betweenYp and Yw (i.e., lowCYg) are an indication of low occurrence of water constraints (AFFHOLDER et al., 2013; KASSIE et al., 2014).

In regions with these conditions, managing yield gap depends less on climate variability than other regions. RSPF was the regions wherein water deficit presented greater importance in yield gap management (considering the absolute participation on TYg), an indication for irrigation use as a management measure to alleviate gaps due to water deficit. Water deficit and climate variability were already pointed as key risk factors in rainfed maize in Rio Grande do Sul state (BERGAMASCHI et al., 2006); and in Mid-Western Brazil due to a markedly drier period in 2ndgrowing season (MSMJ both growing seasons and MTDI on 2nd season presented >=30% of CYg/TYg) (see Figure 2). A similar climate condition (marked drier period) is also found inGOJA, however sowing window of GOJA was simulated to start two weeks earlier, which could have mitigated a posterior water stress. Lower CYg for 2nd maize season when compared to 1st season (except for GOJA and MTDI), is not an indication of greater water availability, since it should be related to lower Yp levels (due to solar radiation, air temperature, photoperiod) and lower Yw levels (due to lower rainfall levels). In contrast, higher CYg indicates greater losses caused by water stress under rainfed systems and, consequently, more opportunities for yield increase if irrigation and other management options were used.

Correlation between climate variables and yields is a useful tool to help the understanding of local constrainst to cropping systems. Correlation with seasonal rainfall was generally higher for all scenarios than for other climatic variables, showing the importance of water supply to crop development. For some scenarios the correlation with minimum temperature was also statistically significant. Average correlation (all region and seasons) of yields and seasonal rainfall was of 0.37, considered a weak to moderate correlation. Poudel and Shaw (2016) found more strong correlation of climate variables and yields of wheat and millet than on maize and rice yields on a mountainous region, with variable climate and high water availability (> 2500 mm year^{-1}). The authors found that climate variables (rainfall and temperature) accounted for about 35% of maize yield changes, while the rest was attributed to management options.

Local yield gaps should be evaluated with as much information as possible on local production characteristics. Absolute yield gap values may present a misguided idea that higher absolute YG values, for example, are related to poor management and low average yields (as found for PRGU, PRPA on 1st season). Southern regions had the highest MYg, not due to its Ya levels, but mainly related to their relative high yield potentials (Yp, Yw). Thus, analyzing indicators as relative yield gaps and yield reference levels represent a help in this process. MSMJ had the largest share of its Yw as being MYg. Along with local Ya and management information, is possible to conclude that in this region MYg has a great importance. Absolute MYg was higher in 1st season, as a result of its general higher Yw values. GOJA presented lowest yield gaps, in both seasons; indication of its Ya being closer from Yw than other regions. Concerning this regions' MYg (4.5 t ha^{-1}) on 1st season; it is worth noting that this lowest value is higher than the highest MYg found in 2nd season, of 3.8 t ha^{-1} for PRPA. Thus, these indicators can be useful in completing the understanding on local production profile and yield gaps, indicating more proportional information for comparison purposes.

Assessed regions have, in general, more management than climate constraints acting on local maize yield gaps, as presented in Table 3 (higher absolute values and total share of MYg) a result also statedby Affholder et al. (2013) when analyzing maize yield gaps also in Brazil. Yield gaps related to crop management represented the major share of the total gap for almost all regions, showing that there are several opportunities to improve maize yield in Brazil, mainly through more intense crop management more aligned with climate conditions. The Global Yield Gap Atlas (GYGA, 2015) found similar shares of MYg and CYg for its assessed regions; however regions with very pronounced water deficit (several regions with Yw varying from 2-8 t ha^{-1}) were probably responsible for these results. The higher variability of MYg also indicates the importance of management strategies in trying to mitigate its impacts on average yields.The partitioning of total yield gap should be analyzed as an aid in understanding the allocation of major effort to reduce crop yield gaps, i.e., mitigation of climate variability and average crop management.

Yield gaps may be used for comparison and directing management strategies. Regions with larger MYg values may be considered to have more opportunities for management improvement and regions with larger CYg values may be considered to have more difficulties to implement this management due to more intense water deficit. PRPA, PRGU and MSMJ all presented MYg > 5 t ha^{-1}, which may not be due to similar conditions, indicating more opportunities for improvement in crop management among all studied regions. However, the highest and the lowest facility of management from these regions were found for PRGU and MSMJ, respectively (lowest and highest absolute CYg). In contrast, in GOJA (both growing seasons), it was found the relative lowest opportunities for management improvements, although climate conditions favor management. Regarding climate (water deficit) conditions, the greater difficulties were found in RSPF and MTDI (1^{st} and 2^{nd} season, respectively). However, the homogeneity with which this happens should also be taken into consideration (i.e., absolute CYg value does not indicate if this is an occurrence more or less variable across years). GOJA (1^{st} and 2^{nd} season) and PRPA (2^{nd} season) presented the lowest difficulties of crop management due to water deficit.

Southern regions (PRGU, PRPA) had the highest attainable yields in the present study. The regions had years with very high Yp and Yw (approximately 20 t ha^{-1}), which contributed to the highest averages of yield reference levels, and consequently high MYg absolute values. This could explain the more frequent existence of contest winning yields in Paraná state (Southern Brazil), where average yields above 20 t ha^{-1} in relatively small properties (when compared to Mid-Western Brazil) have been reached (AGROINDUSTRIAL COOPERATIVE -COAMO, 2008) in the past years. Such high maize yields in Brazil are usually achieved in 1^{st} growing season, although on 2^{nd} growing season higher average yields each year have been reported in Brazil’s Mid-Western. Thus, it is emphasized that all regions could benefit from a more intensive average crop management, considering climate variability, to aid closing the gaps.

The low water limitation for maize yields (in 1^{st} growing season) through a yield gap study in Goiás state was already stated by Affholder et al. (2013). This region (in the present study represented by GOJA) presents a more intense nutrient application for 1^{st} maize season when compared to other regions. Thus, its highest Ya (10 t ha^{-1}) is a result of these conditions, which support the conclusion that in this region farmers are already adopting crop management near the optimum. For the 2nd season, GOJA also had the lowest MYg, which was almost half lower as other regions. This can be attributed to better rainfall amount and its distribution at the beginning of the crop 2nd growing season, as the average sowing date for the 2nd season in GOJA usually starts in January (BRASIL, 2014). The Ya in this region (on 2nd season) varied from 5 to 7 t ha^{-1} for the period 2003-2013. Such conditions allows one to conclude that farmers in GOJA have been growing maize with a better alignment between climate conditions and crop management when compared with other studied regions.

Reliability of Yg estimates depends directly on Yw estimates (KASSIE et al., 2014; LOBELL; CASSMAN; FIELD, 2009; TITTONELL; GILLER, 2013) and a minimum of ten years of data is required fora more accurate Yg determination (KASSIE et al., 2014). This number of years could increase if dealing with environments with high rainfall variability. Determining Yg of such environments could lead to lower accuracy if based on few years of Ya data (e.g. only years with rainfall above or below average values). Regions with relative high MYg variability usually also have high Yw variability. In these cases, crop management more adapted to climate variability is fundamental for improving yields during more favorable years. That adapted crop management may include a precise weather forecast for guiding decisions related to fertilization, crop protection and timeliness of mechanized operations.

Commonly, social-economic factors can also be contributorsto Yg management, such as cost of inputs, credit services and access to information by the farmers. Tittonel and Giller (2013), in a study assessing main causes and consequences of African smallholder agriculture, alerted to the fact that for such conditions, the simple statement of lack of knowledge by part of farmers is insufficient for defining the magnitude and difficulty of managing Yg. Lacks of investments, which can be tied with lack of access to technology required for profits and consequently with the rise of soil degradation, are important issues when evaluatingYg management. Thus, considering soil variability, a detailed analysis of study regions could provide valuable information on nutrient availability and site-specific Yg management.

Lobell, Cassman and Field (2009), through literature survey, reported a typical range of 0.2 to 0.8 for Ya/Yw found for main worldwide cropping systems (wheat, rice and maize), both rainfed and irrigated. Specifically for maize, the values ranged from 0.16 (sub-Saharan Africa) to 0.56 (USA). The authors argued that values above 0.70 are common in wheat and rice but not in maize systems, although for maize the scale of their study (country, continent) is larger than that of the present study (county). In the present study, average Ya/Yw varied from 0.34 (MSMJ) to 0.70 (GOJA) for the 1st season, and from 0.62 (PRPA) to 0.83 (GOJA) for 2^{nd} season. These values indicate how much of maximum attainable yields are being represented by farmers' average yields. In both seasons, GOJA illustrated Ya/Yw equal or above 0.70 on both growing seasons, and MTDI on 2^{nd} growing season (0.75). These results also indicate that the average yields in GOJA (both seasons) and MTDI (2^{nd}) season are close or have already reached a plateau and will most likely stay near those levels in the upcoming years. Lobell, Cassman and Field (2009) indicated a plateau when yields reach 70-80% of potential yield in rainfed systems.

Maximum attainable yields (Yp, Yw) are not likely to change rapidly, since main drivers of average yields at national scales depend on crop genetic improvements (conventional breeding and genetic engineering) and crop management, as also on social, economic and environmental issues (GRASSINI; ESKRIDGE; CASSMAN, 2013). By using past yield trends of staple crops (wheat, maize and rice) starting at the Green Revolution and statistical analysis, the latter authors identify that the rate of increase in cereal crop yields is generally linear. However, the existence of yield plateaus in several countries was pointed out. These plateaus are identified with the availability of 4-18 years of "flat" Ya data, necessary to show significance. They can be associated with the condition of proximity of biophysical limits (regions with better socio-economic conditions) or very low levels (regions with deficient socio-economic conditions, such as maize in Africa). The authors also point that, specifically for Brazilian Cerrado, maize yields experienced a rapid increase after 1990. However, even within this context, they point that relative rates of maize yield gains started to decline.

Few studies have assessed maize yield gap in Brazil. Affholder et al. (2013) assessed rainfed maize yield gap in one region (municipality) in Goiás state through field surveys and modeling. The authors found MYg of 3.7 t ha^{-1} and Ya/Yw of 0.56, slightly lower than the overall average found for the present study. It is argued that if the highlighted study was performed with more actual data, results from Affholder et al. (2013) could be higher, since it was performed with 1994-1997 data, in a transition from low to higher technology farms.

The Global Yield Gap Atlas (GYGA, 2015) estimated rainfed maize yield gaps, also by using simulation approaches and IBGE as source of Ya data, for several Brazilian regions (25 counties). Within each region, up to seven weather stations were used for simulating yield reference levels. They used approximately fifteen years of estimated Yp and Yw, and five years of Ya data for yield gaps determination. The overall average (all counties) of Yp; Yw and Ya were 12.5; 8.4 and 4.4 t ha^{-1}, respectively. Average MYg and TYg were 4.0 and 8.1 t ha^{-1}, respectively. Results are similar to those of the present study, where average MYg and

TYg were 5.7 and 7.9 for 1st season and 3.2 and 4.4 for 2nd growing season, respectively. GYGA's assessed regions comprised counties from Southern to Mid-Western Brazil, with marked differences in climatic conditions (Yp: 9.0-14.0 t ha^{-1}; Yw: 2.5-12.0 t ha^{-1}). The GYGA's MYg was also fairly variable: 0.8-6.0 t ha^{-1}, and TYg varied from 5.5-12.5 t ha^{-1}. Their average water-related yield gap (CYg) was 4.1 t ha^{-1}, higher than the present study, however it comprised locations with very low Yw and Ya (e.g., 5 and 2 t ha^{-1}), which contributed to CYg higher average. Except for the regions with extreme weather limitation (i.e., Yw <= 5 t ha^{-1}), MYg was also the major portion of rainfed maize yield gap found on GYGA's analysis, emphasizing the importance of intensifying and aligning maize management with climate conditions in Brazil.

Using an approach of economics, Rada (2013) evaluated the growth relative to the potential of agricultural production of farm commodities in Cerrado biome (the latter represented by three regions of the present study: MSMJ, MTDI and GOJA). The authors found a significant gap between the most efficient farms and average farms, which in summary indicates that average farmers can increase their crop yields if investments in technology and management practices were performed in an efficient manner. They also highlighted the intensive demand of agricultural inputs as indispensable for managing Cerrado's potential for food production. With this study, it is argued that although in general terms agricultural production in Cerrado still presents a large gap of efficiency on production, specific regions (even in average terms) are already near maize attainable yields, as in GOJA, which could also be found for other main crops.

2.4.5 Strategies for reducing yield gaps

Although on the present study the use of N management was considered as a strategy for analyzing maize yield gap management (see part II of this study), in this section the main implications of its management are discussed. Despite the unquestionable importance of N on the increase of maize yields in Brazil, a brief discussion on other factors that may contribute to the overall system's performance was considered necessary. It was clear in the present study that the overall major issue for reducing yield gap is related to average crop management. The absolute values of MYg varied widely, indicating more regions with average crop management limitations and fewer sites aligned with climate variability. The alignment of crop management with climate variability shows challenges for both growing seasons. In1st season, rainfall levels can be relatively very high (>1000 mm) consequently causing high Yw; or low rainfall levels (300-400 mm), contributing to a low Yw. On such opposite situations, a single management strategy regardind nutrient management can result on very high or low MYg. In 2nd season, even with lower absolute values of seasonal rainfall, its interannual variability is more accentuated than in 1st season (CV of 20-28% in 1st season and of 18-39% in 2nd season), also representing difficulties in achieving yield levels close to Yw. Low soil fertility and acidity, soil erosion, water deficit, stunt and fall armyworm are pointed as the most important factors responsible for maize yield gaps in tropical and subtropical environments on South America (PINGALI, 2001). In this section, average crop management to reduce yield gaps is considered here as being mainly related to soil management, sowing date, irrigation and crop protection.

Proper soil management comprises various measures for improving physical and bio-chemical soil properties for its sustainable use on agriculture (i.e., related to crop's water and nutrient availability and accessibility in the profile) (TROEH; THOMPSON, 2007). Management to maintain or improve overall soil properties that directly affect crop development are many-fold and refers to several areas, such as avoiding soil compaction and erosion, avoiding nutrient depletion and nutrient toxicity. Those can be achieved through measures such as mechanization planning, use of cover crops and/or crop rotation and proper nutrient management, all considering environment specificities (soil, climate, crop). As for crop nutrition, the major importance of N in maize is widely reported. Major yield improvements in maize are related to increases in N fertilization. Average N fertilization in maize is likely to be below the optimum in Brazil, in average terms, although economical constraints can seriously limit such practice. Soil fertility and crop's necessities should be fully analyzed for its proper management, including liming and fertilization practices. Maize's main nutrient requirements are related to N and K (potassium), followed by Ca (calcium), Mg (magnesium) and P (phosphorus) (COELHO; FRANÇA, 1995).

Benefits of using regionally adequate sowing dates are related to minimizing risk of water deficit for the specific crop on main soil types (sandy, medium and clayey texture) and cultivar maturity. These characteristics were comprised by a project, named Agroclimate risk zoning, annually released for several crops in most of Brazilian counties (BRASIL, 2014). Climate variables and water balance are utilized for performing the zoning considering a period of ten days. This period is considered favorable for sowing maize if in 80% of the analyzed years, the crop's water requirements are met during flowering and grain filling, the most critical phases for water deficit. For maize, which is mainly rainfed in most part of Brazil, especially in Central-Southern region of the country, proper sowing dates are fundamental for minimizing water deficit risks (and also frost risk for South Brazil), thus facilitating adequate water use by the crop, as well as water use for best fertilizer management, disease risk and mechanized operation planning.

Irrigation practice in any crop involves high initial costs, demanding a careful economical and also environmental analysis of the current farm's situation. Historical rainfall analysis is the first step in such decision. Specifically for maize, despite the relative high demand of water by the crop (400 to 700 mm), it is considered efficient in the water use (ANDRADE et al., 2006). In Brazil, specifically for Central-Southern portion of the country, irrigation is not a common practice in maize production, being more common in Northeastern Brazil or for seed production. The low climate risk (related to water deficit) of rainfed maize in major portion of Brazil's Mid-Western region for 1st growing season is acknowledged (considering average sowing dates in October) (SANS et al., 2001); however short dry spells in 1st season can occur and intensify yield gaps (ANDRADE et al., 2006). In the Southernmost region of Brazil, mainly Rio Grande do Sul state, water deficit can be an important risk factor for rainfed maize production, justifying its usage (BERGAMASCHI et al., 2006). Irrigation usage is also justified for 2nd growing season of maize, wherein the climatic risk related to water deficit is more elevated and increases with delay on sowing (earliest in January and latest in April), whereas sowing in February is associated with highest yields (CRUZ et al., 2010).

Common management options of maize (and many other) cropping systems, such as recent expansion of area, longer length of sowing dates, no-till adoption, irrigation, decreasing diversity of cropping systems (such as the predominant soybean-maize succession in great part of Brazil) and genetic material are closely related to crop sanitary health, through influence on pathogen dynamics. Specifically for maize, main losses are related to foliar diseases, stem rottenness and grain damage. Although usually not related to low average yields (such as deficient crop nutrition) adequate plant protection is indispensable for sustaining high average yields. Crop health can be mainly managed through proper sowing dates, quality and treated seeds, proper crop rotation and proper crop nutrition, which are responsible for reduction of inoculum potential and stability of genetic resistance (CASELA; FERREIRA; PINTO, 2006).

2.5 Conclusions

This study demonstrated the ability of a calibrated crop model to determine potential and water-limited yield levels and to assess the existence of yield gaps of typical rainfed maize production systems in important Brazilian producer regions. Higher seasonal rainfall with lower interannual and interseasonalvariability contributed to higher yield reference levels (Yp and Yw) for 1st maize season when compared to 2nd season.

Results indicated regions with more opportunities for management improvements than others (high MYg) wherein such management can be facilitated or not due to intensity of water deficit. In an overall analysis, Southern regions (except RSPF) presented opportunities for management improvements facilitated by climate conditions. Mid-Western regions presented more (MSMJ) or less (GOJA) opportunities for yield improvements, wherein climate restrictions were more restrictive on MSMJ (both growing seasons) and MTDI (2nd season). On RSPF climate variability can also be restrictive, thus management practices such irrigation may be considered for yield gap reduction purposes.

In addition, this study was useful to show that in general, for the assessed regions,the major portion of total maize yield gap is associated with crop management rather than water deficit in both maize growing seasons. This was considered an indication of the necessity of more intensive crop management and at the same time better aligned with climate conditions. MYg indicated, in general, more opportunities for increasing yield in the 1stgrowing season than in the second. However, Yg management on 2nd season should not be neglected, especially considering this growing season’s increasingly importancein Central Brazil. For that, a proper weather forecast should also help to make better decisions for crop management, despite lower reference yield levels. Such lower reference yields of 2nd growing season are basically due to climate constraints, such as less and more variable rainfall in Central Brazil and lower temperatures and solar radiation in Southern Brazil.

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3 MODEL-BASED APPROACH FOR MAIZE YIELD GAP ANALYSIS RELATED TO CLIMATE VARIABILITY AND NITROGEN MANAGEMENT: II - ECONOMIC AND ENERGY PROFITABILITY OF YIELDS UNDER NITROGEN FERTILIZATION

Abstract

Crop response to environment and management factors is vital in most studieson agricultural systems. However, performing analysis of many scenarios (e.g., treatments, locations) is usually not feasible due to time and money constraints. Costs related to application of nutrients on crops should be carefully assessed, due to their importance for increasing yields while determining systems returns, since they are usually high in economic cost and energy expensive. Specifically in Brazilian maize production systems, water and nitrogen deficits are the most important factors related to average low yields. This study aimed to assess the profitability, in economic and energy use terms, of the mechanized application of nitrogen (N) fertilizer on typical rainfed maize production systems in six Central-Southern Brazilian regions, in its two growing seasons, as a strategy for managing local yield gaps. A simulation approach was carried out using the crop simulation model CSM CERES-Maize, part of the *Decision Support System for Agro-Technology Transfer* (DSSAT) and the simulation of mechanized application of urea for several N rates. The crop model calibration and local rainfed maize yield gaps due to water deficit and crop management were previously determined. Results indicated that in general, more accentuated water deficit(as found for regions with 2nd growing season) and lower potential of yield response to applied N can represent higher cost of N application (R$ kg-^{1}; MJ kg^{-1}; R$ ha^{-1}; MJ ha^{-1}). In economic terms, in 1st season, the average difference among highest and lowest scenarios of cost of N application (R$ kg^{-1}; MJ kg^{-1}), was greater than 100%, while in 2nd season this average difference was 30%. In energy use terms, those values were also 100% and 20%, for 1st and 2nd season, respectively. As for returns from N application in economic terms (R$ kg^{-1}), in 1st season the average difference among best and worst scenarios was 69%, while in 2nd season was 13%. As for returns from N application in energy terms (MJ kg^{-1}), the average difference among those scenarios was 15 and 4% in 1st and 2nd season, respectively. Considering maximum attainable, average yields, yield gaps, and economic and energy profitability of N application results, a Mid-Western and a Southern region (both growing seasons) were closer to the considered most profitable scenario (higher economic and energy profit variation), although N management was less costly and most profitable in the Southern region. Other regions, 1st and 2nd growing seasons,required greater management improvements to reduce yield gaps and achieve most profitable scenarios, each region having its own specificities related to average crop management and climate conditions. The least favorable results were found for a Mid-Western region, which had both greater differences from most profitable scenarios and highest cost of managing N to reduce MYg. Considering that N management decisions are usually guided by response curves, field history and expected yields, the knowledge of a crop management more aligned with climate conditions, along with maximum attainable yields and yield gaps could provide useful insights for profitable management of closing those gaps.

Keywords: *Zea mays*; Crop management; Management profitability; Simulation analysis

3.1 Introduction

Crop responses to single or multiple environmental and management factors account for a great part of studies of agricultural production systems. The number and type of these factors (e.g., resource factors such as energy, water and nutrients; biotic stress factors such as pests and diseases) (CHAPIN et al., 1987), as well as methods for their evaluation varies greatly. By acknowledging this, it is possible to imagine the variety of studies dealing with a crop's response to a single nutrient (such as maize and nitrogen). Various reports and studies rely on real experiments to assess such subject, at all country levels (COELHO; FRANÇA, 1995; YAMADA; STIPP and ABDALLA, 2000). Although these experiments are especially important for assessing the crop's physiological responses to factor or multiple factors within a system (CHAPIN et al., 1987), the conduction of those experiments can be limited by economic and logistic constraints. Moreover, these types of studies are also usually site- and season-specific (JONES et al., 2003). Analyzing crop response to a single nutrient using several N rates and various locations across a country is nearly impossible to be done under field conditions. For that reason, crop models, when properly used (i.e., proper input data with understanding of conditions and limitations of the model) are a plausible solution to provide representations of reality, i.e., predict the behaviour of the system for given conditions (JONES et al., 2003). According to Cheero-Nayamuth (1999) since agricultural systems comprises complex interactions among its components, which are often not even fully understood, the use of crop models are crude representations of reality. However it must be emphasized the logical necessity of conducting real experiments to promote continuous improvement of crop models, since those experiments provide necessary data and understanding of the processes (comprising soil, plant, atmosphere and management) to be represented.

Nutrients and other inputs management on crop production were able to be used more intensively through agricultural mechanization, since the Green Revolution (DOBERMANN; CASSMAN, 2002). Increase in grain yields, specifically for maize, is commonly related to adequate nutrition, wherein nitrogen (N) plays an important role, being highly demanded by the crop (COELHO; FRANÇA, 1995). Despite negative environmental effects from the improper use of those chemical inputs (LOBELL; CASSMAN; FIELD, 2009; WOODHOUSE, 2010) that should be assessed and mitigated, mechanization allowed increases in work rates and its efficiency, and ultimately contributed for obtaining higher yields since it enables the performance of tasks within the optimum schedule and according to quality and climate requirements (ALVES; MANTOVANI; OLIVEIRA, 2006; WOODHOUSE, 2010). However, mechanization as part of a system's problem investigation has costs that should be carefully analyzed. Analysis of those costs can be economically-oriented (MAFONGOYA et al., 2016; NILSSON; ROSENQVIST; BERNESSON, 2015); related to energy resource use, especifically fossil energy sources (BOYER et al., 2014; WOODHOUSE, 2010) or more rarely, comprising both approaches (GATHALA et al., 2016). The importance of those analysis rely on the fact that mechanized operations on agriculture, including machinery use and applied input is considered both economic and energy intensive (WOODS et al., 2010) and may become unfeasible depending on its impacts and farm's conditions.

In Brazil, studies addressing profitability of nitrogen application on maize are usually performed at one single location and at experimental level (DUETE et al., 2009; KANEKO et al., 2010; SILVA; BUZETTI; LAZARINI, 2005). Those studies, usually performed for the economic perspective of profitability, in general aim to find best time, form and rate of fertilizer application, and rarely analyze the diminishing returns of yields and its impact on profit. On those studies, especially due to economic and time constraints, few N rates are evaluated. Studies addressing profitability of management practices of maize in Brazil using simulation approaches are usually related to water constraints and economic profitability (CARDOSO; FARIA; FOLEGATTI, 2004; GEDANKEN et al., 2003; VIVAN et al., 2015). These studies utilized CERES-MAIZE to evaluate impact of climatic risks and water deficit on maize yields, as well as its impacts on economic profit. The use of a simulation approach enabled the analysis of several scenarios of sowing dates, irrigation strategies and water availability for longer periods than a typical experiment could provide.

Concerning the energy use perspective, few studies have assessed maize's energy use in Brazil (CAMPOS et al., 2004; SANTOS et al., 2000; ZANINI et al., 2003), and they usually evaluate the current energy use efficiency of a given production system. This is mainly because maize's energy use in Brazil is still not a significant reality (SALLA et al., 2010) as well as energy use analysis isusually not considered as often as management decisions.At world level, there is a greater quantity of such energy approach studies, especially because maize is the main source of ethanol in USA (GRASSINI; CASSMAN, 2012; MÉJEAN; HOPE, 2010; SHAPOURI, 2004).

The importance of crop models on systems analysis is unquestionable as well as it has been increasing in recent decades. According to Cheero-Nayamuth (1999) crop models are auxiliary tools which main functions can be: (i) a research tool (LI et al., 2015); (ii) a crop system management tool (in which input management is assessed) (ASSENG et al., 2012; GEDANKEN et al., 2003) and (iii) a policy analysis tool (in which yield forecasting and climate change analysis are included) (ASSENG et al., 2013; HOLZKAMPER et al., 2015).

Thus, the use of simulation models as a tool for analyzing systems management can be a feasible and practical choice for assessing a variety of scenarios and locations, given the use of reliable input data and knowledge of main local characteristics and model limitations.This study aimed to assess the profitability of mechanized application of nitrogen as a strategy of yield gap management of typical rainfed production systems in six Brazilian regions. The objective was accomplished through three main steps, as presented in Figure 1 (following section).

3.2 Materials and Methods

3.2.1 Assessed regions

The assessed regions comprised six Brazilian counties with relevant rainfed maize production, located in the Central-Southern portion of the country distributed across five states. The regions were characterized with details at part I (item 2.2.1) of this study.

3.2.2 Approach

In this study, three main steps were followed (Figure 1) and are described in details in the following sections. In step I, a simulation approach was performed to determine rainfed maize yields under different nitrogen fertilization. In step II, the characterization of N application scenarios, represented by machinery and applied input (fertilizer) was quantified through Material flow analysis, as proposed by Romanelli and Milan (2010a). The quantification of these inputs was considered the only variable among N scenarios. In step III, economic and energy indexes (namely price and embodied energy) of those same inputs were associated with the system’s material flow (GIULIANO et al., 2016; ROMANELLI; MILAN, 2010b) to determine economic and energy cost and return from N scenarios. Thus, the profitability of applying nitrogen on different scenarios aiming to close maize yield gap was determined.

3.2.3 Simulations

In step I, the simulation model was utilized considering water and N restrictions (i.e., rainfed systems with different fertilizer application). Model calibration (for an early-season hybrid) and other input data were discussed in part I of this study. Local weather (1983-2013 daily historical record of maximum and minimum temperature, solar radiation and rainfall), predominant soil profile, soil initial conditions relate to stable fraction of organic matter andmineral N pools and average crop management data were utilized (all detailed in part I of this study). Regional average nitrogen management was collected from local to national databases to characterize typical local mechanized N application and perform simulations and to aid understanding of yield gap management (Annex K). The simulations were performed with the *Decision Support System for AgroTechnology Transfer* (DSSAT) (JONES et al., 2003), by using the maize model (CSM CERES-MAIZE) and CENTURY soil organic matter model coupled with DSSAT. The seasonal analysis tool from DSSAT was used to analyze the effect of management (applied N) andannual weather on crop development. Nitrogen fertilization was simulated through topdress application of urea (typical N management in maize production systems in Brazil). The simulated applications were split according to N rate and soil texture (COELHO, 2007). For clayey or medium texture soil, simulated N applications were performed as described: (i) one application when N rate was up to 120 kg ha^{-1}; (ii) two applications when N rate from 130 to160 kg ha^{-1} and (iii) three applications when N rate was higher than 160 kg ha^{-1}. For a predominant sandy soil profile (found in only one region), for the same presented classes of N rate, two, three and four applications were simulated, respectively. The application was simulated as being non-incorporated in soil.

In step II, to be able to use Material Flow analysis over the N application scenarios, the simulation of mechanized application of urea was performed. The regional mechanized application of N as urea was characterized in terms of its inputs: fertilizer and machinery use (Annex K). The operation was considered to be the only cost variation, associated to maize grain price or embodied energy with harvested yields to provide the economic andenergy balances. Prices were based on the average of 2014/2015 maize growing season using national database as reference (FNP CONSULTORIA & COMÉRCIO, 2015), thus the reader is referred to an inherent price variation of all inputs assessed. Energy indexes of the assessed inputs refer to amount of fossil energy sources utilizedin their industrialization processes and were adopted from literature. The impact of N scenarios to close yield gaps (benefits andlosses) was then assessed.

In step III, the economic and energy profitability of N fertilization of those scenarios was determined. Cost and return of economic and energy resources over N application were assessed between local scenarios and average yields and between regions. Information on regional yield gaps, yield reference levels (see part I of this study), regional N management and profitability of N application were utilized to assess local yield gap management through N application.

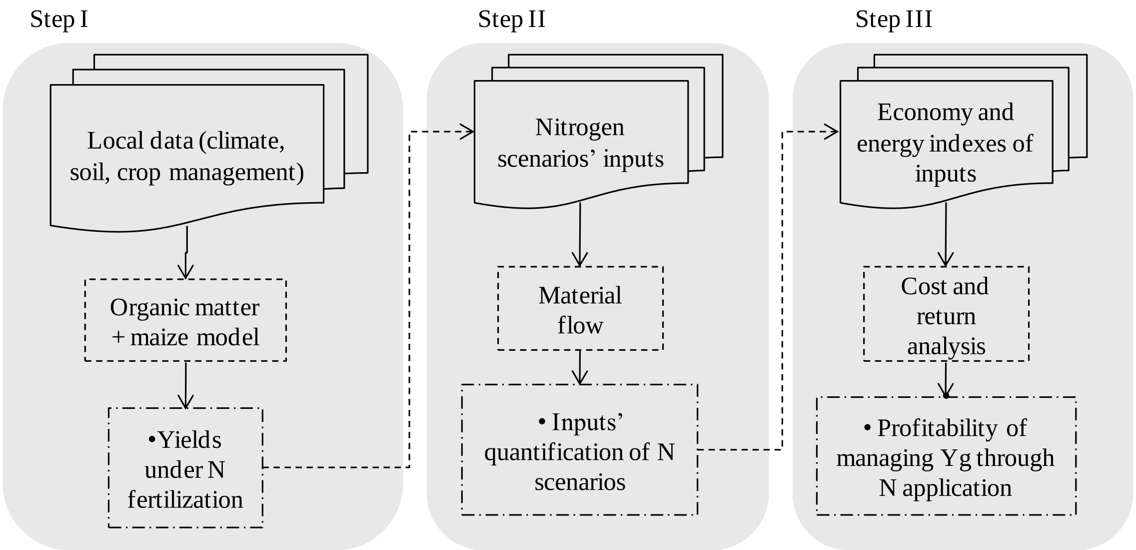

Figure 1 - Main steps performed in the present study. Solid lines of the boxes represent input data, dashed line represents simulation processes and dotted line represents output data.

3.2.4 Material flow of N application scenarios

The inputs quantification of N scenarios was performed though material flow since it provided the basis for several cost analyses. Assessed inputs on N application were machinery (including fuel) and applied input (fertilizer). The material flow approach utilized in this study, as proposed by Romanelli and Milan (2010a) recognizes two main classes of agricultural inputs: directly and indirectly used. The former comprises all inputs directly applied on the field, which are usually obtained by technical recommendation and are represented by their specific application rates, unit ha^{-1} (where unit may be represented by mass or volume). Directly applied inputs in this study is represented by urea. Indirectly applied inputs refer to machinery (represented by operational field capacity and depreciation), and fuel.

3.2.4.1 Directly applied input

Nitrogen fertilization through topdress urea application varied from 20 to 400 kg ha^{-1}. Material flow of fertilization scenarios was thus represented by quantity of nitrogen applied per area.

3.2.4.2 Indirectly applied inputs

Quantification of these inputs depends on the machinery use, since it is directly influenced by different duration of time of operation due to different applied N rates. Machinery use was represented by two different variables: operational field capacity and physical depreciation of the mechanized set, which were used as basis for determining economic and energy demand, respectively.

Foremost for input's characterization, through assessment of publicly available data and contact with local agronomists, typical machinery for urea topdress application in no-till maize production systems was determined (see Annex K). Among the collected data, two mechanized sets were selected to represent the two main Brazilian regions: Mid-Western (MSMJ, MTDI and GOJA regions) and Southern (RSPF, PRGU and PRPA regions) (Annex K). It is emphasized that other machinery types and sizes can also be found on those regions, thus presenting variation on operational parameters and cost of application. According to the selected mechanized sets, the hourly costs of similar sets were adopted from FNP CONSULTORIA & COMÉRCIO (2015) (provided for several agricultural machinery and annual use). Characteristics of the selected mechanized set were adopted from manufacturer's manual (motor power, work width, mass) as well as other machinery and operations' usual characteristics (e.g, typical average work speed and useful life) (AMERICAN SOCIETY OF AGRICULTURAL AND BIOLOGICAL ENGINEERS - ASABE, 2011).

Simulations of the mechanized N application were based on the assumption of the variability of total operation time due to input (fertilizer) reloading. This statement was important to determine the factors influencing on the time used for performing the analyzed operation (also known as field capacity). In general terms, field capacity may be: (i) theoretical (Tfc), influenced only by machinerys' manual characteristics (work width and recommended work speed); (ii) effective (Efc), influenced by actual time to perform the operation; and (iii) operational (Ofc), influenced by the time related to machinery preparation and interruption.

In this study, it was assumed an effective field capacity (Efc) as equal to theoretical field capacity (Tfc), that is, association between work width and speed. The difference among both is that Tfc refers to area covered according to manual's characteristics (maximum work width, typical speed) and on field conditions those characteristics may present some variation, affecting time utilized for working. Both of them refer only to time utilized for the operation, not considering time lost by operator (capability, habits, policy characteristics) and time of work related to field characteristics (shape and size affecting maneuvers), which are usually comprised by field efficiency (ASABE, 2011) and were not comprised in the present study. Field efficiency can be used for determining operational field capacity (Ofc). In this study, Ofc was related only to time used for input reloading, being the latter a fixed estimate (0.25 h). Thus, the variation of operational time lost with input reloading in the different N scenarios could be determined (Eqs. 1 to 4). This approach was considered necessary due to impossibility of measuring time used for operation within the study regions.

$$Ao = Ic / Ur \tag{1}$$

$$To = Ao / Efc \tag{2}$$

$$Ofc = Ao / (To + Tr) \tag{3}$$

$$Efi = Ofc / Efc \tag{4}$$

Where Ao is the area covered by one application (i.e., related to only one input loading), ha; Ic is the storage capacity of the implement, kg; Ur is the urea rate, kg ha^{-1}; To is the time utilized for applying one load of input, considering only the application, h; Tr is the time utilized for input reloading, 0.25 h; Ofc is the operational field capacity of each N application scenario, in this study related only to input refueling, ha h^{-1} and Efi is the efficiency of the assessed operation, %.

Time used for machinery adjustment, maintenance, repairing, refueling, related to shape and size of agricultural fields and other interruptions were not considered in this study. Operational field capacity of N scenarios was used as basis for determination of material flow of indirectly applied inputs. By using Ofc, quantification of machinery use per area, represented by operational use and machinery physical depreciation and operational fuel use were determined for all N scenarios (Eqs 5 to 7).

$$To = 1 / Ofc \tag{5}$$

$$MD = M / (UL * Ofc) \tag{6}$$

$$FC = (P * Fsc) / Ofc \tag{7}$$

Where To is the time worked per area, considering the efficiency relate to a specific N scenario of application, h ha^{-1}; MD is physical machinery depreciation of an N scenario, kg ha^{-1}, M is the machinery's mass, kg; UL is the machinery's useful life, h; FC is fuel consumption of an N scenario, L ha^{-1}; P is the machinery's gross engine power, kW (Annex K); Fsc is a factor for specific consumption of diesel engines, 0.163 L kW^{-1} h^{-1}(MOLIN; MILAN, 2002).

3.2.5 Profitability of N application scenarios

Cost and return analyses were performed using two approaches related to inputs use: economic and energy use. Similarly to the material flow analysis, it was performed only for N application operation, but considering harvested yields as final value. Indicator results shows costs and returns relating N application and harvested yields, and were presented in relative comparison terms, i.e., the variation between scenarios on total system return. Economy and energy indexes were associated with the material flow resulting in the operational cost (R$ ha^{-1} and MJ ha^{-1}) of N scenarios.

In economical terms, fuel cost is already included within the hourly machinery cost. Machinery cost of the mechanized set comprised the sum of tractor and implement costs. In energy terms, material flows of the assessed inputs (machinery depreciation, fuel, labor and fertilizer) in unit ha^{-1} were associated with its embodied energy content, representing the energy demand of N scenarios. Return analysis was performed utilizing the gross income, represented by harvested yields. Thus, economic and energy demand, as well as economic and energy returns were described in Eqs. 8 to 11.

$$Ec = Ur * Uc + (Hct/Ofc + Hci/Ofc) \tag{8}$$

$$En = Ur * Ie + MD * Me + FC * Fe \tag{9}$$

Where Ec is the operation total economic demand, R$ ha^{-1}; Uc is urea cost, R$ kg $^{-1}$; Hct and Hci are the hourly machinery costs of tractor and implement, respectively, R$ h^{-1}; En is the operation total energy demand, MJ ha^{-1}; Ie is the embodied energy of the directly applied input (urea), MJ kg^{-1}; Me is the embodied energy of machinery, MJ kg^{-1}; Fe is the embodied energy of fuel, MJ L^{-1} (See Annex I for details on economy and energy indexes).

The profitability of N scenarios was based on the gross return over investment (N fertilizer application). Gross return refers to system's total return due to harvested yield, considering only the N application, through economic and energy approaches (Eqs. 10 and 11).

$$GFc = (Y * Gp) - Ec \qquad (10)$$

$$GFn = (Y * Ge) - En \qquad (11)$$

Where GFc is the gross return over fertilizer cost, R$ ha^{-1}; Y is maize grain yield, kg ha^{-1}; Gp is maize grain price, R$ kg^{-1}; GFn is the gross return over fertilizer cost, MJ ha^{-1}; Ge is the embodied energy of grain, MJ kg^{-1}.

3.2.6Analysis of yield gap management

The economy and energy profitability of yield gap management through N fertilization was assessed. Results of simulated yields under different N fertilization, profitability indicators, local information on average crop management (Annex K), yield gaps and farmers' average yields (described in part I of this study) were compared and analyzed. Costs and profits over N application were related to mass of harvested yields (R$ kg^{-1}; MJ kg^{-1}) and unit of area (R$ ha^{-1}; MJ ha^{-1}). The indicators were also calculated as rate of variation across N scenarios; either related to 0N scenario or related to the previously lower N rate. This was considered necessary since the analysis of the indicators exclusively by its absolute values may lead to erroneous conclusions on management profitability.

3.3 Results

3.3.1 Simulated yields under N rates

Simulated average yields using 30 years of weather data for each region, both for1st (a) and2nd (b) growing seasons are presented (Figure 2 and Annex M), along with their regression equations, coefficient of determination, significance from F-test and N rate that provided the maximum yield. Considering the average climate conditions, this information suggests which the N scenarios are most likely to provide highest average yields and when the applied N stops promoting yield increases. While minimum average yields were always related to no N application (0N scenario), maximum yields were not necessarily related to the highest N rate. This was particularly evident on 2nd growing season, indicating a lower limit of N use by the crop to achieve highest yields due mainly to water limitation.

In an overall analysis, yield increases were more accentuated up to 200 and 100 kg ha^{-1} on 1st and 2nd growing season respectively, and then they began to stabilize. In terms of season average, highest yields were found at N rates between 270-450 kg ha^{-1} and between 250-285 kg ha^{-1}, in 1st and 2nd growing seasons, respectively (Annex M). Although simulated yields presented relative small decreases at higher N rates, in PRPA it was observed that this condition was achieved above the maximum simulated N rate, indicating a higher potential of response to N application. RSPF and MTDI (1st season) presented the highest average yields at lower N rates (270-275 kg ha^{-1}). In 2nd season, these values were more homogeneous among regions being lower in MSMJ (250 kg ha^{-1}) and highest in PRPA (284 kg ha^{-1}).

Coefficient of determination (R^2) (Annex M) and coefficient of variation (CV%) were also determined for analysis. Highest $R^2$was found for PRGU (0.74); all other regions presented values lower than 0.60. MSMJ (both growing seasons) presented the lowest values (0.11 and 0.23). Concerning the CV (%), highest values (approximately 30%) were found for MSMJ, RSPF and MTDI (1st season) and MSMJ (2nd growing season). The lowest CV was found for GOJA, in both growing seasons (17 and 16%). Average CV of simulated yields from all N scenarios confounded, for each location, varied between 17-36% and 16-30% for 1st and 2nd growing season, respectively.

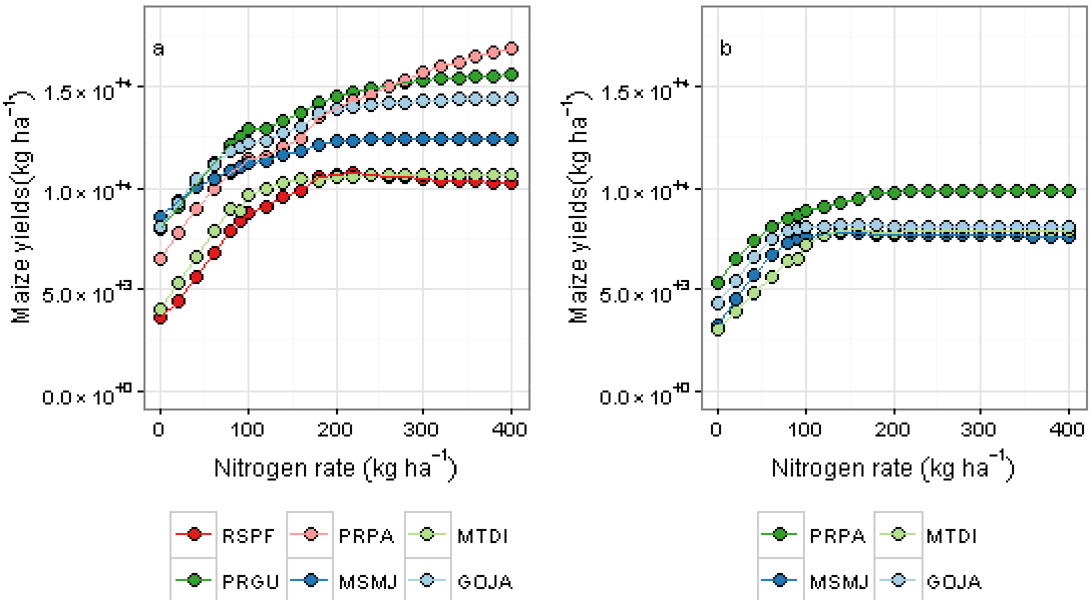

Figure 2 - Average yields under different N rates, considering 30 years of simulation for 1st (a) and 2nd (b) maize growing seasons

3.3.2 Material flow and input costs in N application scenarios

Material flows of the assessed operation (see Annex L) are comparable only when associating it to a common index, such as the economic and energy demand. Operational economic and energy demand per area over N scenarios was associated with the assessed machinery (see Annex N). Fertilizer demand per area only changed with the N scenario, not subject to different machinery types. Fuel and machinery use (operational field capacity and physical depreciation) presented slight variation among two machinery types. Machinery differences in weight and hourly cost affected directly energy and economic demand, respectively. However, differences in hourly cost of assessed mechanized sets and representativity of energy demand from physical machinery depreciation when compared to fertilizer use were also very small. Required machinery use (including fuel), when associated to economic or energy indexes were more representative in the low N rates scenarios. With N rates increases, the fertilizer's economic and energy demand per area became almost the total share of operation's costs.

3.3.3 Profitability of N application scenarios

3.3.3.1 Economic and energy demand across N scenarios

The total economic and energy demands of the operation presented linear increases across N scenarios (Annex N). Absolute differences and variation of operation's economic and energy demand (Ec and En, respectively) between two types of machinery were very small (%), as stated on material flow analysis.

Regarding the inputs' share on operation demand, fertilizer represented the highest share, with 94-99% and 80-98% between lowest and highest N scenarios in the economic and energy approach, respectively. Machinery use represented up to 18% in the economic cost (including fuel) and up to 1% on the energy approach. Fuel, despite being an energy-intensive input, represented up to 5% (in the lowest N rate scenario) of total energy demand in the operation. Total Ec varied between 62.0-1057.0 R\$ ha^{-1} and 64.0-1056.0 R\$ ha^{-1} between lowest and highest N scenarios for Southern and Mid-Western regions, respectively. Total En varied between 1180-22637 MJ ha^{-1} and 1197-22642 MJ ha^{-1}between lowest and highest N scenarios for Southern and Mid-Western regions, respectively.

Yields under N rates presented an expected non-linear increase with increase of N rates, as already pointed in Figures 2 (a,b) and Annex M. Climate variability (mainly water deficit) and local potential of response to N distinguish the shapes of the curves for each region and growing season. The non-linear yield increases over N scenarios (Figure 2), when associated to economic and energy costs of N application directly influenced the variation of economic and energy cost of N application per additional harvested yields (Figure 3).

In Figure 3, the variation of costs per variation of yields is presented using as reference the scenario with no N application (0N scenario). The y axis represents the economic costor energy demand of applying a certain N rate, considering the additional harvested yield obtained from that N scenario using as reference the cost and yields of the scenario without N application (R$ kg^{-1} or MJ kg^{-1}). Points located at higher valuesin Figure 3 indicate higher relative costs (R$ kg $^{-1}$ and MJ kg $^{-1}$) to harvest additional yields (cost of incremental yields) when compared to no N application. All scenarios (regions vs. season) presented statistical differences found for at least one of its specific ΔEc/ΔYield and ΔEn/ΔYield from N scenarios (F test, at 5% of probability).

In the 1st growing season, in both economic and energy approaches, it was found that MSMJ had relative high average yields at low N rates. However those yields showed lower relative variation of yield increase with increasing N rates, directly affecting the economic and energy cost of N application and contributing to its highest cost of incremental yields. The regional (MSMJ) increment ratio in absolute values varied from 0.08-0.30 R$ kg^{-1} over N rates (with average increments over all N scenarios of 0.15 R$ kg^{-1}). In energy terms, the incremental cost for MSMJ varied from 1.5-5.9 MJ kg^{-1} over N rates (with an average of 3.2 MJ kg^{-1}).

In PRPA, the lowest cost for incremental yields was found (both economic and energy), varying from 0.04-0.1 R$ kg^{-1} over N rates (average over N scenarios of 0.07 R$ kg^{-1}). In energy terms, incremental costs of PRPA varied from 0.9-2.1 MJ kg^{-1} over N rates (average of 1.5 MJ kg^{-1}). In PRPA average yields on lowest N rates were even slightly lower than MSMJ, but they presented a continuous increase due to greatest response potential to N application. This region had the lowest and therefore the best economic and energy scenario on 1st growing season. For other regions, average economic increments were 0.08; 0.08; 0.08 and 0.09 R$ kg^{-1} for RSPF, PRGU, MTDI and GOJA, respectively. For those same regions, energy incremental costs were 1.8; 1.7; 1.8 and 2.0 MJ kg^{-1}, respectively.

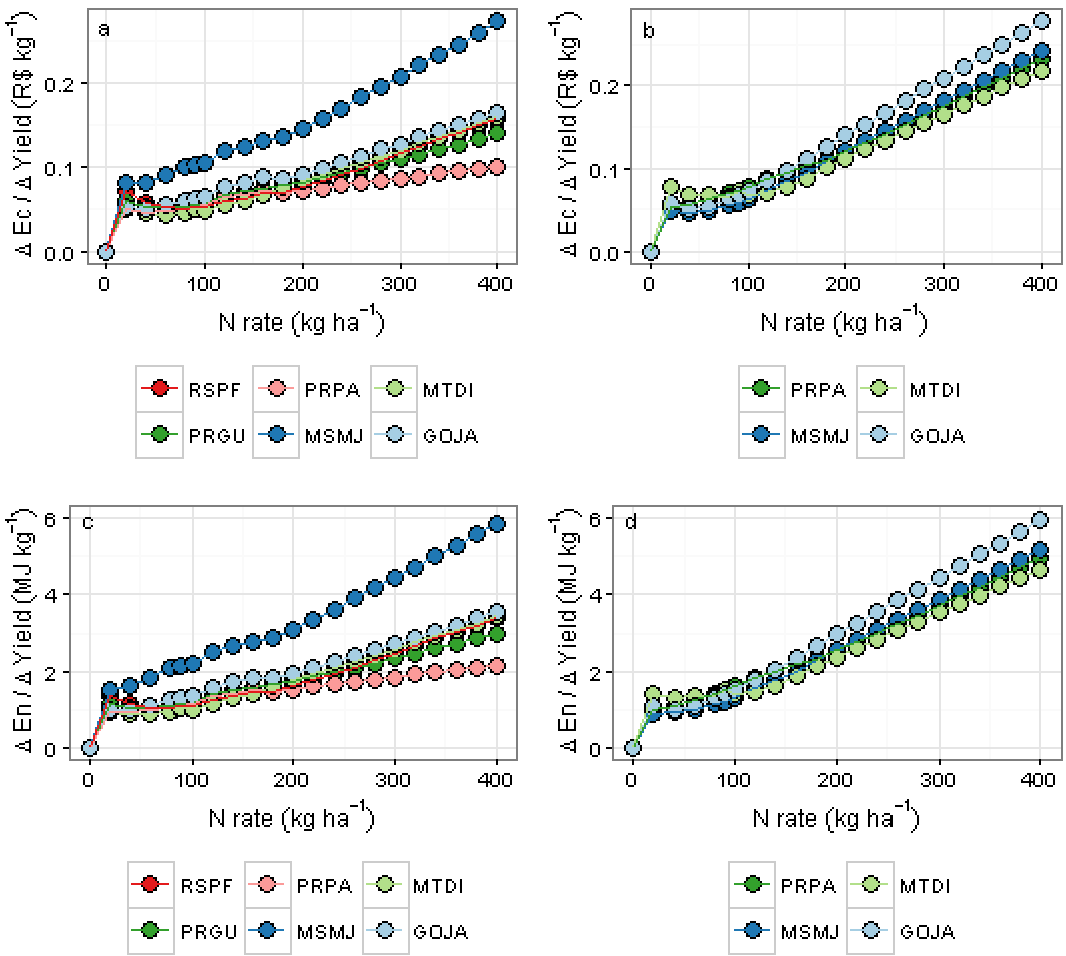

Figure 3 - Cost of economic (a,b) and energy (c,d) incremental yields related to no nitrogen application on 1st (a,c) and 2nd (b,d) maize growing seasons. Each point refers to average yields through thirty years of simulations

Differences among scenario costs in 2nd growing season were not as accentuated as in 1st season, althoughin 2nd season a higher average of absolute costs was found. In 2nd season, the lowest absolute cost for incremental yields was found for MTDI (wherein yields at low N rates were relatively lower and presented a relative high response potential to N application). Economic cost for incremental yields in MTDI varied from 0.07-0.20 R$ kg^{-1}over N rates (average of 0.11 R$ kg^{-1}). In energy terms, it varied between 1.4-4.6 MJ kg^{-1} over N rates (average of 2.4 MJ kg^{-1}). In GOJA it was observed an overall higher cost for incremental yield response from N application, varying from 0.05-0.30 R$ kg^{-1}over N rates (average of 0.14 R$ kg^{-1}).In energy terms, costs in GOJA varied between 1.1-5.9 MJ kg^{-1} over N rates (average of 2.9 MJ kg^{-1}). On other regions, average economic increments were of 0.12 MJ kg^{-1} for both PRPA and MSMJ; and its average energy increments were of 2.6 and 2.5 MJ kg^{-1} for PRPA and MSMJ, respectively. Statistical comparison of cost and and return of a N rate scenario among regions was not performed, since each regional scenario presents several differences acting on average simulated yields.

3.3.3.2 Economic and energy profitability across N scenarios

By using the same previous comparison (variation of money or energy per incremental harvested yields when compared to 0N scenario of application), the gross profit over N scenarios was determined (Figure 4).

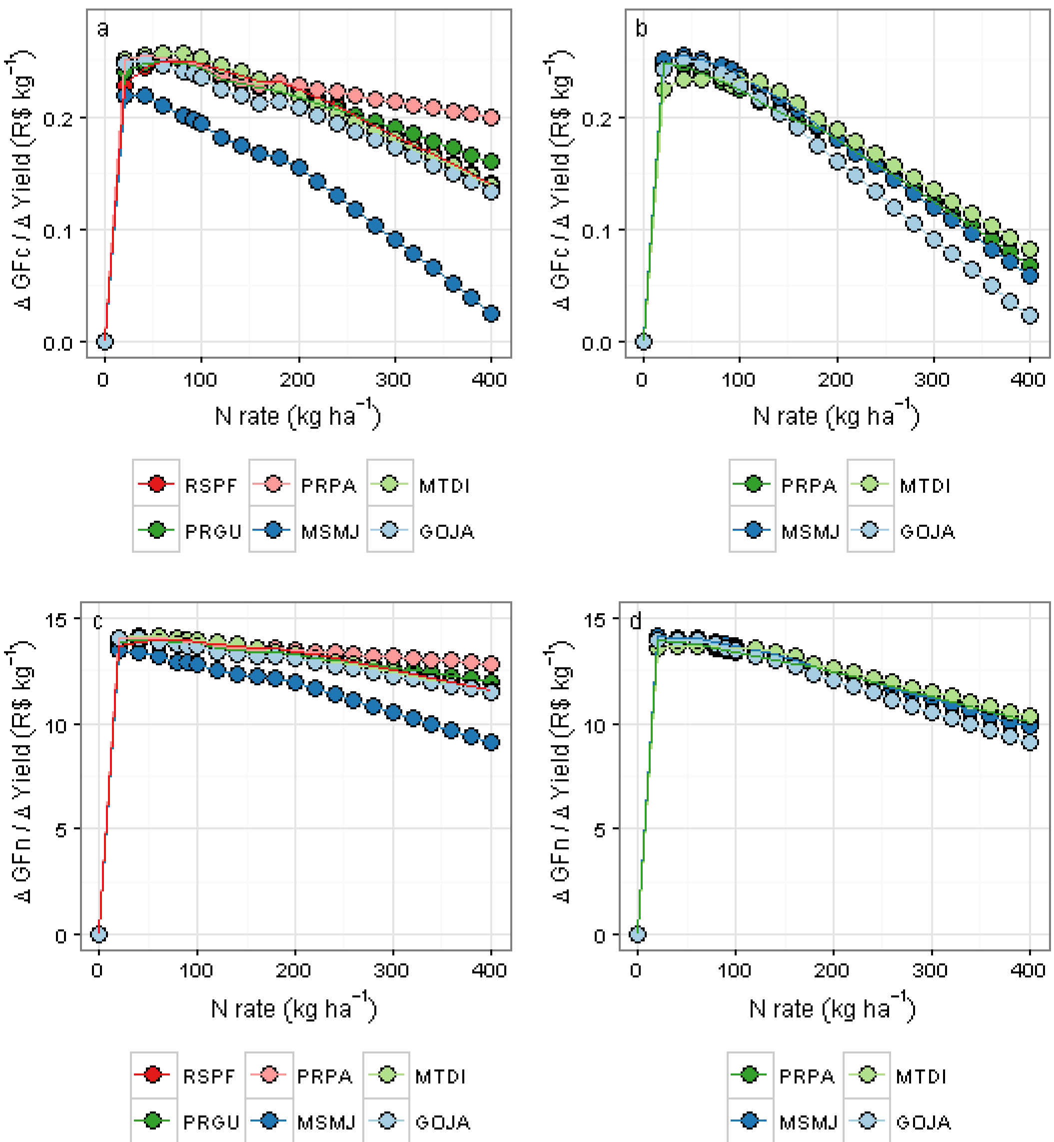

Figure 4 - Gross economic (a,b) and energy (c,d) profit over incremental yields related to no nitrogen application on 1st (a, c) and 2nd (b, d) maize growing seasons. Each point refers to average yields through thirty years of simulations

As for the economic approach, on 1st season MSMJ presented the lowest absolute profit over all N application scenarios. It varied between 0.08 and 0.21 R$ kg^{-1}over N scenarios (average of 0.13 R$ kg^{-1}) for all N scenarios (excepting 0N scenario, in which the indicator was considered to be zero). The higher economic gross profit of N application over incremental yields related to 0N scenario on 1st season was found for PRPA, varying between 0.21-0.25 R$ kg^{-1}over N scenarios (average of 0.22 R$ kg^{-1}). For other regions the average gross profit was of 0.20; 0.20; 0.25 and 0.23 R$ kg^{-1} for RSPF, PRGU, MTDI and GOJA, respectively. On 2nd season, as already observed in Figure 3, results over N scenarios are more homogeneous among locations. The highest average absolute gross profit was found for MTDI, 0.17 R$ kg^{-1}, while other's regions averages were of 0.16; 0.16 and 0.15 R$ kg^{-1} for PRPA, MSMJ and GOJA, respectively.

However, by performing statistical analysis (F test at 5% of probability), not all regions presented differences in the variation of incremental profit per increment of yields (ΔGFc / ΔYield). In PRPA differences were not found for this indicator among simulated N scenarios. This condition is probably due to the continuous increase of yields up to more than 400 kg ha^{-1} of yields, which contributed to its variation of yield being superior to the variation of costs (i.e., ΔGFc / ΔYield was more stable than the other analyzed regions). On 2nd season it was observed differences for all regions and seasons in terms of this indicator (F-test at 5% of probability).

In the energy approach (Figures 4c and 4d), the lowest absolute gross profit on 1st season was also found for MSMJ, varying from 9.4-13.5 MJ kg^{-1} over N scenarios (average of 11.1 MJ kg^{-1}). The highest gross profit was also found for PRPA, varying from 12.5-14.1 MJ kg^{-1}over N scenarios (average of 12.8 MJ kg^{-1}). In other regions, average gross profits were 12.5; 12.6; 12.5 and 12.3 MJ kg^{-1}for RSPF, PRGU, MTDI and GOJA, respectively. On 2nd season, although very similar, the highest absolute average gross profit was found for MTDI - 11.9 MJ kg^{-1}. In other regions, averages were 11.7; 11.8 and 11.4 MJ kg^{-1} for PRPA, MSMJ and GOJA, respectively.

In terms of the statistical analysis of the ΔGFn / ΔYield indicator, on 1st season all regions presented differences over N scenarios (F-test at 5% of probability). However on 2nd season statistical differences again were not observed in PRPA, indicating also the more constant variation of energy profits in this scenario.

By analyzing the simulated N rates, the highest absolute values of ΔGFc / ΔYield were observed at 80; 60; 40; 40; 60; 40 in RSPF, PRGU, PRPA, MSMJ, MTDI and GOJA on 1st season and at 20; 40; 80; 40 in PRPA, MSMJ, MTDI and GOJA on 2nd season, respectively. The highest absolute values of ΔGFn / ΔYield were observed at 80; 40; 20; 20; 40; 20 on 1st season and at 20; 20; 40 and 40 on 2nd season, respectively.

Concerning the profitability variation of N application per unit of area, Tables 1 and 2 summarize economic and energy profit variation across N rates$_{(n)}$, both related to 0N scenario $_{(0N)}$ or previously lower N rate$_{(n-1)}$, per unit of area.This indicator differs from the variation of incremental profit per variation of increments of yields since it accounts only for the variation of gross profit.

Table 1 - Variation of economic gross profit over scenarios of N application

Region	Δ GFc (GFc $_{(n)}$ - GFc $_{(n-1)}$) / GFc $_{(n-1)}$)				Δ GFc (GFc $_{(n)}$ - GFc $_{(0N)}$) / GFc $_{(0N)}$)		
	N scenarios (N rate) Max.	Limit	Mean	SD	N scenarios (N rate) Max.	Mean	SD
RSPF$_{(1)}$	40	20-180	0.03	0.08	180	1.10	0.40
PRGU$_{(1)}$	40	20-240	0.02	0.04	200	0.50	0.16
PRPA$_{(1)}$	20	20-400	0.04	0.05	400	0.80	0.30
PRPA$_{(2)}$	20	20-180	0.01	0.05	180	0.40	0.14
MSMJ$_{(1)}$	20	20-180	0.00	0.02	180	0.15	0.06
MSMJ$_{(2)}$	20	20-100	0.02	0.10	100	0.70	0.30
MTDI$_{(1)}$	20	20-140	0.03	0.09	140	0.96	0.30
MTDI$_{(2)}$	20	20-140	0.02	0.08	140	0.80	0.30
GOJA$_{(1)}$	20	20-200	0.01	0.04	200	0.40	0.12
GOJA$_{(2)}$	20	20-100	0.01	0.07	90	0.40	0.22

While GFc and GFn variation related to 0N scenario (Table 1 and Table 2) were always positive, since it only accounted for increases in profits from 0N application; the GFc and GFn variation from previous N application scenarios (GFc$_{(n)}$/GFc$_{(n-1)}$; GFn$_{(n)}$/GFn$_{(n-1)}$) was able to show the diminishing increases of gross profit, due to the same diminishing increases of yields as N rates increases.

The highest GFc and GFn variation related to its previous scenario, (i.e., the highest increase of those profits) were always found at lowest simulated N rates (20-40 kg ha^{-1}), since the highest relative increases of yields are also observed on those scenarios. The most accentuated responses to N (i.e., higher standard deviation of the variation) also presented the highest mean variation values (RSPF, MTDI on 1st season and MTDI, MSMJ on 2nd season, although regional results were less variable on 2nd season). The limit indicates the peak, i.e., the last N rate before GFc and GFn variation starts to decrease (showing negative values), which is also the scenario with the highest absolute profit. Limit values were higher for 1st season (200-400 kg ha^{-1}) than for 2nd season (100-180 kg ha^{-1}).

Concerning the highest GFc and GFn variation related to 0N scenarios, a limit was not found since GFc and GFn values were always higher than those found for 0N scenario, as presented on Figure 4. The maximum N rate attributed to this indicator shows the peak, i.e., the point with highest GFc and GFn variation from 0N scenario was found. These values do not turn negative because the reference point is the 0N scenario. Highest means as well as standard deviation were also found for regions with highest N responses (RSPF, MTDI on 1st season and MSMJ, MTDI on 2nd season).

Table 2 -Variation of energy gross profit over scenarios of N application

Region	Δ GFn ($GFn_{(n)}$ - $GFn_{(n-1)}$) / $GFn_{(n-1)}$				Δ GFn ($GFn_{(n)}$ - $GFn_{(0N)}$) / $GFn_{(0N)}$		
	N scenarios (N rate)		Mean	SD	N scenarios (N rate)	Mean	SD
	Max.	Limit			Max.		
$RSPF_{(1)}$	40	20-200	0.04	0.08	200	1.40	0.50
$PRGU_{(1)}$	20	20-320	0.03	0.04	320	0.60	0.20
$PRPA_{(1)}$	20	20-400	0.04	0.04	400	0.95	0.40
$PRPA_{(2)}$	20	20-180	0.02	0.03	180	0.60	0.20
$MSMJ_{(1)}$	20	20-200	0.01	0.02	200	0.30	0.10
$MSMJ_{(2)}$	20	20-140	0.03	0.10	100	1.00	0.30
$MTDI_{(1)}$	20	20-220	0.04	0.09	180	1.20	0.40
$MTDI_{(2)}$	20	20-140	0.04	0.08	140	1.13	0.40
$GOJA_{(1)}$	20	20-240	0.02	0.04	200	0.53	0.20
$GOJA_{(2)}$	20	20-100	0.02	0.07	100	0.65	0.20

3.3.3.3 Profitability of yield gap management

Information related to maximum attainable yields (more details in part I of this study), average N management and profitability of N scenarios was summarized (Figure 5). The interval in which positive variation of gross profit over N application (as presented in Tables 1 and 2) is highlighted (green); as well as the average N management (yellow). Points indicate one specific N rate in which it was found the higher variation of profit related to incremental yields (R$ kg^{-1}; MJ kg^{-1}) (presented in Figure 4) (black dot); and in which maximum attainable yields, or Yw, (blue dot), were found.

In economic terms, regional average N management (local average rates of applied N) (Annex K) are within the profitable range, i.e., where gross profits were found. However, not all regional average N management comprises the N scenario in which was found the higher variation of profit (indicated by black dot). MSMJ, MTDI (1st season) and MSMJ, GOJA (2nd season) were the only regions in which average N management comprised the N rates of the higher profit variation scenarios. The maximum attainable yields under N fertilization were within the profitable range of N scenarios only in PRPA (1st season) and MTDI, GOJA (both 2nd season). Higher profit variation N rate scenario is comprised by regional average N management in MTDI (1st season) and GOJA (both growing seasons). The higher economic profit variation was found at relative low N rates (up to 40 kg ha^{-1}) for all regions. This consideration does not imply not having profit on higher rates or that profit on those low N rates are absolute high values. However it indicates that on higher N rates, the average yields started suffering decreases, although still presenting some profits.

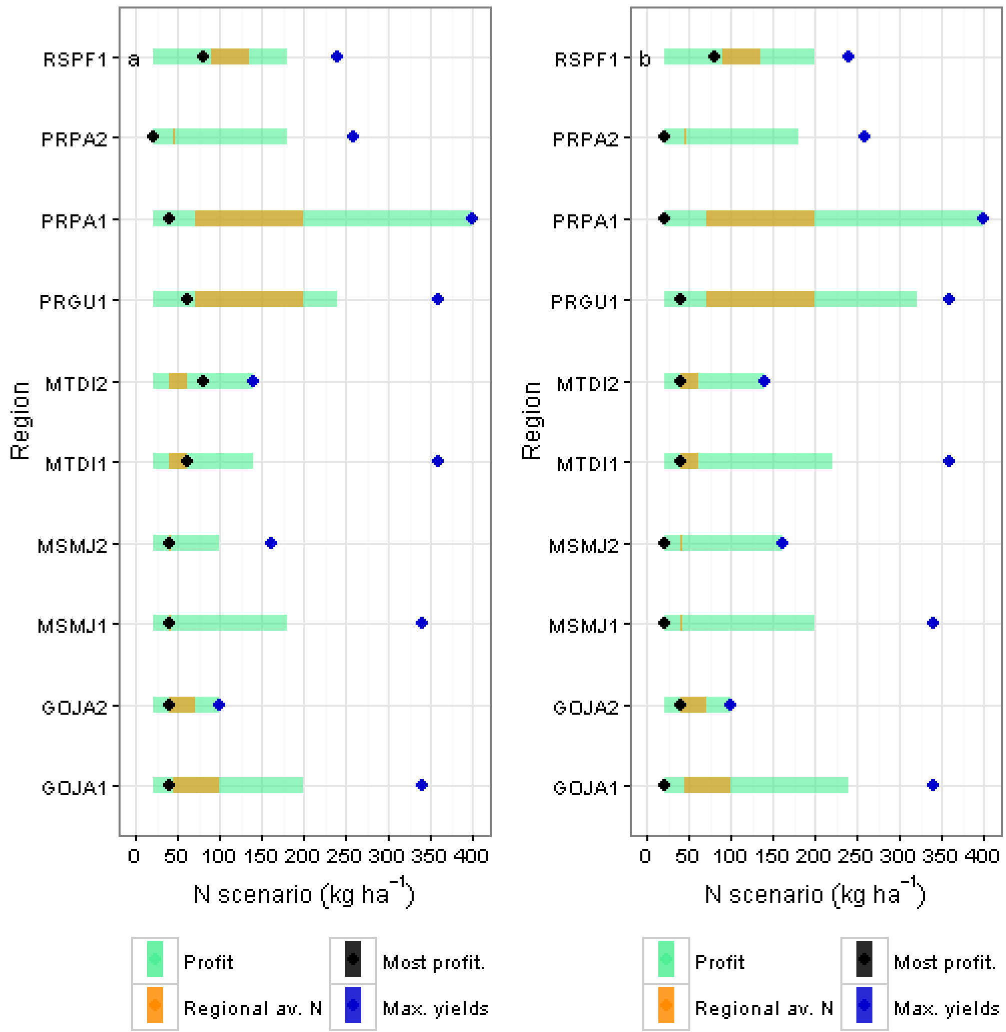

Figure 5 - Relationship between N rates scenarios referring to (i) profit over N application (Profit); (ii) regional average N management (Regional av. N); (iii) most profitable N application (Most profit.); and (iv) maximum simulated yields under N application (Max. yields); for economic (a) and energy (b) approaches. Numbers 1 and 2 following the regions indicate 1st and 2nd growing seasons, respectively

In the energy use approach, it was found that regional average N management was also within the profitable range for all regions. The higher energy profit variation N rate scenario was comprised by regional average N management in MTDI (1st season) and MTDI and GOJA (2nd season). Higher energy profit variation was found at similar or lower N rates when compared to economic return, for all regions and growing seasons. As also found for the economic profitability, highest attainable yields were found beyond the range of energy profit.

Maximum attainable yields (Yw), farmer's real average yields (Ya) and average yields related to the scenarios of N application with higher economic and energy profit variation were assessed to analyze region's yield gap management (Figure 6). The Y_{max} index was determined by relating the average yields from the N scenario with higher profit variation (as presented in Figure 4) and water-limited or maximum attainable yields (Yw). A more detailed description of Yw and Ya can be found in the first part of the present study. And Diff index was determined by relating farmers' average yield (Ya) with average yields from the N scenario with higher profit variation.

Higher profit variation of economic and energy scenarios of average yields were usually found at 60% and higher of Yw. Some regions presented lower values, as PRPA, which was probably influenced by its high Yw values.

In average terms, on 1st season regions were less close to the most economic and energy profitable scenarios of average yields than on 2nd season. However, the current management situation of a real system (i.e., specific yield levels due to its management) is indispensable to understand the relevance of this difference and define actual efforts and its costs to achieve the most profitable local average yields. As an example, a 21% difference of Ya from the scenario with highest profit variation, Y_{max}, for RSPF may be more difficult to be achieved than the 23% found for MTDI, if management is further from optimum on RSPF (e.g., existence of other nutrient deficiency, pests and diseases, etc) and it does not present improvement. This is due to simulations conditions of optimum management (except N availability and climate conditions). Differences were also usually negative, i.e., Ya is usually lower than most profitable scenarios.

Results indicated that in economic terms, GOJA and PRPA (both growing seasons) are closest to the average yields scenarios with higher profit varation (considering a 5% of absolute deviation from the optimum point). MSMJ (1st season) is more distant from this higher profit variation scenario of average yields (-57%). On 2nd season all regions are within a 10% absolute deviation of this point. In energy terms, GOJA and PRPA (both growing seasons) also presented more favorable results (up to 10% deviation) considering the higher profit variation scenario of average yields. MSMJ (1st season) also presented the least favorable results in the energy approach (-54% of Diff.). We emphasize that being "close" or "distant" from the average yields scenarios with highest profit variation is simply information that should be assessed with others mainly related to efficiency of management and other local specificities.

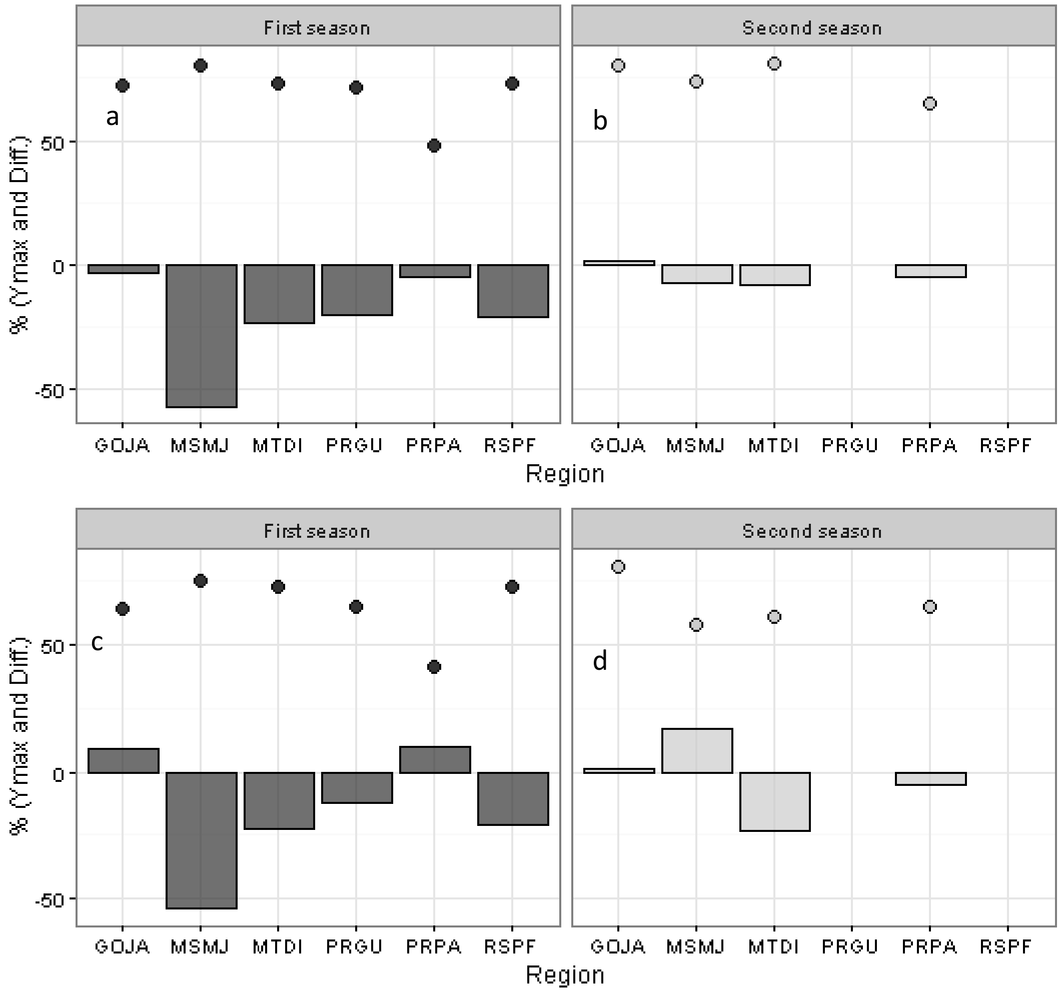

Figure 6 - Relationship between share (%) of average yields from the scenarios with higher economy and energy profit variation and maximum attainable (Yw) yields (Y_{max}); and share (%) of regional average yields (Ya) related to Y_{max} (Diff.). Points indicate Ymax related to Yw, in %; and bars indicate Ya related to average yields from the scenarios with higher economy and energy profit variation. Absolute MYg were, for 1^{s}t and 2^{nd} season, for the same order of regions presented: 4.5; 5.7; 5.6; 6.0; 7.9; 4.6 and 2.0; 3.5; 3.5; 3.8 t ha^{-1}, respectively

3.4 Discussion

3.4.1 Simulated maize yields under N scenarios

The variability of average simulated yields across N scenarios (Figure 2) is directly influenciated by climate conditions and local crop potential of response to applied N (direct function of soil fertility conditions) (OTINGA et al., 2013). This affirmation is also related to the fact that the crop model does not consider other biotic and non-biotic pressures that crop may suffer, such as other nutrient constraint, pests and diseases.In terms of efficiency of nitrogen use by the crop (i.e., fertilizer efficiency, actual utilization of nutrient by the plant) although not comprised in this study, it should be addressed as important influence on yield increase under increasing N rates.

At lower N rates, yield increases are higher since N is the limiting factor; as N rates increase, yield increments become smaller, since other factors (in this study related to climate conditions) may be limiting average yields once approaching its potential (DOBERMANN, 2005). Water constraints are also influenced by factors from the production system other than climate conditions (e.g., amount of rainfall), such as soil properties and its management. The presented results comprise a combination of regional climate and main soil and management conditions, thus differences from the assumed information from the present study might result in variation on results.

Both conditions imposed by the environment (climate constraints and potential of response to N) can be addressed by using statistical parameters. While “flatness” of the curve denotes lower potential of response to N (yield variation between subsequent N rates), it can be evaluated by the average difference between lowest and highest yields under N rates (20 and 400 kg ha^{-1}, respectively). Lowest difference, indicating the lower potential of response to N was found for MSMJ (3.8 t ha^{-1}) and GOJA (3.9 t ha^{-1}), on 1^{st} and season 2^{nd} seasons, respectively. The opposite situation was found for PRPA (10.4 t ha^{-1}) and MTDI (6.6 t ha^{-1}) on 1^{st} and season 2^{nd} seasons, respectively. These observations are an indication of greater yield variation over applied N rates, which are positive results considering the efficiency of use of resources. On 1^{st} season, while all regions presented the usual initial increase and posterior stability of average yields under N rates, PRPA presented different results since its average yields stability was not observed over the simulated N rates. Until the maximum simulated N rate, PRPA continued to present potential to increase yields. This region’s combination of environmental conditions, such as soil conditions (texture, organic matter); climate conditions (temperature, rainfall, solar radiation) are probably responsible for its relatively higher water-limited yields, both growing seasons.

Climate constraints can be addressed by analyzing CYg, rainfall patterns and correlation with yields (see part I of this study) and dispersion of simulated yields under N rates during the thirty years of weather data. Regression equation (Annex M) parameter, R^2, can also be related to climate variability, since great dispersion of interannual yields will result on poor model adjustment (30 years of simulated results). Highest $R^2$was found for PRPA and MTDI (1^{st} and 2^{nd} season); and lowest $R^2$was found for MSMJ (both growing seasons).

Considering the combination of these information (response to N, CYg and model adjustment), most favorable scenarios of N use on environment conditions were found for PRPA and GOJA (1st season) and MTDI (2nd season), despite this latter regions' results of CYg (see part I of this study). Not as usually pointed by studies, Mid-Western regions presented relative favorable environment conditions for N use by the crop, despite the usual lower amount of rainfall on 2nd season (MINUZZI; LOPES, 2015), being MSMJ the least favorable scenario. RSPF may be more affected by climate conditions; water constraints in great part of Rio Grande do Sul state is acknowledged (BERGAMASCHI; MATZENAUER, 2014; BERGAMASCHI et al., 2006) and it helps explain its average yields stability at lower N rates when compared to other regions (GOJA, PRGU and PRPA). Maize is a crop sensitive to water deficit, in which water restriction on reproductive phase can represent up to 50% of yield decreases (BERGAMASCHI; MATZENAUER, 2014).In MSMJ (both growing seasons) although not presenting high absolute CYg (part I of this study), it presented the poorest model adjustment, which may be an indication of constant climate variability affecting average yields. On that region, it was aso found the lowest potential of response to N (lowest variation of yields among N rates).

3.4.2 Input costs at N application scenarios

Operation's greatest economic and energy demand (Annex N) was due to fertilizer (urea), a well reported result comprising all nitrogen fertilizer (ANGELINI et al., 2009; ROMANELLI; MILAN, 2010b; SHAPOURI, 2004). Despite lower share of machinery on economic and energy demand of the operation when compared to fertilizer, it should not be neglected (as commonly done in profitability studies that only account for fertilizer cost), since depending on the size of the farm, the use of mechanization is mandatory and its costs can influence the management decision (GATHALA et al., 2016; NILSSON; ROSENQVIST; BERNESSON, 2015). Machinery size and power can present significative influence on operational costs (per hectare), mainly due to fuel use (a more intensive economic and energy cost input). If the machinery is farm's property or rented, there are costs that should be assessed. In Mid-Western Brazil, it is also common to find self-propelled fertilizer distributors, with larger power and size than the selected for the present study. This kind of machinery would greatly increase operational economic and energy demand. In this study, machinery costs represented up to 20 and 6% of economic and energy total operational cost, respectively, and as N rates increases and N fertilizer costs became extremely high, machinery share of cost decreased gradually. Although those shares seem low, when considering all operations performed within one production cycle, it can represent significant costs (e.g., sowing and harvesting, both operations usually with low operational field capacity).

3.4.3Cost and profitability of N application scenarios

The non-linear relationship between economic and energy use of resources and yields (WOODS et al., 2010) is region specific and it is determinant on defining yield gap management.

In general analysis, it was observed that it is less costly (both economic and energetically) to increase yields by N application on 1st than on 2nd growing season. MSMJ presented the most flat response curve to N application on 1st growing season, and GOJA on 2nd growing season (although results for 2nd season were less variable among regions). Those results determined the regional highest economic and energy costs of N application per incremental harvested yields. Higher potential of response to N, on the other hand, contributed to PRPA’s lowest economic and energy cost of N application per incremental harvested yields on 1st growing season. On 2nd season, MTDI presented slightly lowest cost, despite the greater similarity of results among regions. In practical terms, the application of fertilizer on regions with more flat responses produces relative lower yield increase on those conditions, i.e., the cost of operation (linear increase) has tendency of not being compensated by the increase of yields (non-linear increase).

Regions that presented highest relative cost per increment of harvested yield (R\$ kg^{-1}; MJ kg^{-1}), also presented the lowest relative gross profits per increment of harvested yield and vice versa (Figure 4). PRPA (1st season), both economic and energetically, presented the highest average gross profit, while MSMJ presented the lowest. It should be noted that on 1st season, all regions except MSMJ presented close values of gross profit variation up to 200 kg ha^{-1}. This is particularly important since in real conditions all regions have an average N consumption lower than 200 kg ha^{-1}. Above that N rate, the highest N response of PRPA contributed in maintaining higher relative profit values.

Although absolute values, such as yields under N rates, and relative values, such as incremental cost per incremental yields, have presented an (apparently obvious) significance statistical difference among N scenarios in all regions, the increment of economic profit per increment of yield did not present the same behavior for all regions. In 1st season in PRPA, this was due to yield under N rates behavior, which presented a continous increase over simulated N rates. Thus, in this region and season, the variation of profit due to N application was relatively constant among simulated N rates. In the energy use approach this condition of no statistical differences among the variation of profit over N scenarios was also found only for PRPA, on 2nd season. This should not be confused with not presenting statistic differences in obtained gross profit over N rates increase. In practical terms this is a favorable result, since it indicates that in optimum management conditions, the applied N is more efficiently used for profit purposes.

Although always positive (since GFc and GFn variation on 0N scenario was zero) this indicator was considered useful to evaluate profit, even when considering only one part of total cost of production. The classic example of a linear increasing curve of yields under N rates of several studies (ARNON, 1975) that suggests the most profitable scenario as being the one with the largest difference between gross profit and cost of operation would not represent real values in this study, since GFc and GFn only refers to N application and in this study the most profitable scenario is not related to highest gross profit, but the scenarios with major variation of profit. The variation of gross profit over N application divided per the variation of harvested yields, using the 0N scenario as reference was able to indicate the quantity of money or energy spent per unit of harvested yield. The use of 0N scenario as reference explicit the greater N response (and consequently profit) atlower yields, but decreasing as N rates increase. Therefore, considering that operation costs are at linear increase and average yields are at diminishing increases as N rates increases, it was possible to identify the point with the most profitable use of money and energy per unit of harvested yield.

While on Figures 1 and 2 it was possible to observe highest and lowest cost and profit of N application per kilogram of harvested yields, results of Tables 1 and 2 indicate the variation of gross profit over N application per unit of area across N scenarios (R$ ha^{-1}; MJ ha^{-1}), aiding to understand profit behavior over N increases. It was intended to emphasize that not only points (N rates) with higher absolute profits (maximum difference between gross profit and cost) should be evaluated, but also its rates of variation under fertilization rates (diminishing increases).

When analyzing GFc and GFn related to previous scenarios (Tables 1 and 2) it was possible to determine the points in which there was a higher variation of profit increase between simulated N rates. Maximum variation were found at lowest N rates (20-40 kg ha^{-1}), both growing seasons, since highest variation of N responses at lowest N rates indicates that on those conditions N is the major limiting factor for increasing yields (DOBERMANN, 2005). Maximum limit of this indicator showed the last N application scenario in which profits could be found, i.e. N scenario in which profits still compensate the operational cost. Superior N rates started to present economic and energy losses. The maximum N rates scenarios of these indicators presented in Tables 1 and 2 are also the N rates with higher absolute values of gross profits (as calculated in Eqs. 10 and 11). This indicator shows detailsof the diminishing increases of economic and energy profits.

When analyzing GFc and GFn variation from 0N (Tables 1 and 2), N scenarios referring to maximum values indicated at which point there is the highest profit variation when compared to profits obtained at no N application. The N rates indicating this maximum variation were not found at the same N rates in which maximum absolute profits were achieved, but instead, first N rates in which average profits started to stabilize (presenting little variation that results in little profit variation). When average yields stabilize, the increasing cost (of N application) starts to cause decreases on absolute profit (due to linear increase of operational cost). This indicator does not become negative since absolute average yields and profits of any N scenario are always higher than on 0N scenario.

Considering both economic and energy approaches, it was concluded that in MSMJ (1^{st} season), N application is less profitable, especially at high N rates. This was due to lower response to N application which contributed to its highest cost and lowest return per mass of harvested yield, besides the lowest absolute profit variation through increase of N rates. Regions with more accentuated variability in average yields and N response, as RSPF, PRPA, MTDI, MSMJ (2^{nd} season), despite not being the most efficient in using N per mass of harvested yield, presented the potential to promote relative high increases in profit, especially at N rates <= 100 kg ha^{-1}. On those regions, the importance of quality management (i.e., mitigation of all yield reduction factors related to crop management) is highly important. PRPA also presented the advantage of having more constant variation of profit per harvested yield even on the higher N rates, denoted by statistical analysis. GOJA and PRGU presented more stability on variation of profits, although PRGU presented relative high profit over incremental yields. High applications of N, if with proper management, maylead to higher average yields in PRGU than GOJA, due to N response. On GOJA, especially on 2^{nd} season, variation of profit across N rates was lower. Relative high profits could be achieved approximately up to 100 kg ha^{-1}.

3.4.4 Profitability of yield gap management

Main combined results of part I and II of this study, provided conclusions regarding feasibility of management to increase average yields in the study regions. As already pointed by other authors (LOBELL; CASSMAN; FIELD, 2009), maximum attainable yields (Yw in this study) are usually not profitable. It was verified that for all regions and growing seasons (except PRPA 1st season due to continuous increase of yields through simulated N rates), both in economic and energy approaches, highest attainable average yields are beyond the profit interval (i.e., N rates in which there are some profit, although not necessarily proportional to cost). Despite the finding of yield gaps due to crop management (MYg, presented with more details in part I of this study), management should not be directed to achieve those maximum attainable yields. Rather that, it should be improved to achieve profitable scenarios considering farm’s and regional environment conditions.

The economic and energy profitable zone of management (interval of N rates in which profits were found) (Figure 5), despite being wide, is strongly and directly influenced by local climate conditions (ANDRADE et al., 2012), as well as crop’s response to applied nutrient. However, the scenarios with higher variation of economy an energy profits (per harvested yield or area), considering the diminishing yield increases, was always found at lower N rates (due to more accentuated response to N at lower N rates and average yields). The considered most profitable point was not the one with the highest average yields, rather that it is the point in which resources are utilized in a more efficient manner(DOBERMANN, 2005), per mass of harvested product or area. Both in economic and energy approaches, the isolated results indicating maximum profitable point at low N rates and posterior diminishing increases should be analyzed with caution, since the decrease of yields may lead to another undesirable situation related to decrease of profits, as stated by Woods et al.(2010) when assessing the energy use analysis in crop production systems.

Local average nitrogen management is within the profitable zone in all regions. In most regions, this is due to the low average N application, which is probably influenced by typical water constraints from rainfed systems. In PRGU and PRPA farmers may be less conservative in terms of the nutrient application. This fact may be related to a combination of local characteristics, such as their smaller farms compared to Mid-Western, which facilitates more intensive management (LOBELL; CASSMAN; FIELD, 2009) and their extremely favorable conditions for cropping. The traditional existence of cooperatives, facilitating the adoption of knowledge and technology to farmers may also be related, although not exclusive to those regions. We emphasize that more abundant and local information of N management over all regions may vary this perception. In GOJA a more intensive N management is also found in average maize production (FNP CONSULTORIA & COMÉRCIO, 2015), contributing to this region highest average farmers yields (Ya).

Although in some regions most profitable rates of N are comprised by the range of local average N rates (GOJA, MTDI) (Fig. 5), on Fig. 6 it is observed that on these regions Ya values are below Y_{max}. GOJA and PRPA, both growing seasons, presented the highest values of proximity from most profitable scenarios, considering a 5 and 10% of deviation for the economic and energy approach, respectively. This difference was lower for GOJA, due to its superior average crop management, especially on 2nd growing season, wherein this difference was the lowest found. On that region, local average N management is of approximately 45 kg ha^{-1}, and most profitable (economic and energy) N scenarios was found at 40 kg ha^{-1}; therefore this was the region with the most efficient yield gap management already happening, in average cropping conditions.

The relative high share (%) of average yields from N scenarios with higher profit variation related to local Yw is probably more related to the absence of reduction factors (except water and N) on simulated crop yields, since most profitable scenarios were found at lower N rates. In practice, the more current crop management is deficient, the distance to achieve most profitable scenarios become more accentuated than presented values. Thus, Figure 6 results must be analyzed considering that real conditions of production system can determine variation of results.

In terms of feasibility of yield gaps management, MSMJ (1st season) presented the least favorable results. This scenario is a result from its high MYg, lowest Ya, accentuated climate variability (denoted by CYg and poor model adjustment), low local average N management and highest cost and lowest profit from N application per mass of harvested yields. Thus, improves on quality of crop management should be an elementary measure to reduce the difference between farmers average yields and most profitable average yields scenarios. On 2nd season this region presented more favorable results, due to its relative values of CYg, MYg, cost and profits. Although on 2nd season the region presented the second highest MYg, its average yields were not far from economic and energy most profitable scenarios.

PRPA and GOJA (both growing seasons) presented most favorable scenarios as result from different conditions. On 1st season, the highest and the lowest MYg were found for those regions, respectively. However, PRPA also present a relative high Ya; closeness from most economic and energy profitable yield scenarios; and most favorable results for cost and profit of N application per mass of harvested yields. Thus, despite its large MYg, its management through N fertilization can be more easily compensated. In PRPA (2^{nd} season), water constraints are not accentuated as other regions, however high Yw determined the highest MYg of 2^{nd} growing season. Still, its relative high Ya contributed to its closeness from most economic and energy profitable scenarios. Costs and profits of N application per mass of harvested yields were not limitant. In GOJA (both growing seasons), the region already present the lowest MYg and greater closeness from most economic and enery profitable average yield scenarios, as a result of good management practices despite not presenting favorable cost and profit per mass of harvested yields. Thus, N management to reduce yield gaps on this region may not be much necessary in actual conditions, since the region present highest Ya for both growing seasons, in a stable manner on the last decade.

RSPF, MTDI and PRGU presented intermediate results related to profitabilty analysis. PRGU has a high Ya and low water deficit (compared to other Southern regions), however its relative high MYg is due to high Yw. Its second lower average cost of N application (R$ kg^{-1}; MJ kg^{-1}) may justify intensification N management to reduce the gaps and get closer to most economic and energy profitable average yield scenarios. RSPF has a more intense water limitation than other regions on 1^{st} season, due to climate variability. Considering its relative high local average N management, irrigation practice could provide significant yield increases and closeness from most economic and energy profitable scenarios. On MTDI (1^{st} season), water constraints are usually not a problem, however low local average N management is probably contributing to its MYg and distance of Ya from scenarios with higher profit variation. On 2^{nd} season, as in most Mid-Western regions, water restrictions can be limiting, although the use of irrigation practices should be carefully evaluated, since a non-constant occurrence of water deficit may not be sufficient to invest on such management.

As already stated on part I of this study, all regions could benefit from a crop management more aligned with climatic conditions. This information may seem obvious, but considering that N management in maize in Brazil is usually driven by response curves, field history and expected yields (COELHO, 2007), it may represent aid in determining the most profitable use this expensive input. However it must be emphasized that it was not the objective of the study to recommend N fertilization that fits every production system found within each region; there are a variety of intrinsic factors to the systems that influence N rate suggestions (COELHO, 2007; SAWYER et al., 2006). Also, it was not intended to analyze the several dynamics on nitrogen fertilizer on soil and plant systems. It is recognized the importance of evaluating constraints related to type of fertilizer and its utilization by the plant dynamics on each production system. In this study, several assumptions related to soil initial conditions (organic matter pools, biomass residues), crop management (sowing date, plant density, type of fertilizer and type of aplication) were considered and used to estimate crop's response to applied N in optimum management, and consequently its profitability.

In Brazil, few studies have addressed profitability of nutrient management on maize by means of simulation approach. Andrade et al. (2012) utilized CERES-MAIZE to evaluate economic profitability of different sources (mineral and organics) and rates of N fertilization on rainfed maize in Southeastern Brazil (Minas Gerais state). By using the simulation approach, the authors could utilize more than 40 years of weather data and assess more than ten fertilizer treatments. The authors assessed costs of the whole production cycle and input price variability, evaluating stochastic net profit. As found in this study, the authors pointed to a high interannual variability of profits and yields, due to accentuated climatic conditions, as well as increases on this variability with increase of N rates. The authors found greater economic profitability at 90 kg ha^{-1}, however this result is related to mean absolute net profit, not considering diminishing increases. The high risks of economic losses related to N fertilization were mainly attributed to high climate variability.

Pasuquin et al. (2014) evaluated the economic profitability of the decrease of maize yield gaps through local nutrient (N, P, K) management in Asia by using a combined simulation and experimental approaches. Experiements provided yield data at local usual crop management conditions.The model (DSSAT) provided estimations of Yp and Yw. By using a simulation approach, the authors could evaluate a variety of scenarios related to yield potential and yield gaps values. An extensive experimental data set provided model robustness for yield estimations. As in this study, the authors evaluated the economic profitability of only nutrient application in crop cycle and the variation of profit over N rates.

Concerning the energy use approach for cropping systems in Brazil, this scarcity of studies on maize biomass will probably change in the upcoming future with the beggining of operation of Brazil's first maize ethanol plant, in Mato Grosso state expected for the next two years (SUMMITAG.COM, 2016). Despite sugarcane being an important and energy-profitable biomass source of energy (16% share within Brazil's 40% share of renewable sources of energy in its matrix) (ENERGY RESEARCH COMPANY - EPE, 2015), the diversification of biomass sources in the energy matrix is considered important and may become a relevant option at regional level, at least. Ultimately, an energy use approach analysis of agricultural systems has unarguable and increasing importance on management decisions (CAMPOS; CAMPOS, 2004), not only for its direct and obvious relation with economic issues (e.g. prices of fossil fuel), but with several environmental issues, such as climate changes, depletion of fossil energy sources, air and watercourses pollution, among others (ANGELINI et al., 2009; HALL, 2012; WOODS et al., 2010). The importance of using fossil energy sources on agricultural activity is pointed by the national energy balance, in 2014 the sector was responsible for ~4% of national energy consumption, in which fossil energy sources (oil and derivatives) represented the major share (55%), with a high increase rate (80%) (EPE, 2015).

3.5 Conclusion

A simulation approach was performed to assess the economic and energy profitability of typical mechanized N application (considering the N rates of 20-400 kg ha^{-1}) on rainfed maize production systems in Mid-Western and Southern regions as strategy for managing local yield gaps. Results indicated operation's economy and energy costs are mainly due to nitrogen fertilizer use, especially at high N rates. Potential of response to applied N was of major importance on determining costs of N application and gross profits per incremental harvested yields (R$ kg^{-1}; MJ kg^{-1}) and per unit of area (R$ ha^{-1}; MJ ha^{-1}). Regions and growing seasons with lower N response (i.e., less accentuated variation of yields among N scenarios) presented both the highest cost and lowest profit of N application (MSMJ and GOJA on 1st and 2nd growing seasons, respectively). Thus, regions with more accentuated yield response to applied N presented both the lowest cost and highest profit of N application (PRPA and MTDI on 1st and 2nd growing seasons, respectively). In terms of variation of profit accross N rates (R$ kg^{-1}; MJ kg^{-1}; R$ ha^{-1}; MJ ha^{-1}), while scenarios with highest variation of profit were found at low N rates (20-80 kg ha^{-1}), demonstrating highest efficiency on those scenarios; economic and energy profits could befound until high N rates were achieved (100->400 kg ha^{-1}), all depending on local climate and N response conditions. Feasibility of yield gap management was a result from local environment, management and profitability of N application conditions, very specific for each region and growing season. A Southern (PRPA) and a Mid-Western region (GOJA) presented the most favorable results, originating from different environment and management conditions. On 2nd season, wherein growth conditions usually determine lowerYp and Yw, and N application ismore costly than on 1st season, profitable yield gap management can be found, as a result of efficient average management even at low N rates.

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4 GENERAL CONCLUSIONS AND FINAL REMARKS

Considering that the main objective of this study was to characterize rainfed maize production systems local yield gaps and to evaluate the profitability of applying nitrogen fertilizer as a strategy for closing those gaps, some considerations can be done.

In part I of this study, local environment and average management conditions were necessary to determine the existence and magnitude of local yield gaps associated with water deficit and crop management. The model showed the capacity to predict yield variability related to local weather conditions and management, presenting a similar behavior of yield variability when compared to local farmers' average yields data set. By the end of part I, it became clear that although water constrainst directly influenced yield variability, especially on 2^{nd} growing season, the average crop management was found to be of greater importance on local maize yield gaps. At this point it is necessary to observe that although rainfed production was evaluated, the choice of assessing region with relevance on national production may already have diminished (although not annulling) the importance of water deficit when compared to crop management. If climate conditions were extremely unfavorable, those regions would probably not presente such importance on national crop production, unless irrigated. Great variability of MYg was found for all regions and growing seasons, indicating a variety of local environment and management conditions.

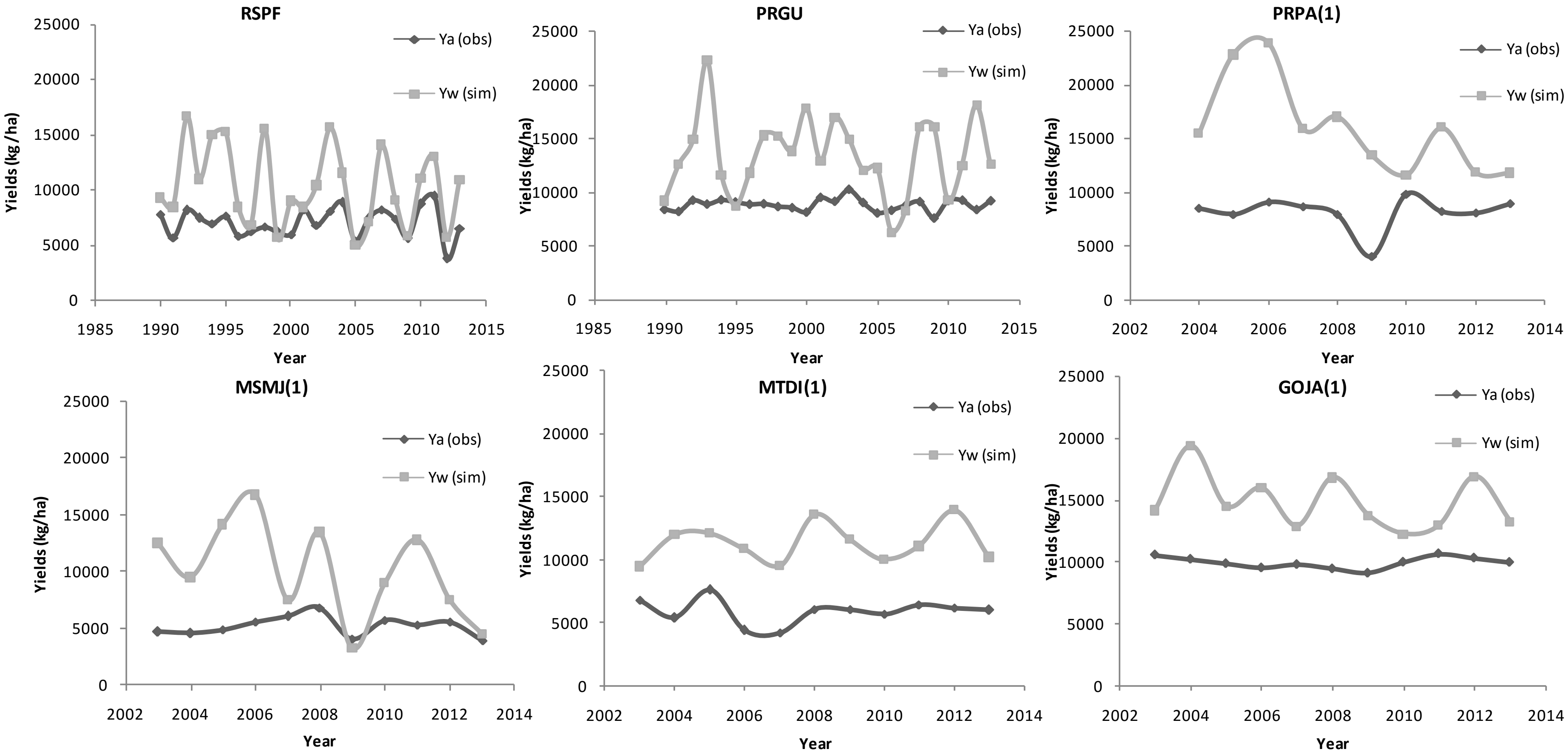
In part II of this study, it was considered necessary to locally characterize typical nitrogen fertilization operation on maize to assess its impacts on average yields and management profitability. The importance of N in maize yield increases is also reflected on its greater importance on total operational economic and energy cost. It was intended to show the difference between N rates scenarios wiht highest absolute profit and N rates scenarios with most efficient use of N on crop yields (here presented as scenarios with highest profit variation or most profitable economic and energy scenarios). While physiological and environment (e.g., soil) factors influence the most efficient use of N per mass of harvested yields or per unit of area found at low N rates (when it is the most limiting factor), the existence of profits can be found at N ranges varying with local environment conditions (climate and soil). Added to that, local management information (such as its efficiency) is of great importance in determining strategies for yield gap management. High MYg or lower season rainfall typical of 2^{nd} growing season could induce the perception of unfavorable results, however with the profitability analysis; those conditions could represent the most favorable scenarios, as found for a Southern and a Mid-Western region. Thus, it is emphasized that local environment and management conditions should be utilized added to usual information utilized for guiding N management on maize production systems to manage yield gaps. The use of a simulation approach, both for crop development and mechanized operation, was of great importance in enabling the analysis of many scenarios with time and money savings. Thus, crop models could be further explored in management decisions of typical production systems, still not usual in Brazil.

Further steps on this type of research may include:(i) the use of other crop simulation models as a manner to assess model uncertainties; (ii) the use of input data on a finer spatial scale (e.g. soil profile, rainfall variability, ranges of farmers decisions) to more precisely estimate yield potentials and quantify yield gaps; (iii) assessment of main crops at national territory level related to most limiting management factor for each crop and climate conditions (which may include climate change scenarios).

APPENDIX

Appendix A– Comparison of farmers' average yield data set (Ya) and simulated yields (Yw) for regional average conditions.

(continued)



Simulated yields were performed using average regional information on crop management and do not consider biotic and non-biotic reduction factors other than climate conditions on rainfed systems. The presented results were analyzed to check model capacity in responding to local environment conditions. Disagreements between simulated and observed yields may be due to variation on sowing date and management reduction factors, all uncertainties concerning regional average yields. (1) and (2) refer to 1st and 2nd growing seasons, respectively.

Appendix A – Comparison of farmers' average yield data set (Ya) and simulated yields (Yw)for regional average conditions.

(conclusion)

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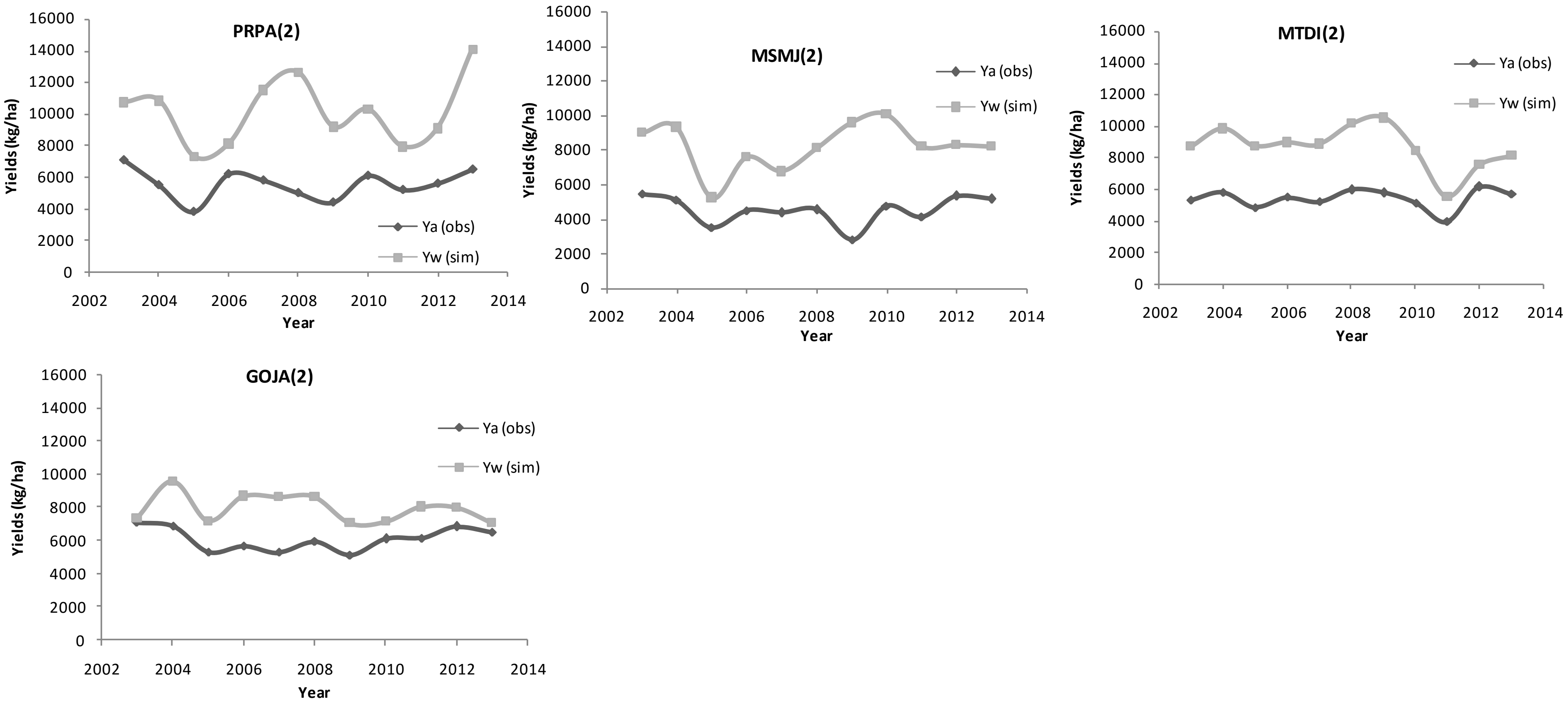


Simulated yields were performed using average regional information on crop management and do not consider biotic and non-biotic reduction factors other than climate conditions on rainfed systems. The presented results were analyzed to check model capacity in responding to local environment conditions. Disagreements between simulated and observed yields may be due to variation on sowing date and management reduction factors, all uncertainties concerning regional average yields. (1) and (2) refer to 1st and 2nd growing seasons, respectively.

ANNEX

Annex A – Regions used in the present study and their main characteristics regarding climate, soil and maize average management.

(continued)

Region	Location (^{0})	Av. Annual Temperature (^{0}C)	Av. Annual Precipitation (mm)	Sand[2] 30; 100 cm (%)	Clay[2] 30; 100 cm (%)	Organic Carbon[2] 30; 100 cm (%)	pH in water[2] 30; 100 cm	Predominant Soil Classification[3] (FAO)	------- (EMBRAPA)	Elevation (m)
1 - RSPF	28^0 15' S, 52^0 24' W	17.9	1746	44 ; 8	42 ; 77	1.4 ; 0.6	4.8; 4.8	Rhodic Ferralsols	Latossolo Vermelho	690
2 - PRGU	25^0 23' S, 51^0 27' W	16.7	1711	6 ; 9	62 ; 57	4.0 ; 1.3	4.7; 4.9	Humic Cambisols	Latossolo Bruno	1100
3 – PRPA[1]	24^0 16' S, 53^0 20' W	20.8	1508	13 ; 10	62 ; 71	1.2 ; 0.6	5.3; 5.4	Rhodic Ferralsols	Latossolo Roxo	320
4 – MSMJ[1]	21^0 37' S, 55^0 10' W	23.4	1401	13 ; 10	62 ; 71	1.2 ; 0.6	5.3; 5.4	Rhodic Ferralsols	Latossolo Roxo escuro	384
7 – MTDI[1]	14^0 24' S, 56^0 25' W	25.8	1705	75 ; 78	18 ; 19	0.9 ; 0.6	4.3; 4.4	Rhodic Ferralsols	Latossolo Vermelho-Amarelo	350
8 – GOJA[1]	17^0 52' S, 51^0 41' W	23.3	1541	13 ; 10	62 ; 71	1.2 ; 0.6	5.3; 5.4	Rhodic Ferralsols	Latossolo Vermelho	710

[1] Presents 2^{nd} growing season; [2] Soil data refer to 0-30 and 30-100 cm depth, respectively; [3]FAO and Embrapa soil classifications (EMBRAPA, 2009; IUSS WORKING GROUP WRB, 2014); [4] SLLL; SDUL; and SAT are model parameters that refer to lower limit of plant extractable soil water (wilting point); drained upper limit (field capacity point); and saturated soil water content, respectively; [5]Typical period for each region (BRASIL, 2014);[6]15/09-25/09;[7] 10/02-20/02; [8] 15/10-25/10; [9] 25/01-05/02; [10] Crop harvested area per total county area, as an average of harvested area of the last five seasons (2009-2013) for 1^{st} and 2^{nd} season, respectively; [11]Average nitrogen management as urea topdress application at county or state level (FNP CONSULTORIA & COMÉRCIO, 2015).Spacing between rows of 0.8 and 0.45 m and plant density of 6.5 and 5.5 plants m^{-2} were adopted as average values for1^{st} and 2^{nd} maize growing season, respectively.

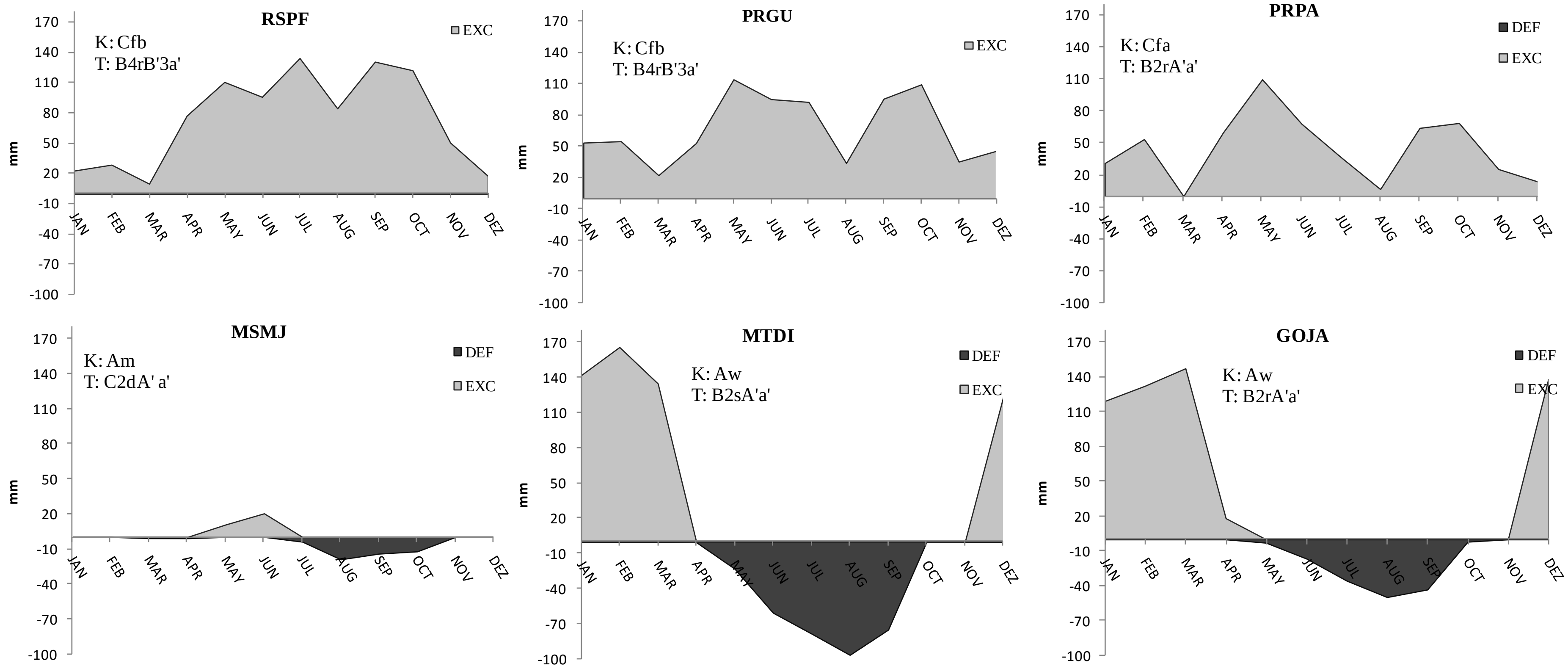
Annex A – Regions used in the present study and their main characteristics regarding climate, soil and crop management.

(conclusion)

Region	SLLL[4] 30; 100 cm $cm^3 cm^{-3}$	SDUL[4] 30; 100 cm $cm^3 cm^{-3}$	SAT[4] 30; 100 cm $cm^3 cm^{-3}$	Sowing window[5]	Maizeharvested area (%)[10]	Nitrogen management[11] (kg ha^{-1})
1 - RSPF	0.16; 0.25	0.25; 0.38	0.45; 0.52	6	3.2	90
2 - PRGU	0.25; 0.24	0.40; 0.39	0.60; 0.57	6	9.2	60
3 - PRPA[1]	0.28; 0.29	0.44; 0.44	0.52; 0.51	6, 7	13.4; 53.4	60; 45
4 - MSMJ[1]	0.28; 0.29	0.44; 0.44	0.52; 0.51	8, 7	0.3; 25.6	45; 40
5 - MTDI[1]	0.16; 0.15	0.25; 024	0.53; 0.66	8, 7	0.2; 7.3	45; 40
6 - GOJA[1]	0.28; 0.29	0.44; 0.44	0.51; 0.50	8, 9	2.1; 17.0	45; 40

[1] Presents 2nd growing season; [2] Soil data refer to 0-30 and 30-100 cm depth, respectively; [3] FAO and Embrapa soil classifications (EMBRAPA, 2009; IUSS WORKING GROUP WRB, 2014); [4] SLLL; SDUL; and SAT are model parameters that refer to lower limit of plant extractable soil water (wilting point); drained upper limit (field capacity point); and saturated soil water content, respectively; [5]Typical period for each region (BRASIL, 2014);[6]15/09-25/09;[7] 10/02-20/02; [8] 15/10-25/10; [9] 25/01-05/02; [10] Crop harvested area per total county area, as an average of harvested area of the last five seasons (2009-2013) for 1st and 2nd season, respectively; [11]Average nitrogen management as urea topdress application at county or state level (FNP CONSULTORIA & COMÉRCIO, 2015). Spacing between rows of 0.8 and 0.45 m and plant density of 6.5 and 5.5 plants m^{-2} were adopted as average values for 1st and 2nd maize growing season, respectively.

Annex B – Climate classification according to Koppen and Thorthwaite systems and Thornthwaite climatological water balance of the studied regions.



[1]"K" refers to Adapted Köppen climate classification (ALVARES et al., 2013) and "T" refers to Thornthwaite climate classification (THORNTHWAITE, 1948); [2] Figures presents the normal climatological water balance (1983-2013) (deficit and surplus periods for an availabe soil water capacity of 100 mm) according to Thornthwaite (THORNTHWAITE, 1948), adapted from Rolim et al. (1998) for the study regions.

Annex C – Summary of climate variables and its relationship with simulated yields (1983-2013) for the studied regions.

Scen.	----------------AVSR----------------				-----------------TMAX------------------				------------------TMIN---------------				--------------------TSRF------------------			
	CYCV	CV(%)	MEAN	SD	CYCV	CV(%)	MEAN	SD	CYCV	CV(%)	MEAN	SD	CYCV	CV(%)	MEAN	SD
1	-0.24	6.10	21.54	1.31	-0.28	5.10	27.16	1.40	0.17	3.50	16.14	0.56	0.58*	28.65	850.80	243.75
2	0.05	12.78	16.75	2.14	-0.14	3.61	26.29	0.95	-0.34	2.97	16.33	0.48	0.22	20.86	950.63	198.35
3	0.00	12.56	18.07	2.27	-0.35	4.26	30.12	1.28	-0.57*	3.23	19.63	0.63	0.35	22.97	841.64	193.37
4	0.34	13.47	12.24	1.66	0.00	5.14	26.88	1.38	-0.41*	5.89	16.84	0.99	0.06	39.56	653.73	258.67
5	-0.14	16.46	17.59	2.89	-0.34	4.92	31.42	1.54	-0.42*	2.84	21.27	0.60	0.65*	22.29	706.90	157.62
6	0.18	14.52	13.85	2.01	0.01	4.93	28.96	1.43	-0.33	4.02	18.15	0.73	0.42*	37.61	508.72	191.34
7	0.05	5.82	21.55	1.25	-0.34	2.24	32.55	0.72	-0.45*	3.72	22.22	0.82	0.47*	26.64	935.20	249.20
8	0.16	12.02	18.04	2.16	-0.19	1.47	32.13	0.47	0.25	4.05	20.21	0.82	0.32	29.56	667.06	197.21
9	0.03	3.51	19.91	0.70	0.15	1.68	30.73	0.51	-0.01	1.90	19.98	0.37	-0.07	17.28	936.00	161.77
10	-0.17	3.90	18.27	0.71	-0.43*	1.78	30.04	0.53	-0.15	3.23	17.69	0.57	0.11	20.10	745.27	149.80

Scen.: scenario referent to region and rowing season, where 1:RSPF, 2:PRGU, 3: PRPA (1st season), 4: PRPA (2nd season), 5: MSMJ (1st season), 6: MSMJ (2nd season), 7: MTDI (1st season), 8: MTDI (2nd season), 9: GOJA (1st season), 10: GOJA (2nd season); AVSR: Seasonal average solar radiation; TMAX: seasonal average maximum temperatures; TMIN seasonal average minimum temperatures; TSRF: tota seasonal rainfall; TSEP: total seasonal evapotranspiration; CYCV: correlation of simulated yields with climate variables (-1 to 1); CV: coefficient of variation (%); SD: standard deviation (unit of the variable); MEAN: seasonal average of the climate variable; * indicates significance (5% of probability from t test).

Annex D – Yield reference levels comparison test by constrasts.

(continued)

Treatments						Comparison
Yield level	Region	Season	Yield level	Region	Season	
Yp	GOJA	S1	Yp	GOJA	S2	**
Yp	GOJA	S1	Yp	MSMJ	S1	ns
Yp	GOJA	S1	Yp	MSMJ	S2	**
Yp	GOJA	S1	Yp	MTDI	S1	**
Yp	GOJA	S1	Yp	MTDI	S2	**
Yp	GOJA	S1	Yp	PRGU	S1	ns
Yp	GOJA	S1	Yp	PRPA	S1	**
Yp	GOJA	S1	Yp	PRPA	S2	**
Yp	GOJA	S1	Yp	RSPF	S1	ns
Yp	GOJA	S1	Yw	GOJA	S1	ns
Yp	GOJA	S1	Yw	GOJA	S2	**
Yp	GOJA	S1	Yw	MSMJ	S1	**
Yp	GOJA	S1	Yw	MSMJ	S2	**
Yp	GOJA	S1	Yw	MTDI	S1	**
Yp	GOJA	S1	Yw	MTDI	S2	**
Yp	GOJA	S1	Yw	PRGU	S1	ns
Yp	GOJA	S1	Yw	PRPA	S1	ns
Yp	GOJA	S1	Yw	PRPA	S2	**
Yp	GOJA	S1	Yw	RSPF	S1	**
Yp	GOJA	S2	Yp	MSMJ	S1	**
Yp	GOJA	S2	Yp	MSMJ	S2	ns
Yp	GOJA	S2	Yp	MTDI	S1	**
Yp	GOJA	S2	Yp	MTDI	S2	**
Yp	GOJA	S2	Yp	PRGU	S1	**
Yp	GOJA	S2	Yp	PRPA	S1	**
Yp	GOJA	S2	Yp	PRPA	S2	ns
Yp	GOJA	S2	Yp	RSPF	S1	**
Yp	GOJA	S2	Yw	GOJA	S1	**
Yp	GOJA	S2	Yw	GOJA	S2	ns
Yp	GOJA	S2	Yw	MSMJ	S1	**
Yp	GOJA	S2	Yw	MSMJ	S2	ns
Yp	GOJA	S2	Yw	MTDI	S1	ns
Yp	GOJA	S2	Yw	MTDI	S2	ns
Yp	GOJA	S2	Yw	PRGU	S1	**
Yp	GOJA	S2	Yw	PRPA	S1	**
Yp	GOJA	S2	Yw	PRPA	S2	ns
Yp	GOJA	S2	Yw	RSPF	S1	ns
Yp	MSMJ	S1	Yp	MSMJ	S2	**
Yp	MSMJ	S1	Yp	MTDI	S1	**
Yp	MSMJ	S1	Yp	MTDI	S2	ns
Yp	MSMJ	S1	Yp	PRGU	S1	ns
Yp	MSMJ	S1	Yp	PRPA	S1	**

(continued)

Yp	MSMJ	S1	Yp	PRPA	S2	**
Yp	MSMJ	S1	Yp	RSPF	S1	ns
Yp	MSMJ	S1	Yw	GOJA	S1	ns
Yp	MSMJ	S1	Yw	GOJA	S2	**
Yp	MSMJ	S1	Yw	MSMJ	S1	**
Yp	MSMJ	S1	Yw	MSMJ	S2	**
Yp	MSMJ	S1	Yw	MTDI	S1	**
Yp	MSMJ	S1	Yw	MTDI	S2	**
Yp	MSMJ	S1	Yw	PRGU	S1	ns
Yp	MSMJ	S1	Yw	PRPA	S1	ns
Yp	MSMJ	S1	Yw	PRPA	S2	**
Yp	MSMJ	S1	Yw	RSPF	S1	**
Yp	MSMJ	S2	Yp	MTDI	S1	ns
Yp	MSMJ	S2	Yp	MTDI	S2	**
Yp	MSMJ	S2	Yp	PRGU	S1	**
Yp	MSMJ	S2	Yp	PRPA	S1	**
Yp	MSMJ	S2	Yp	PRPA	S2	ns
Yp	MSMJ	S2	Yp	RSPF	S1	**
Yp	MSMJ	S2	Yw	GOJA	S1	**
Yp	MSMJ	S2	Yw	GOJA	S2	ns
Yp	MSMJ	S2	Yw	MSMJ	S1	ns
Yp	MSMJ	S2	Yw	MSMJ	S2	ns
Yp	MSMJ	S2	Yw	MTDI	S1	ns
Yp	MSMJ	S2	Yw	MTDI	S2	ns
Yp	MSMJ	S2	Yw	PRGU	S1	**
Yp	MSMJ	S2	Yw	PRPA	S1	**
Yp	MSMJ	S2	Yw	PRPA	S2	ns
Yp	MSMJ	S2	Yw	RSPF	S1	ns
Yp	MTDI	S1	Yp	MTDI	S2	ns
Yp	MTDI	S1	Yp	PRGU	S1	**
Yp	MTDI	S1	Yp	PRPA	S1	**
Yp	MTDI	S1	Yp	PRPA	S2	ns
Yp	MTDI	S1	Yp	RSPF	S1	**
Yp	MTDI	S1	Yw	GOJA	S1	**
Yp	MTDI	S1	Yw	GOJA	S2	**
Yp	MTDI	S1	Yw	MSMJ	S1	ns
Yp	MTDI	S1	Yw	MSMJ	S2	**
Yp	MTDI	S1	Yw	MTDI	S1	ns
Yp	MTDI	S1	Yw	MTDI	S2	ns
Yp	MTDI	S1	Yw	PRGU	S1	**
Yp	MTDI	S1	Yw	PRPA	S1	**
Yp	MTDI	S1	Yw	PRPA	S2	ns
Yp	MTDI	S1	Yw	RSPF	S1	ns
Yp	MTDI	S2	Yp	PRGU	S1	**
Yp	MTDI	S2	Yp	PRPA	S1	**

(continued)

Yp	MTDI	S2	Yp	PRPA	S2	**
Yp	MTDI	S2	Yp	RSPF	S1	**
Yp	MTDI	S2	Yw	GOJA	S1	ns
Yp	MTDI	S2	Yw	GOJA	S2	**
Yp	MTDI	S2	Yw	MSMJ	S1	ns
Yp	MTDI	S2	Yw	MSMJ	S2	**
Yp	MTDI	S2	Yw	MTDI	S1	ns
Yp	MTDI	S2	Yw	MTDI	S2	**
Yp	MTDI	S2	Yw	PRGU	S1	ns
Yp	MTDI	S2	Yw	PRPA	S1	**
Yp	MTDI	S2	Yw	PRPA	S2	**
Yp	MTDI	S2	Yw	RSPF	S1	**
Yp	PRGU	S1	Yp	PRPA	S1	ns
Yp	PRGU	S1	Yp	PRPA	S2	**
Yp	PRGU	S1	Yp	RSPF	S1	ns
Yp	PRGU	S1	Yw	GOJA	S1	ns
Yp	PRGU	S1	Yw	GOJA	S2	**
Yp	PRGU	S1	Yw	MSMJ	S1	**
Yp	PRGU	S1	Yw	MSMJ	S2	**
Yp	PRGU	S1	Yw	MTDI	S1	**
Yp	PRGU	S1	Yw	MTDI	S2	**
Yp	PRGU	S1	Yw	PRGU	S1	ns
Yp	PRGU	S1	Yw	PRPA	S1	ns
Yp	PRGU	S1	Yw	PRPA	S2	**
Yp	PRGU	S1	Yw	RSPF	S1	**
Yp	PRPA	S1	Yp	PRPA	S2	**
Yp	PRPA	S1	Yp	RSPF	S1	**
Yp	PRPA	S1	Yw	GOJA	S1	**
Yp	PRPA	S1	Yw	GOJA	S2	**
Yp	PRPA	S1	Yw	MSMJ	S1	**
Yp	PRPA	S1	Yw	MSMJ	S2	**
Yp	PRPA	S1	Yw	MTDI	S1	**
Yp	PRPA	S1	Yw	MTDI	S2	**
Yp	PRPA	S1	Yw	PRGU	S1	**
Yp	PRPA	S1	Yw	PRPA	S1	**
Yp	PRPA	S1	Yw	PRPA	S2	**
Yp	PRPA	S1	Yw	RSPF	S1	**
Yp	PRPA	S2	Yp	RSPF	S1	**
Yp	PRPA	S2	Yw	GOJA	S1	**
Yp	PRPA	S2	Yw	GOJA	S2	ns
Yp	PRPA	S2	Yw	MSMJ	S1	ns
Yp	PRPA	S2	Yw	MSMJ	S2	ns
Yp	PRPA	S2	Yw	MTDI	S1	ns
Yp	PRPA	S2	Yw	MTDI	S2	ns
Yp	PRPA	S2	Yw	PRGU	S1	**

(continued)

Yp	PRPA	S2	Yw	PRPA	S1	**
Yp	PRPA	S2	Yw	PRPA	S2	ns
Yp	PRPA	S2	Yw	RSPF	S1	ns
Yp	RSPF	S1	Yw	GOJA	S1	ns
Yp	RSPF	S1	Yw	GOJA	S2	**
Yp	RSPF	S1	Yw	MSMJ	S1	**
Yp	RSPF	S1	Yw	MSMJ	S2	**
Yp	RSPF	S1	Yw	MTDI	S1	**
Yp	RSPF	S1	Yw	MTDI	S2	**
Yp	RSPF	S1	Yw	PRGU	S1	ns
Yp	RSPF	S1	Yw	PRPA	S1	ns
Yp	RSPF	S1	Yw	PRPA	S2	**
Yp	RSPF	S1	Yw	RSPF	S1	**
Yw	GOJA	S1	Yw	GOJA	S2	**
Yw	GOJA	S1	Yw	MSMJ	S1	**
Yw	GOJA	S1	Yw	MSMJ	S2	**
Yw	GOJA	S1	Yw	MTDI	S1	**
Yw	GOJA	S1	Yw	MTDI	S2	**
Yw	GOJA	S1	Yw	PRGU	S1	ns
Yw	GOJA	S1	Yw	PRPA	S1	ns
Yw	GOJA	S1	Yw	PRPA	S2	**
Yw	GOJA	S1	Yw	RSPF	S1	**
Yw	GOJA	S2	Yw	MSMJ	S1	**
Yw	GOJA	S2	Yw	MSMJ	S2	ns
Yw	GOJA	S2	Yw	MTDI	S1	ns
Yw	GOJA	S2	Yw	MTDI	S2	ns
Yw	GOJA	S2	Yw	PRGU	S1	**
Yw	GOJA	S2	Yw	PRPA	S1	**
Yw	GOJA	S2	Yw	PRPA	S2	ns
Yw	GOJA	S2	Yw	RSPF	S1	ns
Yw	MSMJ	S1	Yw	MSMJ	S2	**
Yw	MSMJ	S1	Yw	MTDI	S1	ns
Yw	MSMJ	S1	Yw	MTDI	S2	ns
Yw	MSMJ	S1	Yw	PRGU	S1	**
Yw	MSMJ	S1	Yw	PRPA	S1	**
Yw	MSMJ	S1	Yw	PRPA	S2	ns
Yw	MSMJ	S1	Yw	RSPF	S1	ns
Yw	MSMJ	S2	Yw	MTDI	S1	**
Yw	MSMJ	S2	Yw	MTDI	S2	ns
Yw	MSMJ	S2	Yw	PRGU	S1	**
Yw	MSMJ	S2	Yw	PRPA	S1	**
Yw	MSMJ	S2	Yw	PRPA	S2	ns
Yw	MSMJ	S2	Yw	RSPF	S1	ns
Yw	MTDI	S1	Yw	MTDI	S2	ns
Yw	MTDI	S1	Yw	PRGU	S1	**

(conclusion)

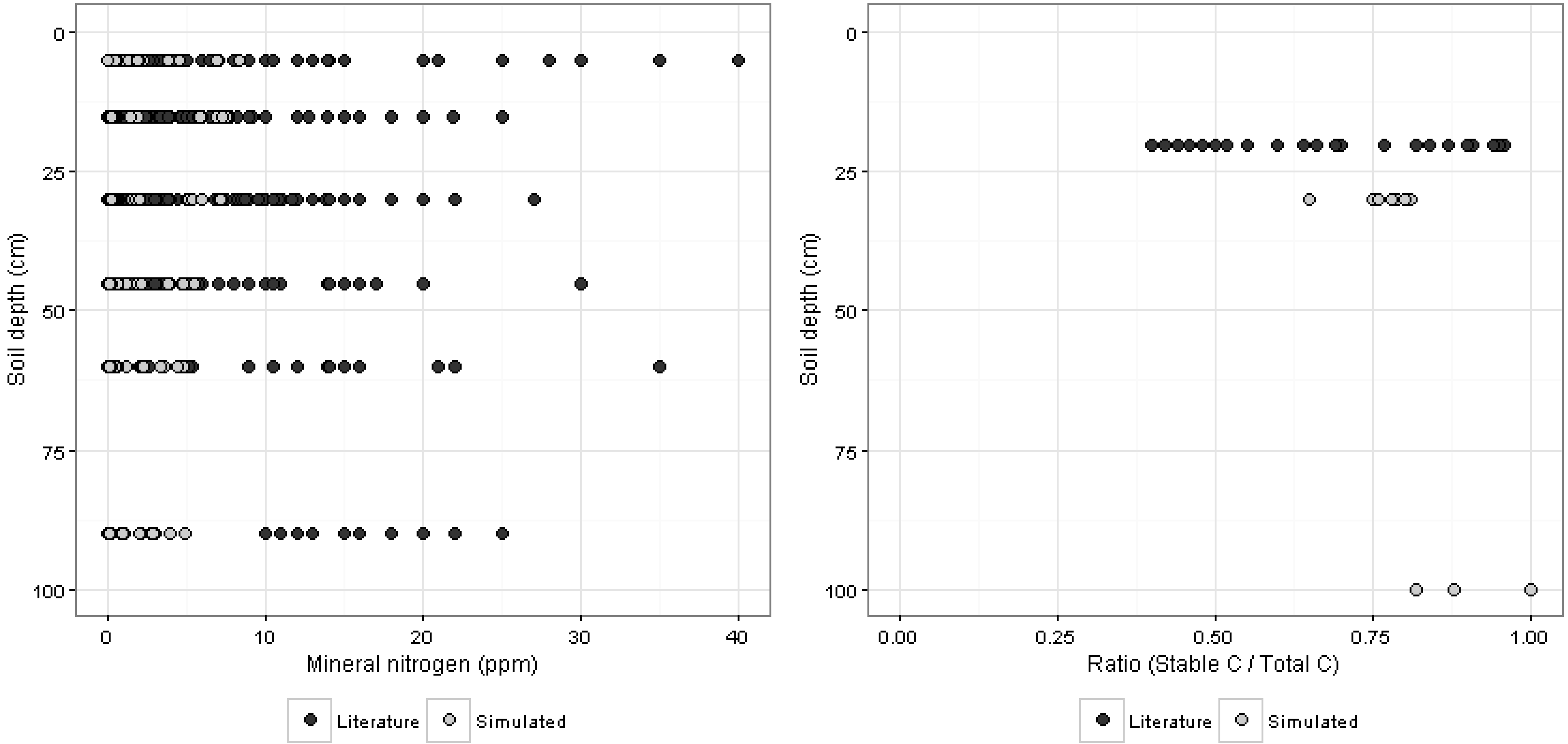
Yw	MTDI	S1	Yw	PRPA	S1	**
Yw	MTDI	S1	Yw	PRPA	S2	ns
Yw	MTDI	S1	Yw	RSPF	S1	ns
Yw	MTDI	S2	Yw	PRGU	S1	**
Yw	MTDI	S2	Yw	PRPA	S1	**
Yw	MTDI	S2	Yw	PRPA	S2	ns
Yw	MTDI	S2	Yw	RSPF	S1	ns
Yw	PRGU	S1	Yw	PRPA	S1	ns
Yw	PRGU	S1	Yw	PRPA	S2	**
Yw	PRGU	S1	Yw	RSPF	S1	**
Yw	PRPA	S1	Yw	PRPA	S2	**
Yw	PRPA	S1	Yw	RSPF	S1	**
Yw	PRPA	S2	Yw	RSPF	S1	ns

AnnexE – Reference of values of mineral N and stable C utilized for comparison with simulated values.

Number	Location (State / County)	Land use/ Management	Sampling depth (cm)	Predominant soil texture	Soil pH	Mean annual rainfall (mm)	Range of values[1]	Reference
1	MT / Comodoro	NV, PA, CS	0-20	Sandy	6.4	1900	0.06-1.2 / 0.8-1.5	(FRAZÃO et al., 2010)
2	MG / Araponga	NV, PA, CS	0-60	Clayey	5.5	1500	0.2-5.4/ 0-14.1	(ISMINIO, 2012)
3	GO / Morrinhos	NV, PA, CS	0-100	Clayey	5.5	1380	5-35/ 12-40	(D'ANDRÉA et al., 2004)
4	SP / Botucatu	CS	0-50	Medium	4.5	1320	4-11/ 3-16	(ROSOLEM; FOLONI; DE OLIVEIRA, 2003)
5	MG / Papagaios	CS	0-120	Clayey	5.5	1320	9-14/ 11-15	(ANDRADE et al., 2013)
6	RS / Eldorado do Sul	CS	0-30	Clayey	5.3	1340	1.5-9.9/ 1.3-13.8	(RAMBO et al., 2008)
7	MG / Uberlândia	CS	0-60	Clayey	5.1	1480	0.3-4.9/ 0.2-2.6	(LARA CABEZAS; SOUZA, 2008)
8	MG / Coimbra	NV, CS	0-20 cm	Clayey	5.2	1350	70-90	(LEITE; MENDONÇA; MACHADO, 2004)
9	RS / various counties	NV, CS	0-20 cm	Various (9 pofiles)	-	1320 to 1850	50-70	(FERNANDES, 2002)
10	MG / Sete Lagoas	NV, PCS, CS	0-20 cm	Very clayey	4.6	1320	90-95	(WENDLING et al., 2014)

[1] Range of values of mineral N references (numbers 1-7) refer to Nirate/Ammonia, both in ppm; range of values of stable C references (numbers 8-10) refer to the participation of stable C on soil's total organic C (SOC). NV: native vegetation; PA: pasture; CS: cropping system; PCS: perennial cropping system.

AnnexF – Comparison of simulated results of soil initial conditions related to mineral N and stable C pools with literature.



Obs: In this Figure, a summarization of values is presented. Mineral N and stable C were simulated for all soil layers in the profile (0-120 cm). Stable C values are presented as the average of 0-30 and 30-120 cm of soil). Total C is the soil's total organic C.

AnnexG - Cultivar trial data utilized in the calibration and validation processes. Set I was used for calibration and set II for validation.

Region	Season (Set)	Sowing date (dd/mm)	Plantdensity (pl m^{-2})	DFF[1] (days)	DFH[2] (days)	Yield (t ha^{-1})	Source
RSPF	2009/10 (I)	25/10	6.9	68	152	9.5	(BERGAMASCHI et al., 2013; EMBRAPA, 2010)
	2010/11; 2009/10 (II)	19/10; 03/11	6.9; 5.6	68	184	13.1; 7.9	
PRGU	2011/12; 2010/11 (I)	18/10; 08/10	6.8; 6.9	80; 80	183; 179	13.9; 13.2	(EMBRAPA, 2013; SHIOGA et al., 2011, 2012, 2013)
	2012/13; 2012/13 (II)	09/10; 13/10	6.7; 6.0	75; 78	195; 183	14.0; 12.6	
PRPA	2009/10; 2010/11 (I)	14/10; 13/10	7.1; 5.3	59; 59	161; 161	11.9; 12.6	(EMBRAPA, 2008; SHIOGA et al., 2010, 2011, 2012)
	2007/08; 2011/12 (II)	25/10; 05/10	6.3; 6.5	59; 59	145; 147	10.1; 11.6	
PRPA	2010; 2005 (I)	18/03; 30/03	6.1; 5.5	65; 59	159; 163	6.3; 7.1	(EMBRAPA, 2010; STULP, 2007)
	2005; 2005 (II)	30/01; 15/02	5.5; 6.0	59; 59	163; 163	5.2; 6.7	
MSMJ	2010/11 (I)	10/10; 29/11	5.1; 5.9	58; 60	141; 131	10.1	(EMBRAPA, 2010, 2011; LOURENÇÃO, 2011)
	2010/11; 2009/10 (II)	24/11; 18/11	5.6; 9.0	61; 63	166; 166	9.2	
MSMJ	2011 (I)	10/02	5.5	63	160	6.3	(AGROESTE, 2011; EMBRAPA, 2010)
	2010 (II)	11/02	6.3	63	161	9.8	
MTDI	2012/13 (I)	08/11	7.0	59	120	8.6	(EMBRAPA, 2012, 2013)
	2011/12 (II)	28/09	6.2	57	120	11.2	
MTDI	2013 (I)	04/02	5.2	61	150	8.3	(ASSUNÇÃO; FRASSON, 2013; EMBRAPA, 2012)
	2012; 2013 (II)	22/02; 15/02	5.6; 5.5	59; 57	152; 153	8.8; 9.2	
GOJA	2012/13 (I)	05/12	7.3	58	151	12.1	(EMBRAPA, 2013)
	2012/13 (II)	30/10	7.9	65	151	16.4	
GOJA	2013 (I)	13/01	6.4	60	128	6.2	(LEÃO, 2008; RODRIGUES JUNIOR, 2013)
	2007 (II)	16/02	5.5	60	136	7.5	

[1] Days for anthesis; [2] days for harvest of the trial.

AnnexH– Genetic coefficients of early season cultivar calibrated in DSSAT for each studied region and season

Region	Growing season	Genetic coefficients[1]					
		P1	P2	P5	G2	G3	PHINT
RSPF	1	240.0	0.5	1300.0	690.0	6.2	42.0
PRGU	1	300.0	0.5	1460.0	700.0	7.0	42.0
PRPA	1	240.0	0.5	1600.0	860.0	8.5	42.0
PRPA	2	215.0	0.5	1000.0	850.0	7.2	42.0
MSMJ	1	240.0	0.5	1500.0	800.0	7.6	42.0
MSMJ	2	230.0	0.5	1200.0	690.0	6.1	42.0
MTDI	1	255.0	0.5	1100.0	800.0	7.5	42.0
MTDI	2	290.0	0.5	1500.0	750.0	5.3	42.0
GOJA	1	245.0	0.5	1150.0	800.0	8.6	42.0
GOJA	2	245.0	0.5	1130.0	690.0	5.0	42.0

[1]P1 is 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; P2 is the 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); P5 is the thermal time from silking to physiological maturity (expressed in degree days above a base temperature of 8°C) (in practice, in the present study P5 was considered to be degree days from silking to observed harvest, as physiological maturity was not observed); G2 is the Maximum possible number of kernels per plant; G3 is the Kernel filling rate during the linear grain filling stage and under optimum conditions (mg kernel^{-1} day^{-1}) and PHINT is Phylochron interval; the interval in thermal time (degree days) between successive leaf tip appearances. P2 was considered as 0.5, a common value for tropical hybrids, since daylength is usually lower than critical photoperiod (12.5 h) which also decreases in 2nd season. PHINT or phyllochron interval was adopted as an average of experiments of an early season cultivar in Southeastern region of Brazil (SOLER; SENTELHAS; HOOGENBOOM, 2005)

AnnexI -Absolute differences between observed and simulated values of phenology and yield for model evaluation

Region	Growing season	------Daystoanthesis----- (days)		-----Daystomaturity----- (days)		------Grain yield[1]------- (kg ha^{-1})	
		Observed	Simulated	Observed	Simulated	Observed	Simulated
RSPF	1	68	69	184	154	13113	14254
RSPF	1	68	66	184	152	7950	9192
PRGU	1	75	71	195	190	14003	14652
PRGU	1	78	69	183	192	12597	12663
PRPA	1	59	55	145	141	10117	10595
PRPA	1	59	56	147	139	11623	10847
PRPA	2	59	53	163	122	5220	5959
PRPA	2	59	51	163	122	6770	7239
MSMJ	1	61	53	166	143	10601	10174
MSMJ	1	63	57	166	146	9427	8382
MSMJ	2	63	59	161	153	9875	9546
MTDI	1	57	53	120	111	11265	12970
MTDI	2	59	60	152	151	8792	7402
MTDI	2	57	60	153	145	9222	8605
GOJA	1	65	56	151	122	16458	18497
GOJA	2	60	59	136	136	7515	7370

[1] kg ha^{-1}

AnnexJ - Statistical parameters of model evaluation of an early season maize cultivar related to phenology and yield for each studied region.

Region	Growing season	RMSE			MAE		
		Yield[1]	DFA[2]	DFM[3]	Yield	DFA	DFM
RSPF	1	1192	1.6	31	1191	1.5	31
PRGU	1	461	6.9	7.3	357	6.5	7
PRPA	1	644	3.5	6.3	627	3.5	6
PRPA	2	618	7.1	41	603	7	41
MSMJ	1	798	7.1	21.5	736	7	21.5
MSMJ	2	329	4	8	329	4	8
MTDI	1	1704	4	9	1704	4	9
MTDI	2	1076	2.2	5.7	1004	2	4.5
GOJA	1	2038	9	29	2038	9	29
GOJA	2	145	1	0	145	1	0

[1]kg ha^{-1}; [2] days for anthesis; [3] days for maturity.

AnnexK - Characterization of average nitrogen management through topdress urea application of studied regions.

Region	Growing season	Average Nitrogen management (kg ha^{-1})	Tractor	Implement
RS	1	90-135	Tractor 66kW	Fertilizer distributor (1.4 m^3)
PR	1	70-200	Tractor 66kW	Fertilizer distributor (1.4 m^3)
PR	2	45	Tractor 66kW	Fertilizer distributor (1.4 m^3)
MS	2	40	Tractor 88kW	Fertilizer distributor (2.3 m^3)
MT	2	40-60	Tractor 88kW	Fertilizer distributor (2.3 m^3)
GO	1	45-100	Tractor 88kW	Fertilizer distributor (2.3 m^3)
GO	2	40-70	Tractor 88kW	Fertilizer distributor (2.3 m^3)

The N management information was obtained from national database (FNP CONSULTORIA & COMÉRCIO, 2015) and from contact with research institutes (not-published): “CEPEA” (Center for Advanced Studies in Applied Economics) and “Cooperativa Agrária Agroindustrial” (Agrarian Cooperative Agroindustrial) which provided data on all region’s and Paraná state, respectively, average N management of maize. Typical field speed for fertilizer aplication was considered as 11 km h^{-1}; useful life of tractor and implement were considered as 12000 and 2000 hours, respectively, according to ASAE standard D497.7 (ASABE, 2011). Mass and work width were adopted from manufacturer’s manual: 7 and 5.1 t for the 125 cv and 90 cv tractors, and 1.1 and 0.8 t for fertilizer distributors of 2.3 and 1.4 m^3, respectively.Annual use of machinery was adopted as 600 and 300 h for tractors and fertilizer distributors, respectively(ASABE, 2011).

AnnexL - Material flow of N application scenarios for Mid-Western regions (MSMJ, MTDI, GOJA) (continued)

N (Urea) rate (kg ha^{-1})	Ofc (ha h^{-1})	To (h ha^{-1})	Efi (%)	Fuel (L ha^{-1})	Depreciation of tractor (kg ha^{-1})	Depreciation of implement (kg ha^{-1})
20 (44)	10.58	0.09	0.96	1.36	0.06	0.08
40 (89)	10.19	0.10	0.93	1.41	0.06	0.09
60 (133)	9.82	0.10	0.89	1.46	0.06	0.09
80 (178)	9.48	0.11	0.86	1.51	0.06	0.09
90(200)	9.32	0.11	0.85	1.54	0.06	0.10
100 (222)	9.17	0.11	0.83	1.56	0.06	0.10
120 (267)	8.87	0.11	0.81	1.62	0.07	0.10
140 (311)	8.60	0.12	0.78	1.67	0.07	0.10
160 (356)	8.34	0.12	0.76	1.72	0.07	0.11
180 (400)	8.09	0.12	0.74	1.77	0.07	0.11
200 (444)	7.86	0.13	0.71	1.82	0.07	0.11
220 (489)	7.64	0.13	0.69	1.88	0.08	0.12
240 (533)	7.44	0.13	0.68	1.93	0.08	0.12
260 (578)	7.24	0.14	0.66	1.98	0.08	0.12
280 (622)	7.05	0.14	0.64	2.03	0.08	0.13
300 (667)	6.88	0.15	0.63	2.09	0.08	0.13
320 (711)	6.71	0.15	0.61	2.14	0.09	0.13
340 (755)	6.55	0.15	0.60	2.19	0.09	0.14
360 (800)	6.40	0.16	0.58	2.24	0.09	0.14
380 (844)	6.25	0.16	0.57	2.29	0.09	0.14
400 (889)	6.12	0.16	0.56	2.35	0.10	0.15

Input prices utilized were average values for the study regions (FNP CONSULTORIA & COMÉRCIO, 2015), where urea and labor prices were of R$ 1165.0 t^{-1} and R$ 7.0 h^{-1}, respectively. As for tractor prices, they were of R$ 105.0 h^{-1} and R$ 90.0 h^{-1} for Mid-western and Southern regions, respectively. Implement prices were of R$ 20.0 h^{-1} and R$ 14.0 h^{-1}, respectively. Input's embodied energy contents were of 56.3 MJ kg^{-1} for nitrogen (IPT, 1986); 45.7 MJ l^{-1} for diesel (BOUSTEAD; HANCOCK, 1979); 69.8 and 57.2 MJ kg^{-1} for tractor and implement, respectively (MACEDÔNIO; PICCHIONI, 1985) and 15 MJ kg^{-1} for maize harvested grain (PIMENTEL; BURGESS, 1980).

Annex L– Material flow of N application scenarios for Southern regions (RSPF, PRGU, PRPA) (conclusion)

N (Urea)rate (kg ha^{-1})	Ofc (ha h^{-1})	To (h ha^{-1})	Efi (%)	Fuel (L ha^{-1})	Depreciation of tractor (kg ha^{-1})	Depreciation of implement (kg ha^{-1})
20 (44)	10.32	0.10	0.94	1.04	0.04	0.06
40 (89)	9.72	0.10	0.88	1.11	0.04	0.07
60 (133)	9.19	0.11	0.84	1.17	0.05	0.07
80 (178)	8.71	0.11	0.79	1.23	0.05	0.08
90(200)	8.49	0.12	0.77	1.27	0.05	0.08
100 (222)	8.28	0.12	0.75	1.30	0.05	0.08
120 (267)	7.89	0.13	0.72	1.36	0.05	0.08
140 (311)	7.54	0.13	0.69	1.43	0.06	0.09
160 (356)	7.21	0.14	0.66	1.49	0.06	0.09
180 (400)	6.91	0.14	0.63	1.56	0.06	0.10
200 (444)	6.64	0.15	0.60	1.62	0.06	0.10
220 (489)	6.39	0.16	0.58	1.68	0.07	0.10
240 (533)	6.15	0.16	0.56	1.75	0.07	0.11
260 (578)	5.94	0.17	0.54	1.81	0.07	0.11
280 (622)	5.73	0.17	0.52	1.88	0.07	0.12
300 (667)	5.54	0.18	0.50	1.94	0.08	0.12
320 (711)	5.37	0.19	0.49	2.01	0.08	0.12
340 (755)	5.20	0.19	0.47	2.07	0.08	0.13
360 (800)	5.04	0.20	0.46	2.13	0.08	0.13
380 (844)	4.90	0.20	0.45	2.20	0.09	0.14
400 (889)	4.76	0.21	0.43	2.26	0.09	0.14

Input prices utilized were average values for the study regions (FNP CONSULTORIA & COMÉRCIO, 2015), where urea and labor prices were of R$ 1165.0 t^{-1} and R$ 7.0 h^{-1}, respectively. As for tractor prices, they were of R$ 105.0 h^{-1} and R$ 90.0 h^{-1} for Mid-western and Southern regions, respectively. Implement prices were of R$ 20.0 h^{-1} and R$ 14.0 h^{-1}, respectively. Input's embodied energy contents were of 56.3 MJ kg^{-1} for nitrogen (IPT, 1986); 45.7 MJ l^{-1} for diesel (BOUSTEAD; HANCOCK, 1979); 2.2 MJ h^{-1} for labor (SERRA et al. 1979); 69.8 and 57.2 MJ kg^{-1} for tractor and implement, respectively (MACEDÔNIO; PICCHIONI, 1985) and 15 MJ kg^{-1} for maize harvested grain (PIMENTEL; BURGESS, 1980)

Annex M – Average values of simulated yields under N rates (t ha^{-1}) during 30 years of weather data

Region	Growing season	N rate (kg ha^{-1}) 0	20	40	60	80	90	100	120	140	160	180	200	220	240	260	280	300	320	340	360	380	400
RSPF	1	3.6	4.5	5.6	6.8	7.9	8.3	8.7	9.1	9.5	9.9	10.5	10.6	10.7	10.7	10.6	10.5	10.4	10.4	10.3	10.3	10.3	10.3
PRGU	1	8.0	9.0	10.2	11.2	12.1	12.5	12.9	12.9	13.3	13.7	14.2	14.5	14.7	14.9	15.0	15.1	15.3	15.3	15.4	15.5	15.5	15.5
PRPA	1	6.5	7.7	8.9	9.9	10.8	11.1	11.4	11.5	12.0	12.4	13.5	13.9	14.3	14.6	15.0	15.3	15.7	15.9	16.2	16.4	16.7	16.9
PRPA	2	5.3	6.5	7.4	8.0	8.5	8.7	8.9	9.1	9.3	9.5	9.7	9.8	9.8	9.8	9.9	9.9	9.9	9.9	9.9	9.9	9.9	9.9
MSMJ	1	8.6	9.4	10.0	10.5	10.8	11.0	11.2	11.4	11.6	11.9	12.2	12.3	12.3	12.4	12.4	12.4	12.4	12.4	12.5	12.5	12.5	12.5
MSMJ	2	3.2	4.5	5.7	6.7	7.3	7.4	7.6	7.6	7.7	7.8	7.7	7.7	7.7	7.7	7.7	7.6	7.6	7.6	7.6	7.6	7.6	7.6
MTDI	1	4.1	5.3	6.6	7.9	9.0	8.9	9.7	10.0	10.3	10.4	10.4	10.5	10.6	10.6	10.6	10.6	10.6	10.6	10.6	10.7	10.6	10.6
MTDI	2	3.0	3.9	4.8	5.6	6.4	6.5	7.1	7.7	7.9	7.9	7.8	7.8	7.8	7.8	7.8	7.8	7.9	7.9	7.9	7.9	7.9	7.9
GOJA	1	8.1	9.3	10.4	11.2	11.8	12.0	12.3	12.4	12.7	13.0	13.7	13.9	14.0	14.1	14.2	14.2	14.3	14.3	14.4	14.4	14.4	14.4
GOJA	2	4.3	5.4	6.6	7.4	7.8	8.0	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1
Mean	1	6.5	7.5	8.6	9.6	10.4	10.6	11.0	11.2	11.6	11.9	12.4	12.6	12.8	12.9	13.0	13.0	13.1	13.2	13.2	13.3	13.3	13.4
	2	4.0	5.1	6.1	6.9	7.5	7.6	7.9	8.1	8.3	8.3	8.3	8.3	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4

Regression equations and coefficient of determination, determined for all simulated years and N rates, presented in the same order of regions and growing seasons as in Annex M were: (i)* $3993 + 51x – 0.094x^2$, R^2= 0.38; (ii)* $8622 + 43x – 0.067x^2$, R^2= 0.51; (iii)* $7109 + 44x – 0.049x^2$, R^2= 0.74; (iv)* $6163 + 29x – 0.051x^2$, R^2= 0.34; (v)* $9022 + 24x – 0.040x^2$, R^2= 0.11; (vi)* $4574 + 28x – 0.056x^2$, R^2= 0.23; (vii)* $5111 + 45x – 0.082x^2$, R^2= 0.33; (viii)* $3678 + 35x – 0.064x^2$, R^2= 0.50; (ix)* $8812 + 37x – 0.059x^2$, R^2= 0.58; (x)* $5518 + 24x – 0.047x^2$, R^2= 0.43. Symbol (*) indicates at least one difference among tested treatments (N rates) within each location (F test, 5% of probability). Model derivation indicated N rates that provided the maximum yields in the studied regions, presented in the same order as Table in Annex M, 271; 320; 449; 284; 300; 250; 274; 273; 314 and 255 kg ha^{-1}, respectively.

Annex N – Economic and energy demand per area for N application scenarios

N Scenario	------------Economic (R$ ha^{-1})---------- Fertilizer	Machinery[1] (MW / ST)[2]	---------------------------Energy (MJ ha^{-1})------------------------ Fertilizer	Machinery (MW / ST)	Fuel (MW / ST)2
20	51.8	11.8 / 10.1	1126	8.7 / 6.6	62.0 / 47.6
40	103.6	12.2 / 10.7	2252	9.0 / 7.0	64.4 / 50.6
60	155.3	12.7 / 11.3	3378	9.4 / 7.4	66.7 / 53.5
80	207.1	13.1 / 11.9	4504	9.7 / 7.8	69.1 / 56.4
90	233.0	13.4 / 12.2	5067	9.9 / 8.0	70.3 / 57.9
100	258.9	13.6 / 12.6	5630	10.0 / 8.2	71.5 / 59.4
120	310.7	14.0 / 13.2	6756	10.4 / 8.6	73.9 / 62.3
140	362.4	14.5 / 13.8	7882	10.7 / 9.0	76.3 / 65.2
160	414.2	14.9 / 14.4	9008	11.0 / 9.4	78.6 / 68.2
180	466.0	15.4 / 15.0	10134	11.4 / 9.8	81.0 / 71.1
200	517.8	15.9 / 15.7	11260	11.7 / 10.2	83.4 / 74.0
220	569.6	16.3 / 16.3	12386	12.0 / 10.6	85.8 / 77.0
240	621.3	16.8 / 16.9	13512	12.0 / 11.0	88.2 / 79.9
260	673.1	17.2 / 17.5	14638	12.7 / 11.4	90.5 / 82.8
280	724.9	17.7 / 18.1	15764	13.0 / 11.8	92.9 / 85.8
300	776.7	18.1 / 18.8	16890	13.3 / 12.2	95.3 / 88.7
320	828.4	18.6 / 19.4	18016	13.7 / 12.6	97.7 / 91.6
340	880.2	19.0 / 20.0	19142	14.0 / 13.0	100.1 / 94.6
360	932.0	19.5 / 20.6	20268	14.4 / 13.4	102.4 / 97.5
380	983.8	19.9 / 21.2	21394	14.7 / 13.9	104.8 / 100.4
400	1035.6	20.4 / 21.9	22520	15.0 / 14.3	107.2 / 103.4

[1] Economic cost of fuel in included in machinery's cost; [2] MW refers to regions of Mid-Western Brazil: MSMJ, MTDI, GOJA; ST refers to regions of Southern Brazil: RSPF, PRGU, PRPA.