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Soybean and maize off-season sowing dates when cultivated in succession: impacts of climate variability on yield and profitability

Rogério de Souza Nóia Júnior

Dissertation presented to obtain the degree of Master in Science. Area: Agricultural Systems Engineering

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Rogério de Souza Nóia Junior
Agronomist

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Advisor:
Prof. Dr. **PAULO CESAR SENTELHAS**

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Fernando Pessoa

CONTENTS

RESUMO

Soja e milho safrinha cultivados em sucessão: impactos da variabilidade climática na produtividade e rentabilidade

Na última década, a soja e o milho safrinha, cultivados em sucessão no Brasil, contribuíram com 23.8 ± 1.9% e 6.9 ± 0.9 % da produção mundial, respectivamente. Mais de 80% da soja e do milho brasileiro são produzidos em condições de sequeiro, o que resulta em uma alta variabilidade interanual da produtividade e, consequentemente, aumenta os riscos de falhas no abastecimento alimentar no Brasil e no mundo. Entre os fenômenos causadores da variabilidade climática e da produtividade agrícola no Brasil, o El Niño Oscilação Sul (ENOS) é o mais importante. A melhor maneira para minimizar os impactos do ENOS, principalmente os associados ao déficit hídrico em culturas de sequeiro, é definindo as datas de semeaduras mais favoráveis, onde as chances de grandes perdas são menores. Assim, os objetivos deste estudo foram: determinar a melhor data de semeadura para o sistema de produção em sucessão soja – milho safrinha, baseado na rentabilidade econômica em escala nacional; indicar a influência das fases do ENOS (El Niño, La Niña e Neutro) sobre a sucessão soja – milho safrinha em escala espacial e temporal, em diferentes datas de semeaduras; e determinar a magnitude da quebra de produtividade da sucessão soja – milho safrinha devido ao déficit hídrico e ao manejo sub ótimo do cultivo. Para atingir os objetivos, simulações de produtividade para soja e milho safrinha foram realizadas usando três modelos de simulação de cultura (FAO-AZM, DSSAT e APSIM), previamente calibrados, em uma abordagem multi-modelos. As produtividades das culturas da soja e do milho foram simuladas para 29 locais em 12 estados, com as datas de semeadura da soja variando de 21 de setembro a 1º. de janeiro, para um período de 34 anos (1980-2013). A semeadura do milho ocorreu imediatamente após a colheita da soja. A data de semeadura ótima para a sucessão soja – milho safrinha variou de acordo com a região brasileira, tendo o déficit hídrico, radiação solar e a temperatura do ar como as principais variáveis que influenciam o sistema. As fases do ENOS afetaram a produtividade da soja e do milho safrinha no Brasil, tendo, efeitos opostos durante as fases quentes (El Niño) e frias (La Niña). Os impactos das fases do ENOS também variaram de acordo com as datas de semeadura. As quebras de produtividade da sucessão soja – milho safrinha variaram entre os locais, datas de semeadura e safras. Entretanto, as quebras de produtividade causadas pelo déficit hídrico foram, em média, superiores àquelas causadas pelo manejo subótimo das culturas, o que pode ser explicado pela alta variabilidade espacial e interanual das condições meteorológicas no território brasileiro.

Palavras-chave: Modelagem de crescimento de cultura, Produtividade potencial, Atingível e real, Déficit hídrico, Manejo de culturas agrícolas

ABSTRACT

Soybean and maize off-season sowing dates when cultivated in succession: impacts of climate variability on yield and profitability

In the last decade, Brazilian soybean and maize, cultivated in succession, accounted for 23.8 ± 1.9% and 6.9 ± 0.9 % of world´s production, respectively. More than 80% of soybean and maize production in Brazil is under rainfed conditions, which results in a high interannual yield variability and, consequently, increasing the risks for food supply, not only in the country but also around the world. Among the natural phenomena that cause climate and yield variability in Brazil, El Niño Southern Oscillation (ENSO) is the most important. The best way to minimize the impacts of ENSO, mainly those associated to water deficit in rainfed crops, is by defining the most favorable sowing dates, when the probability of crop failure is small. Based on that, this study aimed: to determine the best sowing dates for the soybean-maize production system, based on the economic profitability at national scale; to assess the influence of the ENSO phases (El Niño, La Niña and Neutral) on spatial and temporal soybean and maize off-season yield variabilities for different sowing dates; and to determine the magnitude of the current soybean–maize succession yield gap due to water deficit and crop management in different Brazilian producing regions. To achieve such goals, soybean and maize off-season simulations were performed using three previously calibrated and validated crop simulation models (FAO-AZM, DSSAT and APSIM), in a multi-model approach. Soybean and maize yields were simulated for 29 locations in 12 states, with soybean sowing dates ranging from 21st September to 1st January, for a period of 34 years (1980–2013). Maize sowings were simulated in the same day soybean was harvested. The optimal sowing dates for soybean-maize succession varied according to the Brazilian region, with water deficit, solar radiation and air temperature being the main weather variables that influenced this crop system. ENSO phases affected soybean and maize yields across the country, having, in general, opposite effects during the warm (El Niño) and cold (La Niña) phases, but also depending on the sowing date considered. The yield gap (YG) of soybean-maize succession varied among locations, sowing dates and growing seasons. However, the yield gaps caused by water deficit (YGw) were, on average, higher than those caused by sub-optimal crop management (YGm), which can be explained by the high inter-annual and spatial climate variability observed in the Brazilian territory.

Keywords: Crop modeling, Potential, Attainable and actual crop yield, Water deficit, Crop management

1. GENERAL INTRODUCTION

1.1. Introduction

World food security is the major challenge for the human society in the next decades (FAO, 2018). Food demand has increased in an exponential way since 1961, which was also accompanied by changes in the consumption patterns (COLE et al., 2018). The current food demand has been partially supplied by a combination of measures, involving technological advances, governmental policies, agricultural innovation and improvements in the infrastructure for food distribution (KEATING et al., 2014). However, according to FAO (2018), during 2017 a total of 821 million people was undernourished, which has requiring immediate actions to improve agricultural production, either by increasing production area or yields. The challenge is even bigger if considering that by 2050 the world´s population will achieve 9.7 billion people, which will require an increase of 70% in food production (COLE et al., 2018; GODFRAY et al., 2010).

Among the countries with potential to meet the world´s food demand, Brazil appears as the main one, considering both area available for agriculture expansion and possibility of crop yield improvements (RAY et al., 2012). According to FAO (2018), Brazil accounts for about 6.5% of world´s grain production. Soybean and maize crops together are responsible for about 90% of Brazilian grain production (CONAB, 2018). These crops are normally cultivated in succession, which is known as soybean–maize off-season crop system. Even considering the importance of these two crops in the country, their yields can still be substantially improved (BATTISTI et al., 2018; DUARTE, 2018; SENTELHAS et al., 2015b).

Several studies have suggested that climate variability and change have strong impacts on global food production and, consequently, food security (ANDERSON et al., 2017; SIVAKUMAR; DAS; BRUNINI, 2005; SMITH et al., 2011). Climate variability is driven mainly by natural phenomena, such as the El Niño Southern Oscillation (ENSO), which has been responsible for crop yield variability around the world (CAPA-MOROCHO; RODRÍGUEZ-FONSECA; RUIZ-RAMOS, 2014; SANTOS et al., 2018). For example, the strong El Niño event of 2015/16 was responsible for soybean and maize off-season yield reductions in Brazil, reaching respectively 4% and 31% less than the previous growing season (IBGE, 2018). Besides that, climate variability also affects production area, intensity and severity of pests and diseases, farmers' decision-making, and the level of investment in technology (IIZUMI; RAMANKUTTY, 2015; NÓIA JÚNIOR et al., 2018c).

In order to meet the challenge of improving world food security, researches should be done to evaluate the impacts of climate variability and change on food production, with the purpose of investigating the magnitudes and causes of the yield gaps of different crops around the world, aiming to propose actions to reduce them. Based on that, the present study had as hypotheses that, for a given crop/cultivar, sowing date is the first management action to define crop yield level in a specific environment. Considering the crop system comprised of soybean and maize off-season, cultivated in succession, the general objective of this study was to evaluate, using a multi-model approach, the impacts of climate variability on yield and profitability of these two crops, cultivated in succession, in different Brazilian producing regions, and to assess how sowing dates change according to the ENSO phases in these regions. According to that, the specific objectives of this study were:

a) To determine the best sowing dates for soybean and maize off-season, cultivated as single crops and in succession, according to the climate variability in different Brazilian producing regions;

b) To assess the impacts of ENSO phases on the best sowing dates for soybean and maize off-season, cultivated as single crops and in succession;

c) To determine the yield gaps of soybean and maize off-season crops, cultivated in succession, and the magnitude of their main causes, water deficit (YG_W) and/or suboptimal crop management (YG_M), in different Brazilian regions.

1.2. Literature review

Soybean and maize crops in Brazil

Soybean (*Glycine max* [L.] Merrill) is one of the most important crops in the world, mainly to its adaptive capacity and nutritional qualities (SEGUIN et al., 2010). Soybean grains present a high caloric content and high-quality proteins, which makes it an important component for animal feeding and human diet (ROMÃO et al., 2012). Due to these characteristics, soybean is nowadays the fourth crop in the world in terms of cultivated area (FAO, 2018). Due to its importance, the production of soybean has grown exponentially both in the world and in Brazil (Figure 1A). Brazil cultivated, in 2017/2018 growing season, 35 million hectares with soybean (Figure 1B), accounting for 27% of the world soybean production (FAO, 2018). In this season, Brazilian production was 118 million tons, with an average yield of approximately 3300 kg ha^{-1} (CONAB, 2018), surpassing the world average yield (Figure 1C).

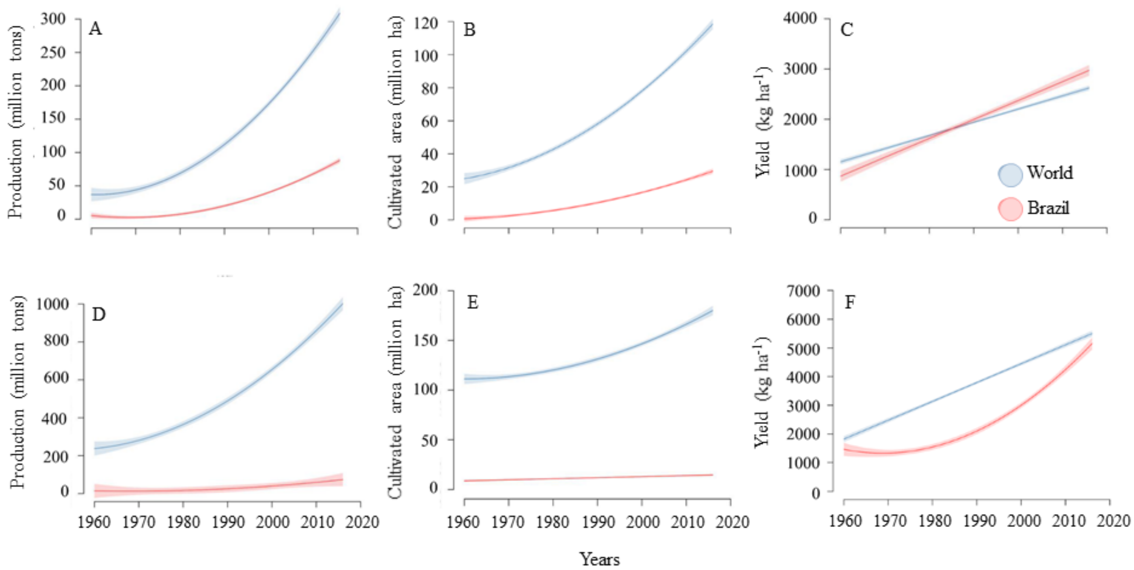

Figure 1. Productions, cultivated areas and yields for soybean (A, B and C) and maize (D, E and F) in Brazil and in the world from 1960 to 2018. Adapted from FAO (2018).

As mentioned for soybean, maize (*Zea mays*) is also a very important crop around the world. This cereal has the third largest cultivated area and is the second most produced in the world (FAO, 2018). The growth of maize production and cultivated area in the world has occurred, similarly to soybean, exponentially; however, in Brazil they have been much lower than observed worldwide (Figure 1D, E). Although the growth in production in Brazil is low, the rate of yield growth since 1990 has increased and is very close to world average (Figure 1F). The reason for such improvement in the maize yield is mainly associated to the use of maize as a second crop, which get started in the

1990s, cultivated in succession to soybean. In the 2017/18 growing season, maize production in Brazil was about 90 million tons, of which 63 million tons (70%) was from the maize off-season (CONAB, 2018).

Maize off-season, also known as “safrinha” or second crop, is sown in Brazil from January to April, after the summer crop, usually soybean. This production system is known as soybean – maize off-season succession. However, maize off-season potential yield is lower than that for maize cultivated as a summer crop, which is a consequence of weather conditions during the crop cycle, with lower solar radiation, air temperature and photoperiod (SOLER; SENTELHAS; HOOGENBOOM, 2009). Besides, maize off-season yield is also affected by the high rainfall variability during the half end of its crop cycle, during autumn and winter, which imposes climatic risks for this crop, impacting the entire production system (FIORINI et al., 2018; SOLER; SENTELHAS; HOOGENBOOM, 2007). Thus, it is important to know how weather variables affect the soybean and maize crops, which will help to determine how such impacts can be mitigated.

Among the several factors that affect crops´ development and growth, the soil water availability, resulting from the crop water balance, is the main one in Brazil, causing average yield losses of about 30% for soybean (SENTELHAS et al., 2015a) and 50% for maize off-season (DUARTE, 2018). Water deficit causes metabolic limitations to photosynthesis, associated with impaired ATP synthesis (SINGH et al., 2014), which affects ribulose-1,5-biphosphate (RuBP) regeneration (GALMÉS; MEDRANO; FLEXAS, 2007), limiting the rate of CO_2 fixation (PERDOMO et al., 2017) and, consequently, crop yield. For mild to moderate water deficit, diffusive limitations, caused as a consequence of stomatal closure and increased leaf resistance to CO_2 transport from the atmosphere to the carboxylation site, are cited as the main responsible for photosynthesis rate decrease (VON CAEMMERER; FURBANK, 2016). Another consequence of stomatal closure is a reduction in transpiration rates, limiting leaf cooling capacity (MATHUR; AGRAWAL; JAJOO, 2014), which is the most important process for dissipating heat, regulating leaf temperature (GARRUÑA-HERNÁNDEZ et al., 2014; NÓIA JÚNIOR et al., 2018a), and reducing yield losses due to thermal stress.

Thermal stress, although having less impact, can increase respiratory rates and impair CO_2 assimilation, leading to a rapid depletion of the carbon stored by the plants (MCDOWELL, 2011). At high temperatures, the photosynthetic process is affected by a reduction in carboxylation process efficiency, while at low temperatures its reduction is mainly due to stomatal closure (NÓIA JÚNIOR et al., 2018b); however, low temperatures can also impair carboxylation efficiency, mainly under very low temperatures and frost conditions.

Soybean is adapted to temperatures within the range of 20 to 30 °C (SILVA; SEDIYAMA; BORÉM, 2015). The optimum temperature for maize cultivation is between 25 and 30 °C (FANCELLI, 2015), and low temperatures can increase the duration of its phenological phases, lengthening the crop cycle. Thus, considering the optimum climatic conditions for maize, it is observed that the maize off-season cultivation, in several Brazilian regions, is of high risk. In southern Brazil, this risk is higher when the reproductive phase of this crop coincides with low temperatures, whereas in the center-north of the country it happens when such phase coincides with the beginning of the dry season (SOLER; SENTELHAS; HOOGENBOOM, 2007).

Aiming to minimize the impacts of climate variability on maize off-season, Brazilian farmers are anticipating soybean sowing to the period between mid-September and early October and using early cultivars, in order to harvest soybean and to sow maize as soon as possible (BRACCINI et al., 2010; GARCIA et al., 2018). However, anticipating soybean sowing to mid-September can be risky, since rainfall is highly variable during this month in most of the soybean regions in Brazil (ALVARES et al., 2013). Therefore, the choice of the best soybean sowing date will determine the success of soybean – maize off- production system. However, the best sowing date for soybean – maize off-season succession varies between growing seasons, which is mainly caused by ENSO phases. Several authors have indicated ENSO as a major source of yield variability in Brazil (ANDERSON et al., 2017, 2018; LUNT et al., 2016), which makes necessary to understand how such phenomenon impacts soybean and maize yields for different sowing dates, allowing to redefine crop planning according to the ENSO phases (CAPA-MOROCHO; RODRÍGUEZ-FONSECA; RUIZ-RAMOS, 2014; SHIN et al., 2010; ZHANG et al., 2015).

El Niño Southern Oscillation (ENSO)

ENSO is characterized by sea surface temperature anomalies in the equatorial Pacific Ocean. When such anomaly is positive and surpass +0.5 °C, it is the warm phase, known as El Niño. When the anomaly is negative and below -0.5 °C, it is the cold phase, also called as La Niña. These anomalies affect global atmospheric circulation, having consequences for the weather conditions around the world (ANDERSON et al., 2018; BERLATO; FONTANA, 2001; CAPA-MOROCHO; RODRÍGUEZ-FONSECA; RUIZ-RAMOS, 2014; IIZUMI et al., 2014). During the Neutral years, when sea surface anomaly is between -0.5 and +0,5 °C, Pacific Ocean is warmer close to Australia and Indonesia than near South American, which results in an atmospheric pressure gradient that makes the winds to blow from east (South America) to west (Australia). However, near the limit of the troposphere, the winds blow from west to east, generating a latitudinal cell of atmospheric circulation, called Walker Cell.

During El Niño events there is a weakening of east-west circulation, and sometimes it allows the reversion of the wind direction in the Walker Cell. Such phenomenon changes the humidity transport in the atmosphere and, consequently, affects temperature and rainfall patterns in several parts of the world (CHIODI; HARRISON, 2015). In Brazil, El Niño causes different impacts, reducing rainfall in the North and Northeast regions (MOURA et al., 2019), and increasing it in the South of the country. In Central Brazil, the impacts of El Niño vary, depending on the intensity of the phenomenon (PENALBA; RIVERA, 2016).

La Niña promotes an intensification of the east-west winds of the Walker Cell, which has as consequence intensification of rainfall in the Northeast region, and frequent droughts in southern Brazil (GELCER et al., 2013; PINHEIRO et al., 2018).

The variation in the amount and frequency of rainfall caused by different phases of ENSO generates variability of agricultural production, mainly in the South and North/Northeast regions of Brazil, but also affecting other ones during some of these phases (ANDERSON et al., 2017). The most affected crops, are the annual ones cultivated under rainfed conditions, like soybean and maize off-season (SOLER; SENTELHAS; HOOGENBOOM, 2009).

The temporal and spatial variations of soybean and maize off-season yields in Brazil during the last three events of each phase of ENSO (El Niño and La Niña) are presented in Figure 2. Soybean and maize yields were affected in almost all Brazilian regions, but with different patterns. El Niño improved soybean production is the three states of the South region, whereas La Niña improved soybean production in the states located in the center-north of the country. La Niña also had a positive effect on maize off-season yield, mainly in the state of Mato Grosso.

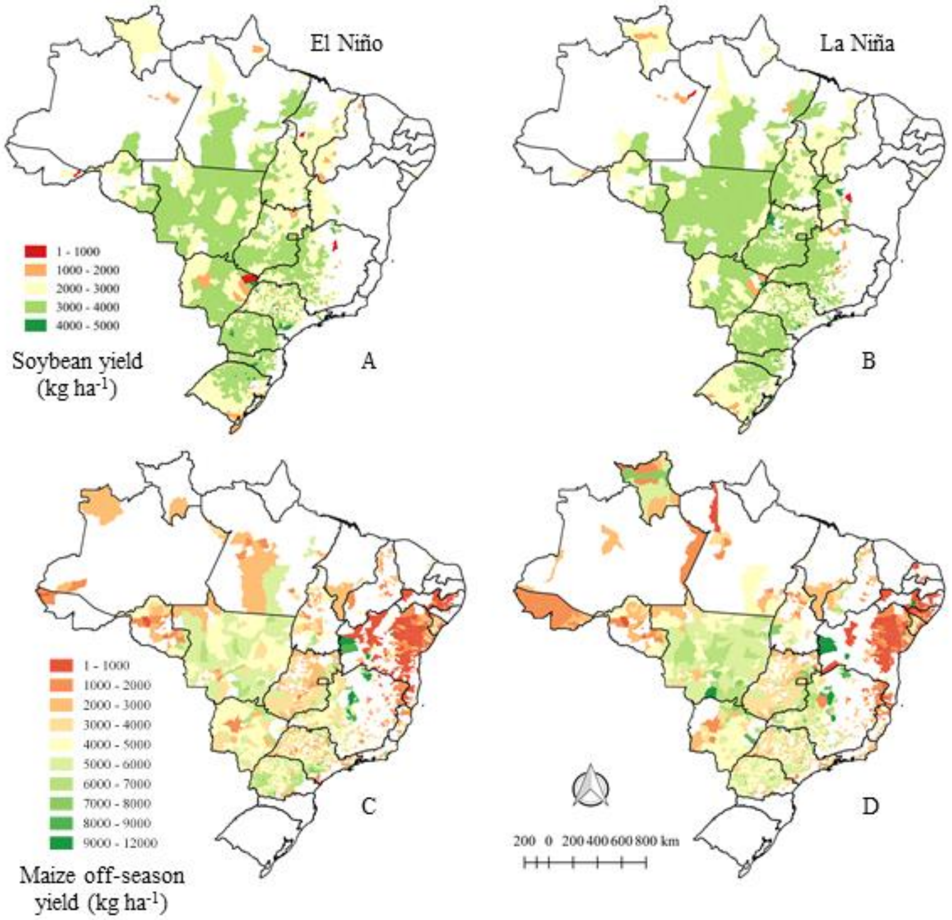

Figure 2. Average actual soybean (A and B) and maize off-season (C and D) yields for three growing seasons of El Niño (A and C: 2004/05, 2009/10 and 2015/16) and La Niña years (B and D: 2007/2008, 2010/11 and 2011/12). Adapted from IBGE (2018).

Therefore, the influence of ENSO on soybean–maize off-season succession in Brazil is questioned. Adoption of this succession is already risky, since both the anticipation of soybean sowing and the delay of maize sowing can result in significant yield losses. Under El Niño influence, for example, the risks may be even greater in the central-north than in the south-central region, while during La Niña years, this may reverse. The best understanding of the relationships between agricultural yield and climate variability (associated with ENSO) can be obtained with the aid of crop simulation models, which provide information that can assist in the decision-making process while minimizing the risks of yield losses (BATTISTI; SENTELHAS; BOOTE, 2017; DUARTE, 2018).

Crop simulation models

Crop simulation models can be defined as dynamic simulators of crop growth and development. The simulation takes place through numerical integration of the biological, biophysical, and biochemical processes constituting the agricultural system. The crop simulation models allow a better understanding of the impacts of each component of the agricultural system, generating results which help the agricultural planning, as well as the crop monitoring, assisting the farmers during the decision-making processes (DUARTE, 2018; REYNOLDS; THORNLEY, 1982).

The crop simulation models can be classified according to the principles involved in their development and programming. The models can be empirical, employing simple relationships between yield and independent variables, usually meteorological; mathematical-physiological, explaining part of the physiological processes through mathematical equations; or mechanistic, dealing with a large part of the processes involved in the production and partitioning of photoassimilates, through equations and empirical relationships.

Among the crop simulation models, the FAO - Agroecological Zone Model (DOORENBOS; KASSAM, 1979; KASSAM, 1977), Agricultural Production Systems Simulator v. 7.7 (HOLZWORTH et al., 2014; KEATING et al., 2003), referred to as APSIM; and the software Decision Support System for Agrotechnology Transfer – DSSAT platform (BOOTE et al., 2003; JONES et al., 2003), are between the most widely used and known in the world. The FAO model is based on the estimation of potential (Yp) and water-limited (Yw) yields, using mathematical equations that simulate Yp for a standard crop, which is then corrected for the crop of interest, through the leaf area index, harvest index and humidity of the final product. After that, Yw is obtained by penalizing Yp by the relative water deficit, given by the ratio between actual and maximum crop evapotranspiration subtracted from one (1 - ETa/ETc), which is modulated by a water deficit sensitivity index (ky), specific for each crop and phenological phase (BATTISTI; SENTELHAS; BOOTE, 2017; DUARTE, 2018). The APSIM and DSSAT are mechanistic models, i.e. deal with a large part of the processes involved with development, growth and yield of the crops, considering the main interactions between genotype, weather, soil and crop management. The mechanistic models have more complex input variables, and requires the calibration of several coefficients related to soil, species and genotype (BATTISTI; SENTELHAS; BOOTE, 2017; BENDER, 2017; DUARTE, 2018). On the other hand, they provide a more complete set of outputs.

There are several applications of crop simulation models. Among the possibilities of use, there are: determination of best sowing dates (SOLER; SENTELHAS; HOOGENBOOM, 2007); quantification of ENSO phenomenon impacts on crop development, growth and yield (CAPA-MOROCHO; RODRÍGUEZ-FONSECA; RUIZ-RAMOS, 2014); quantification of the climate change impact on crop yield and how much crop management strategies can mitigate them (BATTISTI et al., 2017, BENDER, 2017); and determination of the magnitude and causes of crop yield gaps (ANDREA et al., 2018; BATTISTI et al., 2018; DIAS; SENTELHAS, 2018; DUARTE, 2018; MONTEIRO; SENTELHAS, 2017; VISSES; SENTELHAS; PEREIRA, 2018).

As there is no error-free crop simulation model, some authors have emphasized the importance of using several models, in an ensemble, in order to reduce the estimate yield errors (ASSENG et al., 2013; BATTISTI; SENTELHAS; BOOTE, 2017; DIAS; SENTELHAS, 2017; DUARTE, 2018; MARTRE et al., 2015). According to Battisti et al. (2017), the mean absolute errors of five soybean crop models in Brazil was around 550 kg ha^{-1}, which was reduced to 256 kg ha^{-1} when their ensemble was used. For maize, Duarte (2018) showed that the root mean square error of the FAO, APSIM and DSSAT models for maize (in-season and off-season) can be reduced by about 60% when using the ensemble of their results rather than the results of a single one.

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2. SOYBEAN-MAIZE SUCCESSION IN BRAZIL: IMPACTS OF SOWING DATES ON CLIMATE VARIABILITY, YIELDS AND ECONOMIC PROFITABILITY

ABSTRACT

The soybean-maize succession is an important production system used in Brazil. The greatest challenge related to this kind of system is to define the best sowing dates for the producing regions with different climatic characteristics, improving farmer´s economic profitability. Thus, the aim of this study was to determine the best sowing dates for the above-mentioned crop system considering simulations with three crop simulation models (FAO-AZM, DSSAT and APSIM) in a multi-model approach, and to determine the economic profitability of this system at national scale. Previously calibrated and validated models were used to simulate soybean yields for 29 locations in 12 states, with sowing dates ranging from end of September to beginning of January for a period of 34 years (1980-2013). The maize off-season sowing was done just after the soybean harvest, ranging from end of January to beginning of May. The yield data was converted to gross revenue according to the prices commonly practiced in Brazil and then to net revenue by subtracting the production costs for each assessed region. The optimal sowing date varied according to the Brazilian region. For Central Brazil, the highest net revenue was obtained when soybean was sown between the end of September and beginning of October. This period is also recommended in Southern Brazil, because sowing delay can reduce maize yield due to risks of frosts and low solar radiation availability. In the Northern Brazil, mainly in Pará state, the soybean sowing should start in November, when net revenue is maximized.

Keywords: Crop simulation models, Multi model approach, Yield gap and water deficit

2.1. Introduction

Global demand for agricultural products is increasing, pressured by population growth associated with changes in consumption patterns (TILMAN et al., 2011). By 2050, agricultural yield is required to grow by 60 to 120% over 2005 levels to meet world´s demand for food, fiber and energy (GODFRAY et al., 2010). However, the agricultural yields are not growing at the required rate to meet this demand (FOLEY et al., 2011; RAY et al., 2013), with about 20% of the world's agricultural lands presenting stagnated yield growth (FINGER, 2010; PELTONEN-SAINIO; JAUHIAINEN; LAURILA, 2009; RAY et al., 2012). Based on that, the world is going to face the greatest challenges of the 21st century, which is to meet the world's future food security needs.

The progress required for meeting the world's food security needs could be made by expanding agricultural land, increasing cropping efficiency, and closing yield gaps (FOLEY et al., 2011). Many areas across the world, such as parts of Africa, Latin America and Eastern Europe show significant opportunities to increase crop yields (NEUMANN et al., 2010; SÁNCHEZ, 2010). Among these regions, Brazil plays an important role since it accounts for about 6.5% of world´s grain production (FAO, 2019), and has the possibility of cultivating at least two crops per year.

Soybean and maize have a great importance for Brazilian agriculture. These two crops account for 90% of grain production in the country (CONAB, 2019). In the 2017/2018 growing season, Brazil had 35 million hectares cultivated with soybean and 16 million hectares with maize, with a total production that represents, respectively 27 and 6% of world´s production (FAO, 2019). In the most recent growing seasons, approximately 70% of the Brazilian maize production was from the crop cultivated off-season (autumn–winter growing season), also known as "safrinha" (CONAB, 2019).

Maize off-season crop is mainly sown from January to April, after the harvesting of summer crop, usually soybean, being known as soybean–maize succession. This succession is an important production system in the Brazilian agriculture, contributing to increase grain production in the same area, increasing the profitability of the land. In the most recent growing seasons, maize off-season yield has surpassed that of maize in season, cultivated during the spring-summer period (CONAB, 2019). However, the maize off-season yield is still greatly affected by the high weather variability (rainfall, air temperature and solar radiation) during the autumn and winter, which imposes climatic risks for this crop, impacting entire production system (Soler et al., 2007; Soler et al., 2009).

Aiming to minimize the impacts of climatic variability on maize off-season, growers are anticipating soybean sowing for the period between mid-September and early October and using early cultivars, in order to harvest soybean and to sow maize as soon as possible (BRACCINI et al., 2010; GARCIA et al., 2018). However, anticipating soybean sowing to mid-September can be risky, since rainfall is highly variable during this month in most of the soybean regions in Brazil (ALVARES et al., 2013), imposing yield losses by water deficit. Therefore, our hypotheses are that the choice of the most favorable soybean sowing date will determine the success of the soybean-maize succession, minimizing climatic risks and improving profitability, and that well-calibrated crop simulation models are able to provide a robust quantitative framework to address that.

Based on the above-mentioned hypotheses, the objective of this study was to determine the best sowing dates for soybean-maize succession in different Brazilian producing regions, based on water limited yields (Yw), determined by three different crop simulation models, and on net revenue.

2.2. Materials and Methods

Sites, climate and soil data

This study considered 29 locations spread throughout the country, following previously developed protocols (GRASSINI et al., 2015; VAN BUSSEL et al., 2015). The analyses were made for a 100-kilometer-radius circular area around existing weather stations (WS), associated to climatic zones according to Köppen's climate classification (ALVARES et al., 2013). Such procedure ensured that each WS was surrounded by a corresponding buffer zone that consisted of a single climatic zone. In the cases when two buffer zones overlapped within the same climatic zone, they were separated in such way that the border between them was equidistant to each WS (Figure 1).

According to IBGE (2019), Brazil has 1259 locations cropped with soybean-maize succession. These locations are distributed in 12 states: Paraná (PR), São Paulo (SP), Minas Gerais (MG), Mato Grosso do Sul (MS), Mato Grosso (MT), Goiás (GO), Rondônia (RO), Pará (PA), Tocantins (TO), Piauí (PI), Maranhão (MA) and Bahia (BA), with more than 90% of these areas concentrated in four different Köppen´s climatic zones (ALVARES et al., 2013): Am, Aw, Cfa and Cwa. Based on that, 29 weather stations were selected to represent the soybean-maize succession growing areas in the 12 states and four climatic zones (Table 1).

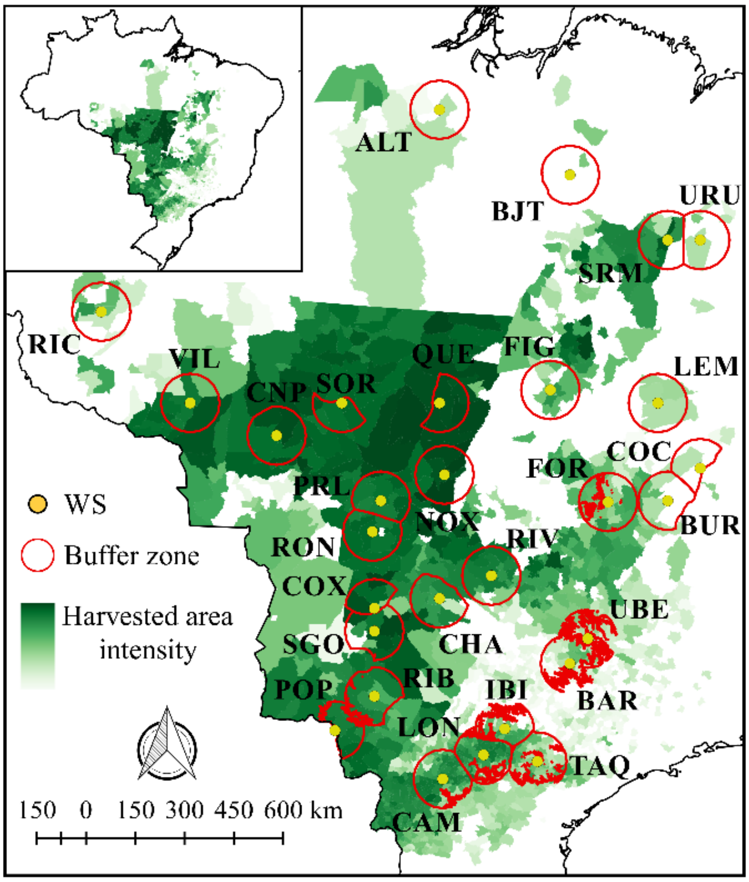

Figure 1. Weather stations (WS) selected for the present study and their associated buffer zones in the main soybean-maize succession producing regions of Brazil. Harvested area intensity corresponds to the ratio between soybean-maize succession harvested area in the location and total area of the municipality, for the period from 2013 to 2017 (IBGE, 2019). Locations codes for each weather station are presented in Table 1.

Long-term weather data (1980–2013) were collected from the Brazilian Institute of Meteorology (INMET) and Integrated Agrometeorological Information Center of São Paulo (CIIAGRO). Missing weather data at most stations were sporadic and occurred in about 20% of the days, a percentage considered acceptable by Grassini et al. (2015), and were filled out with data from Xavier climatic database (XAVIER; KING; SCANLON, 2015). According to Battisti et al. (2018), Xavier climatic database was the most suitable for estimating soybean potential and water-limited yields in Brazil. Similar results were found by Duarte (2018) and Bender and Sentelhas (2018) for maize crop.

The predominant soil types of each site were selected using the soil map from (IBGE, 2014). Information about sand, clay, and silt contents, pH, bulk density and organic carbon and nitrogen contents for each soil type (see Table S.1 in the Supplementary material), were obtained from RADAMBRASIL (1974). The soil water holding capacity of each soil was estimated using pedo-transfer functions developed by Reichert et al. (2009).

Table 1. State and locations from where the weather stations (WS) were selected, their associated codes, geographical coordinates, Köppen's climate (ALVARES et al., 2013) and soil classification, according to Brazilian system of soil classification (IBGE, 2018).

State	Location	Latitude (degrees)	Longitude (degrees)	Elevation (meters)	köppen's climatic	Soil classification
BA	Cocos (COC)	-14.10	-44.50	500	Aw	Oxisol
BA	Luís Eduardo Magalhães (LEM)	-12.40	-46.41	603	Aw	Oxisol
GO	Chapadão do Céu (CHA)	-18.50	-52.50	840	Am	Ultisol
GO	Rio Verde (RIV)	-17.80	-50.91	774	Aw	Oxisol
GO	Formosa (FOR)	-15.54	-47.33	935	Aw	Oxisol
MA	São Raim. das Mangabeiras (SRM)	-7.53	-46.03	259	Aw	Oxisol
MG	Uberaba (UBE)	-19.73	-47.95	737	Cwa	Oxisol
MG	Buritis (BUR)	-15.52	-46.40	894	Aw	Oxisol
MS	Ponta Porã (POP)	-22.55	-55.71	650	Cfa	Oxisol
MS	Rio Brilhante (RIB)	-21.77	-54.52	324	Am	Oxisol
MS	S. Gabriel do Oeste (SGO)	-19.42	-54.55	646	Am	Oxisol
MS	Coxim (COX)	-18.51	-54.73	251	Aw	Oxisol
MT	Rondonópolis (RON)	-16.45	-54.56	284	Aw	Ultisol
MT	Primavera do Leste (PRL)	-15.83	-54.38	450	Aw	Oxisol
MT	Nova Xavantina (NOX)	-14.70	-52.35	316	Aw	Oxisol
MT	Campo Novo do Parecis (CNP)	-13.78	-57.83	525	Aw	Oxisol
MT	Sorriso (SOR)	-12.55	-55.72	379	Aw	Oxisol
MT	Querência (QUE)	-12.62	-52.22	361	Aw	Oxisol
PA	Altamira (ALT)	-3.21	-52.21	74.0	Am	Oxisol
PA	Bom Jesus do Tocantins (BJT)	-5.36	-49.13	95	Aw	Oxisol
PI	Uruçuí (URU)	-7.44	-44.34	399	Aw	Oxisol
PR	Campo Mourão (CAM)	-24.04	-52.40	616	Cfa	Oxisol
PR	Londrina (LON)	-23.30	-51.15	610	Cfa	Ultisol
RO	Vilhena (VIL)	-12.73	-60.15	615	Am	Oxisol
RO	Rio Crespo (RIC)	-9.75	-62.75	157	Am	Oxisol
SP	Taquarituba (TAQ)	-23.19	-49.38	561	Cfa	Oxisol
SP	Ibirarema (IBI)	-22.74	-50.38	484	Cfa	Ultisol
SP	Barretos (BAR)	-20.55	-48.54	534	Aw	Oxisol
TO	Figueirópolis (FIG)	-12.10	-49.10	291	Aw	Ultisol

Crop models

Recent studies have demonstrated that the use of several crop simulation models in a multi-models approach or ensemble is a promising way to improve accuracy and reduce uncertainties when simulating crop yields (ASSENG et al., 2013; MARTRE et al., 2015). It was recently confirmed for soybean (Battisti et al., 2017) and maize (BATTISTI; SENTELHAS; BOOTE, 2017; DUARTE, 2018) crops in Brazil. Based on that, the present study simulated soybean and maize yields with three different crop simulation models, as follows: FAO – Agroecological Zone Model (BATTISTI et al., 2017; KASSAM, 1977; RAO; SARMA; CHANDER, 1988); Agricultural Production Systems Simulator v. 7.7 (HOLZWORTH et al., 2014; KEATING et al., 2003), referred to as APSIM; and Crop Simulation Model – CROPGRO – Soybean v.4.6.1 and Cropping Simulation Model – CERES – Maize, both present in the software Decision Support System for Agrotechnology Transfer – DSSAT platform (BOOTE et al., 2003; JONES et al., 2003). The multi-model ensemble was obtained from the arithmetic mean of the yields simulated by these three models.

Calibration and validation of the above-mentioned models to simulate Yp and Yw were done by Battisti et al. (2017) for soybean and by Duarte (2018) and Bender (2017) for maize off-season. Details about the performance of these models with the calibration proposed by the authors and their respective validations are presented in Tables S2 and S3 in the Supplementary material.

Initial conditions, sowing dates and cultivar

For running these models, the initial soil water content was defined based on the water balance initiated six months before sowing, considering the prior crop as fallow. The Yp, Yw and yield gap caused by water deficit (YG_W) were estimated for 11 different sowing dates for soybean and maize off-season, in succession, starting at September 21st and finishing in beginning of January, with an interval of 10 days. Maize sowing was simulated immediately after the soybean harvest, as commonly practiced in the farms in Brazil. During the simulations, soybean presented a mean cycle of 114 days, whereas maize off-season had 136 days of cycle (Figure 2).

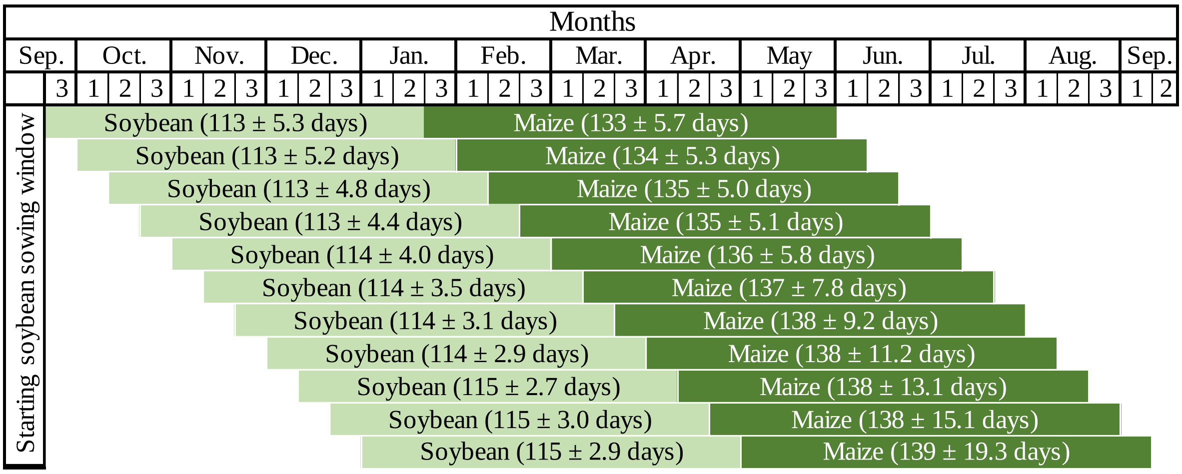

Figure 2. Schematic representation of the sowing dates for the soybean-maize succession in Brazil. The months were divided into three 10-day periods, which corresponds to the numbers 1, 2 and 3 in the upper part of the figure. The duration of the cycle was obtained through the ensemble of the three crop simulation models.

The 29 locations used in the present study are located in different latitude, thus in order to maintain the soybean cycle around 115 days throughout Brazilian territory, three soybean maturity group (6.5, 7.5 and 8.5) were selected, based on recommendations from Battisti et al. (2017). More details about soybean crop cycle can be found in Figures S11 in the Supplementary material.

Yield gap analysis

The yield gap analysis was performed using the following concepts:

Potential yield (Yp): is the maximum yield obtained by a genotype under optimum conditions, which means without water, nutritional or phytosanitary stresses, being influenced only by the interaction of this genotype in a given plant population with meteorological conditions (solar radiation, temperature and photoperiod).

Water limited yield (Yw): is the Yp penalized by water deficit, being Yw $\leq$ Yp. Therefore, Yw has no limitations regarding nutrients supply and biotic stresses, caused by pests, diseases or weeds.

Yield gap caused by water deficit (YG_w): is the difference between Yp and Yw.

Economic Analyzes

The 5-year (2013-2017) averages of soybean and maize prices and production costs were obtained from Securities, Commodities and Future Exchange of BOVESPA (BM&FBOVESPA), accessed from the Center for Advanced Studies in Applied Economics (CEPEA, 2018) and National Supply Company (CONAB, 2019), respectively. This recent 5-year time period was selected to avoid actual price and production costs underestimations due the inflationary trend. With the constant variation of the selling price of soybean and maize, this study considered three different price scenarios:

Optimistic: that considers high prices when selling both products;

Average: that considers average prices when selling both products;

Pessimistic: that considers low prices when selling both products.

The average prices and production costs (PC) were obtained from the arithmetic average of the 5-year period. The high and low prices scenarios were, respectively, those that considered the average plus standard deviation and average minus standard deviation. The net revenue (NR, R$ ha^{-1}) was calculated by the following equation:

$$NR = \left(\frac{Yw}{60} \text{ x } P\right) - PC \qquad \text{(Eq. 1)}$$

where Yw is the soybean or maize water-limited yield (kg ha^{-1}), P the soybean or maize selling price (R$ 60 kg $bags^{-1}$), PC the soybean or maize production cost (R$ ha^{-1}, Table S4 at Supplementary material). Yw was divided by 60 to convert kg ha^{-1} to bags ha^{-1}, because selling price is given in R$ per bag (Table S5 in Supplementary material).

For profit chances analysis, calculations were made for the three considered scenarios (Optimistic, Average and Pessimistic), using Eq. 2:

$$\text{Profit Chances (\%)} = \frac{NR(+)}{TY} \text{ x } 100 \qquad \text{(Eq. 2)}$$

where NR(+) is the number of years in which net revenue was positive, TY is the total of crop growing seasons analyzed (33).

Data analysis

The statistical analyses were carried out using the software R (R CORE TEAM, 2017). In order to obtain an integrated assessment of the climate variables on the soybean and maize off-season yields, the data were subject to a principal component analysis (PCA). The PCA method reduces the dimensionality of data with a large number of measured variables by transforming these to a new, considerably smaller set of variables called Principal Components (PCs). To each crop (soybean and maize off-season) was performed one PCA. The data were standardized by dividing the difference between each data point and the arithmetic mean of the variable of interest by standard deviation of the variable, so that the results were not influenced by the magnitude of the variable units. The variables used in PCA analysis were: solar radiation (SR), air temperature (Ta), relative air humidity (RH), rainfall (Rain), the ratio between actual and maximum crop evapotranspiration (ETa/ETc), and the water-limited and potential yields for maize and soybean crops. These variables were averaged by growing season for each sowing date and location. Two PCs were selected considering all variables, following the criterion indicated by Kaiser (1974), which is based on the presence of PCs with eigenvalues greater than 1 (Figure S12 in the supplementary material). The pre-standardized data used in this analysis are also available in supplementary data (Tables S6 and S7 in the supplementary data). For further information on principal component analysis, see Demšar et al. (2013) and Yeater et al. (2015).

To present the results in a more comprehensive way, a hierarchical grouping analysis was performed by the nearest neighbor method, and from this a dendrogram was obtained, joining the weather station (WS) in eight groups (Figure 3). This analysis was performed using meteorological data (average mean for 34 years – mean, maximum and minimum air temperature, rainfall and solar radiations) and soil attributes (texture and water holding capacity) from each WS. Thus, it was considered that only one WS can represent the result of all that are in the same group.

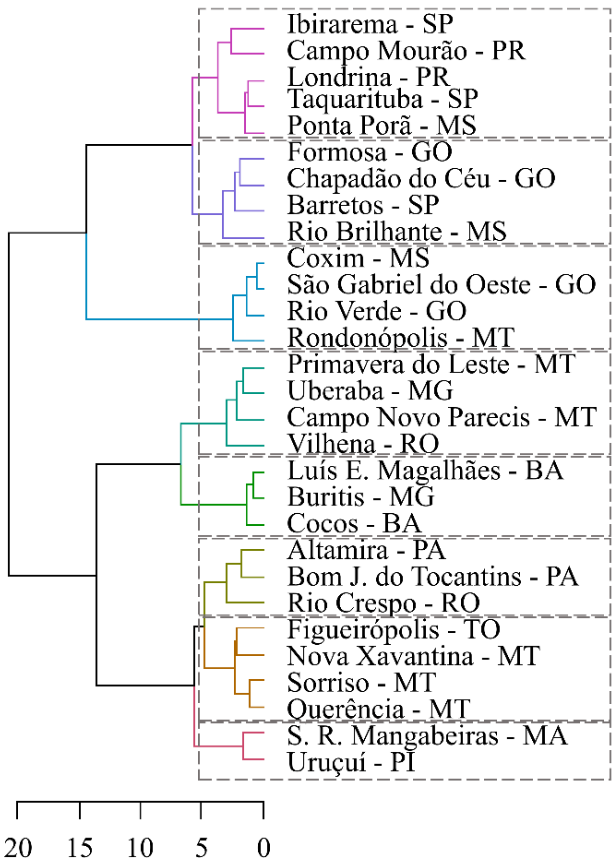

Figure 3. Dendrogram obtained through hierarchical clustering analysis by the nearest neighbor method, indicating the formation of eight weather stations groups.

2.3. Results

Inter-comparison of the soybean and maize crop models

The previously calibrated crop models showed a similar performance to estimate Yw for soybean and maize off-season crops in three locations used as examples (Figure 4), with simulated yields presenting the same pattern of variation along the different sowing dates and locations. For soybean, the highest differences between the models were obtained in Rio Verde, state of Goiás, where from late September to late October, the APSIM model presented the highest Yw, whereas the FAO model presented the lowest ones. From the middle of November, the highest Yw was obtained by FAO model, which also presented the highest inter-annual variability. In Taquarituba and Altamira, the soybean yields simulated by each one of the crop models were very close and presented similar trends and inter-annual variability in response to the sowing date.

For maize off-season, all the crop models, in all locations and sowing dates presented similar Yw. The major difference between the three crop models was observed for the inter-annual variability, with the FAO model showing the lowest values (Figure 4).

Considering the soybean and maize off-season yield variabilities presented by the three crop simulation models used, the best option to minimize the uncertainties was to make the ensemble of them, as recommended by Asseng et al. (2013) and Martre et al. (2015).

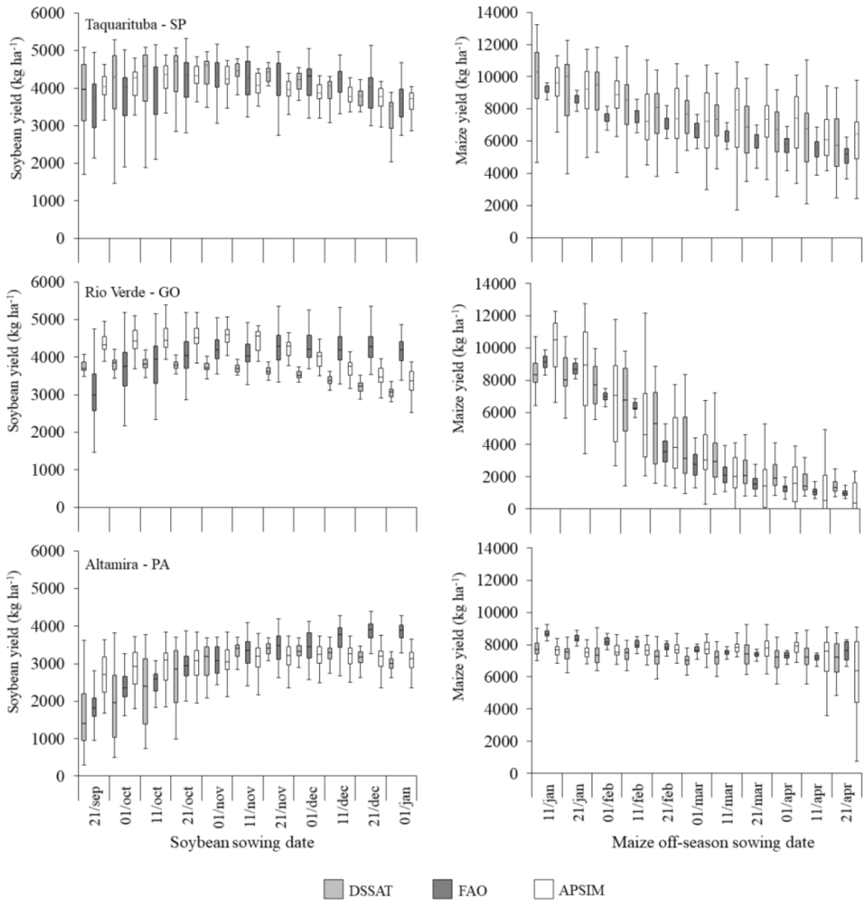

Figure 4. Inter-annual variability of soybean and maize off-season crops simulated by DSSAT, FAO and APSIM crop simulation models for three different locations, representing the three soybean maturity groups (MG) used as reference: Taquarituba, SP (MG 6.5), Rio Verde, GO (MG 7.5), and Altamira, PA (MG 8.5).

Impact of sowing date on yield of soybean-maize succession

Soybean and maize off-season Yw were highly affected by sowing dates, and the impact on that differed considerably across the country (Figure 5). For most of the Brazilian regions, soybean yield reached the highest values when sown in the end of October. The sowing anticipation to September and delay to November and December caused yield losses. In some locations (e.g. Nova Xavantina, MT, and Barretos, SP), the average soybean yield loss caused by anticipating or delaying of the sowing exceeded 500 kg ha^{-1}. For Altamira, PA, and São Raimundo das Maganbeiras, MA, the maximum soybean water-limited yields were obtained when sowing was performed from middle of November till beginning of January.

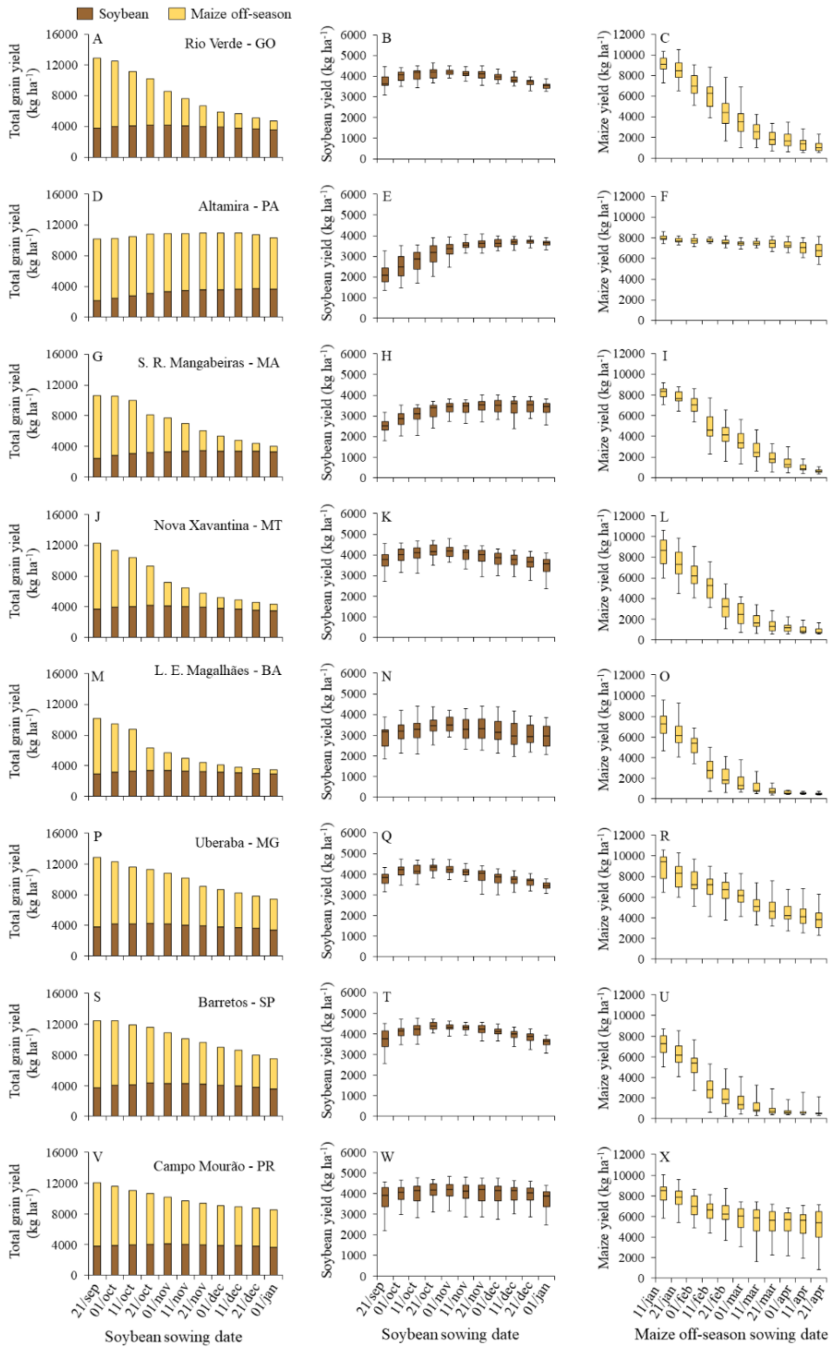

Figure 5. Total average grain yield for the succession of soybean and maize crops (left), inter-annual variability of soybean (center) and maize off-season (right) water-limited yields for different sowing dates and locations in Brazil. The results for the other 21 locations are presented in the Supplementary material (Figures S1, S2 and S3). The Yw data presented are the ensemble of three crop simulation models. The error bars present the variation of all dataset.

The delay of soybean sowing date promoted almost linear yield losses for maize off-season crop (Figure 5). For all regions, the maximum maize off-season yield was obtained when sowing was carried out in early January. In some locations, such as Luis Eduardo Magalhães, BA, and Nova Xavantina, MT, soybean sowing at the end of October delayed maize sowing to middle of February, causing maize yield losses of over 4000 kg ha^{-1}. Thus, the highest total grain yield (sum of soybean and maize yields), for most of Brazilian regions, was obtained when soybean sowing was anticipated to September, allowing maize to be sown in early January (Figure 5).

Soybean-maize succession yield gap caused by water deficit in Brazil

The lower water-limited yields obtained by the soybean crop when sown in September resulted in the highest yield gaps caused by water deficit (Figure 6), which can exceed 1800 kg ha^{-1}. In the majority of assessed locations, the lowest soybean YG_w occurred when soybean was sown between the end of October and middle of November.

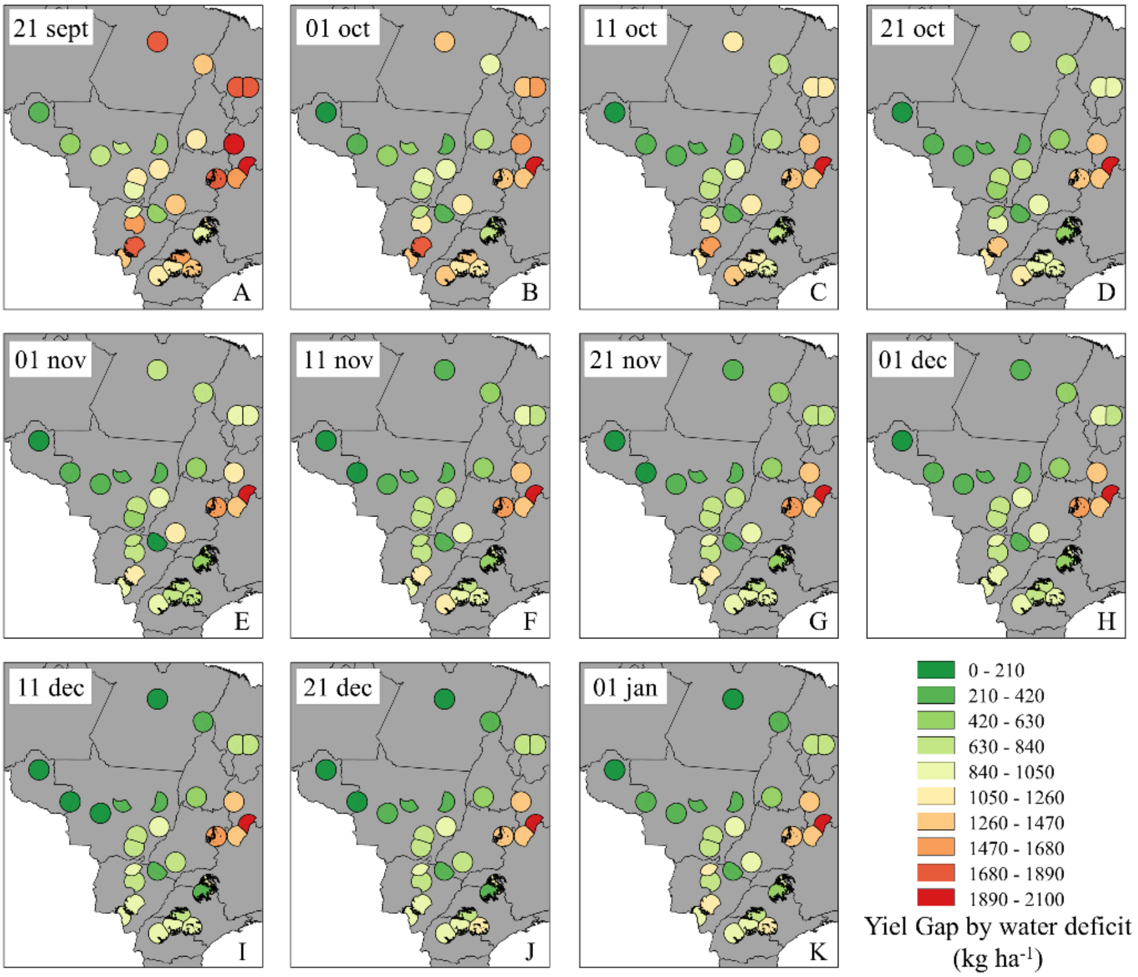

Figure 6. Spatial and temporal variation of soybean yield gap caused by water deficit in Brazil, cultivated in succession with maize off-season, at different sowing dates.

The soybean YG_w magnitude varied substantially across the assessed locations. Those located in the north of Mato Grosso and Roraima states (e.g Sorriso, MT, and Vilhena, RO) showed the lowest YG_w, while those located in western Bahia and northern Minas Gerais (e.g. Luis E. Magalhães, BA, and Buritis, MG) were the most affected by water deficit, presenting the highest YG_w. It was also observed that locations in northern Brazil presented the lowest YG_w when soybean crop was sown in December (Figure 6).

For the maize off-season, the lowest YG_w was obtained when it was sown between January and beginning of February (Figure 7). After that, YG_w increased gradually, mainly in the locations of the states of Mato Grosso do Sul, Mato Grosso, Goiás, Minas Gerais, Tocantins, Maranhão e Piauí. In central Brazil, the maize sown after the end of March resulted in YG_w of up to 9000 kg ha^{-1}, which makes its cultivation unsuitable (Figure 7). Thus, for most of the Brazilian locations under analysis, the delay of soybean sowing will force maize off-season to be cultivated under intense water deficit, reducing its yield substantially.

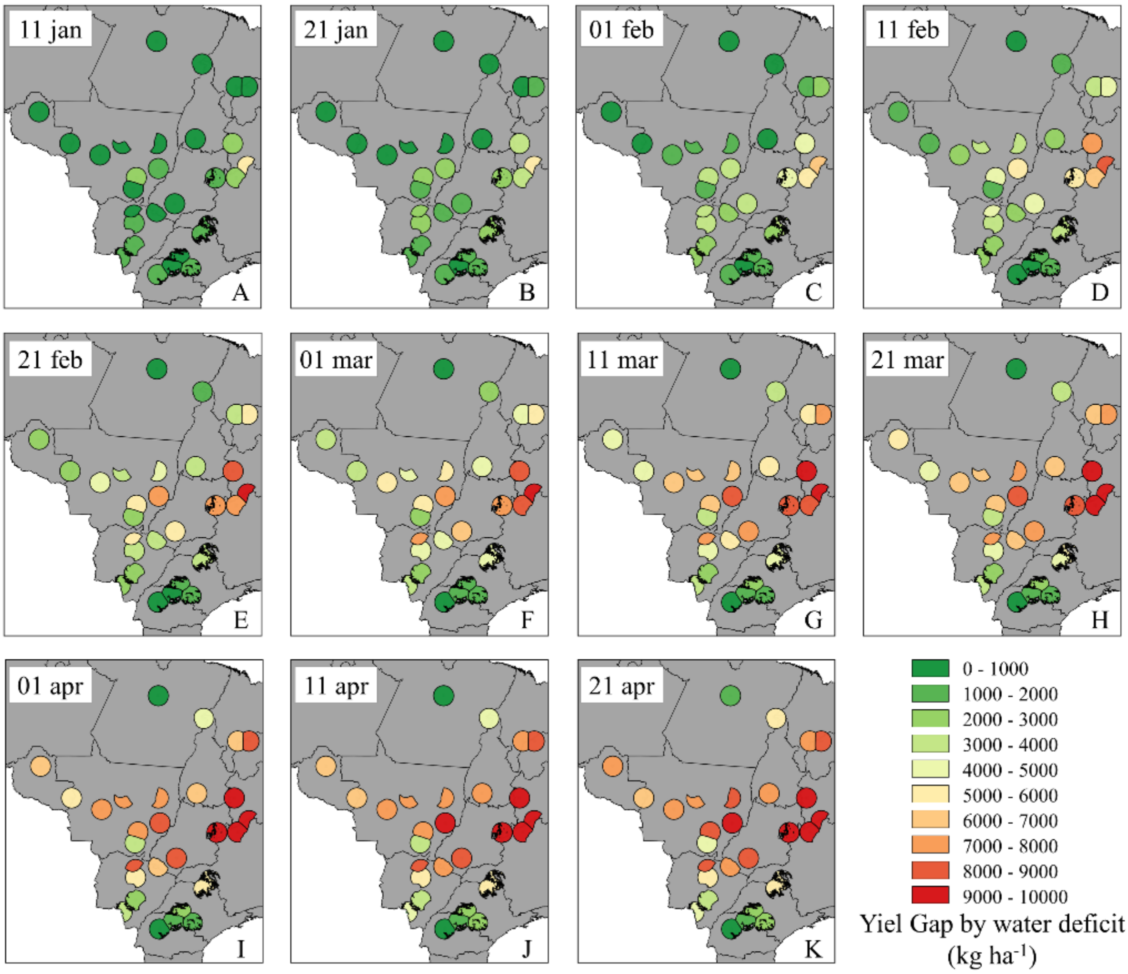

Figure 7. Spatial and temporal variation of maize off-season yield gap caused by water in Brazil, cultivated in succession with soybean, at different sowing dates.

In the southern Brazil, as well as in Altamira, in the north of Pará state, the delay of maize sowing did not make YG_w larger; however, in the state of Paraná and southern São Paulo temperature becomes a critical factor for maize off-season production, since late sowing will increase the risks of low temperatures, which make the crop cycle longer and the risks of frosts higher.

In order to better understand the factors that affect soybean and maize off-season yields as a function of the sowing dates in Brazil, a multivariate analysis was carried out and will be presented in the following section.

Understanding the impact of sowing date on yields of soybean-maize succession in Brazil

The multivariate approach (Principal component analysis, PCA) allowed an integrated assessment of the sowing dates effects on soybean and maize off-season potential (Yp) and water-limited (Yw) yields in the main producing regions in Brazil. For that, solar radiation (SR), air temperature (Ta), relative air humidity (RH), rainfall

(Rain) and the ratio between actual and maximum crop evapotranspirations (ETa/ETc) were assessed individually and in an integrated way (Figure 8).

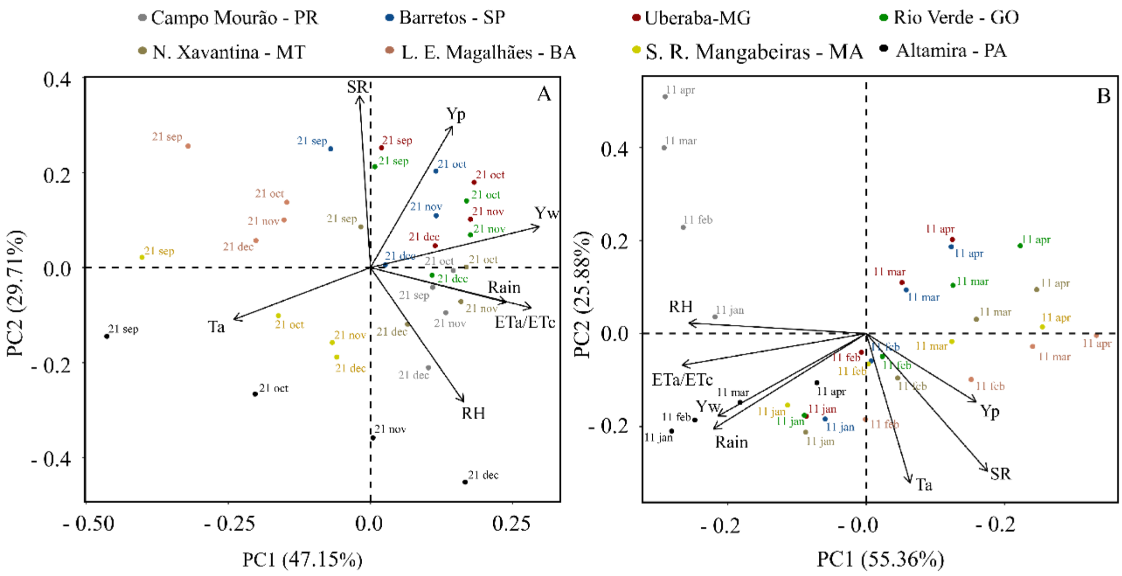

Figure 8. Biplot of the loadings of the original variables in the first two canonical variables for soybean (A) and maize off-season (B), when cultivated in succession in different sowing dates. The percentage of total variance explained by each canonical variable is indicated in parentheses. The first quadrant, in the upper left-hand corner, includes negative values of x and positive values of y. The fourth quadrant is the upper right-hand corner of the graph, the section where both x and y are positive. The second quadrant, in the lower right-hand and the third quadrant is the lower right-hand.

For soybean, the first component (PC1) is the contrast of Ta and the weighted averages of Rain, ETa/ETc and Yw (0.492 x ETa/ETc + 0.415 x Rain + 0.516 x Yw – 0.418 x Ta), whereas the PC2 includes the contrast between RH and weighted average of SR and Yp (0.628 x SR + 0.517 x Yp – 0.492 * RH). Thus, regarding to PC1, it can be interpreted that the points located in the first and second quadrants present the lowest values of ETa/ETc and Rain and the highest of Ta, and analyzing the PC2 the points presented in the first and fourth quadrant are those with the highest values of SR, Yp and the lowest of RH. These two components (PC1 and PC2) explain 47,15 and 29.71% of the data variance, respectively. These results also show the high positive correlation between Rain and ETa/ETc, and the negative correlation between RH and SR. The biplot chart indicates that in Altamira, PA (in the sowing dates of 21 September and 21 October), and São Raimundo das Mangabeiras, MA, the high Ta negatively affects the soybean Yp and Yw. In Altamira, in the sowing dates of 21 November and 21 December, the large amount and days of rain from November to July generate a reduction of incident solar radiation, which also caused reduction of Yp and, consequently, Yw (Figure 8).

Soybean sown in September is extremely affected by the water deficit, as already presented. The PCA analysis shows that the points corresponding to this month, for some regions, are concentrated in the first quadrant (Opposite side of the variables RH, Rain and ETa/ETc), which means that the lower RH and Rain generate a reduction of ETa/ETc, causing soybean yield losses by water deficit. All the points corresponding to the location of Luis Eduardo Magalhães, BA, are concentrated in the first quadrant, indicating that the water deficit is the major problem for soybean production in this region (Figure 8A). For the others locations, the corresponding points of soybean sowing performed in October and November are concentrated in the fourth quadrant, indicating that they are the best for obtaining high yields.

For maize off-season, the PC1 explained 55,36% of the data variation and it is characterized by contrast between SR and the weighted average of ETa/ETc, Rain, RH and Yp (0,325 x SR – 0.493 x ETa/ETc – 0.409 x Rain – 0,475 RH – 0,397 Yw). The PC2 is represented by the weighted averages of Ta (-0,549 x SR - 0,595 Ta), explaining 25,88% of the data variation (Figure 8B). From this analysis, a high positive correlation between Yw and Rain was observed, which indicates that water availability is the main factor that affects the maize off-season yield in most of Brazil. However, in Campo Mourão, PR (points concentrated in the first quadrant), in southern Brazil, Ta and SR showed to be the most important factors that explain the Yp reduction, which, consequently, decreased Yw. On the other hand, in Altamira, PA (points concentrated in the second quadrant), the abundant amount of Rain allowed to obtain high maize off-season Yw in all sowing dates simulated (Figure 8B).

Economic risks of soybean-maize succession in Brazil

To determine the best sowing date for soybean-maize succession in different Brazilian regions it is of crucial importance to consider the profitability of each crop. The net revenue, obtained by the balance between gross revenue and production costs for soybean and maize off-season crops, demonstrated that the best soybean sowing date should be between late September and early October, except for Altamira, PA (Figure 9). In an average scenario of prices, the net revenue for soybean-maize succession has little chances of profitability when soybean is sown after the end of October in Rio Verde, GO (Figure 9c), São Raimundo Mangabeiras, MA (Figure 9i), Nova Xavantina, MT (Figure 9l), and Luiz Eduardo Magalhães, BA (Figure 9o). For Uberaba, MG (Figure 9r), Barretos, SP (Figure 9u), and Campo Mourão, PR (Figure 9x), the net revenue remains reasonable for soybean sowing till the end of November. For Altamira, PA, the results are totally different, with the best sowing date occurring between late November and mid-December when the chances of profitability is above 80% in any of the scenarios projected.

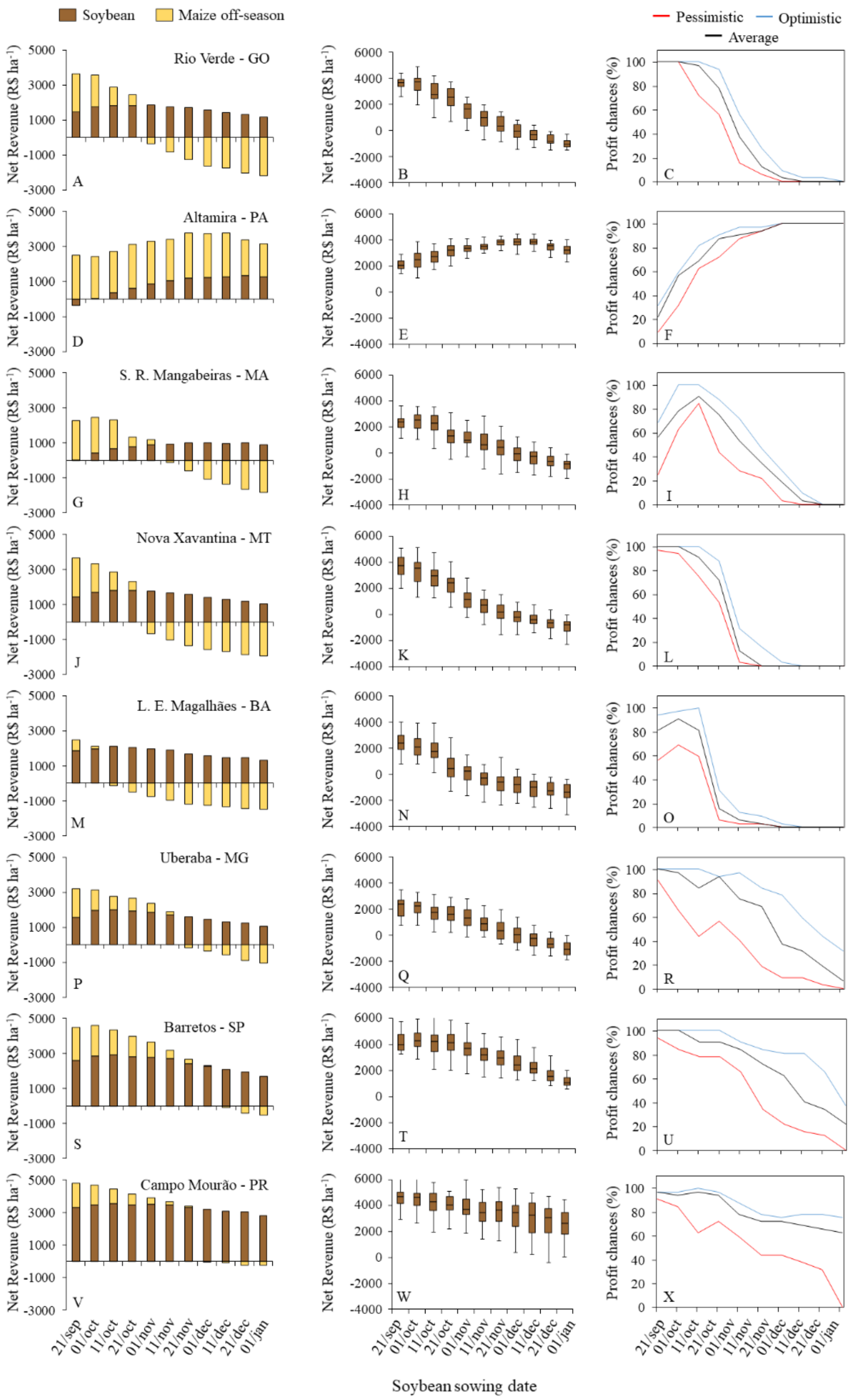

Figure 9. Net revenue for soybean and maize off-season crops in succession (left), its inter-annual variation (center), and profit chances (right) in optimistic (high sales price), average (average sales price) and pessimistic (low sales price) scenarios for both crops, in different sowing dates and locations of Brazil. The results for all the other 21 locations are presented in the Supplementary material (Figures S8, S9 and S10). The error bars present the variation of all dataset.

2.4. Discussion

The crop models used in this study, calibrated by Battisti et al. (2017) for soybean, and by Bender (2017) and Duarte (2018), for maize off-season, showed a similar yield variability along the sowing dates, which shows their feasibility for simulating Yw of these crops. However, expressive differences were obtained in some cases, which can be associated to the different ways the models consider some crop processes. According to Asseng et al. (2013), different crop models vary with their nature in terms of process simulated, environmental conditions and objectives of the study for which they were developed, being better to use an ensemble of models than only one when the objective is to study the influence of weather and soil conditions on crop yield (MARTRE et al., 2015), as we made in this study.

The anticipation of soybean sowing to late September resulted in higher values of YG_w. However, such procedure allows maize off-season to be sown in January, providing higher total grain yields in south-central Brazil. In addition, this anticipation allows to harvest soybeans in early January, when the sales price is higher than February and March (Table S5 in the Supplementary material), which compensates the yield losses. Furthermore, soybean sowing in late September or early October, reduces Asian soybean rust severity, reducing production costs (RODRIGUES et al., 2013). According to Zuil et al. (2012), soybean and maize grown in environments with higher temperatures and solar radiation availability, especially during grain filling, which occurs when the soybean sowing occurs in late September (Figure 8), could help to obtain grain with higher oleic acid percentage, contributing to have many cooking and health benefits (ERKKILÄ et al., 2008).

The delay in soybean sowing from late September or early October to the end of October and November, decreases YG_w in most of the locations assessed (Figure 6); however, such delay forces maize to be sown in late February and March, which increases maize YG_w in central Brazil (Figure 7), as also observed by Soler et al. (2007). In this region, the delay of soybean sowing can make maize YG_w to surpass 9000 kg ha^{-1}, which is a consequence of the climate characteristics of this regions, where the rainfall decreases substantially just after the end of the summer, as described by Alvares et al. (2013). According to Soler et al. (2007), after February the soil water content in all layers are reduced, affecting the roots depth and making the plants more susceptible to water deficit. Besides that, the air relative humidity decreases (Figure 8), increasing vapor pressure deficit between leaves and atmosphere, making leaf resistance to vapor flow higher, reducing photosynthesis (LARCHER, 2003; TAIZ; ZEIGER, 2013). All these processes make YG_w higher.

The obtained results indicate that both the anticipation and delay of soybean sowing and, consequently, of maize generate yield losses in both crops. A way to mitigate that is by implementing irrigation. The area available for irrigation expansion in Brazil is approximately 75 million hectares (BRAZIL, 2014), and the government expects to increase from the present 6 to 12 million hectares in the next 10 years (FAO, 2017), which will be a good opportunity for farmers to increase their yields, since the soybean and maize potential yields are high in all Brazilian regions (Figures S4 and S6 Supplementary material). Other alternative for improving the yields of these crops could be the selection of drought-tolerant cultivars (GOMES et al., 2013) and/or the optimization of soil profile by crop rotation, deeper soil preparation and correction (BATTISTI; SENTELHAS, 2017; CATUCHI et al., 2012). Even considering the major effect of rainfall and soil water availability on soybean and maize yields, these are not the only climatic aspects related to that. Air temperature and solar radiation also affect grain yield, mainly for maize off-season crop (Figure 8).

Altamira, PA, in northern Brazil, presents, according to Köppen classification, an Am climate type (ALVARES et al., 2013), which corresponds to a tropical humid climate with short dry season. The short dry season occurs from August to October, making early soybean sowing very risky. The rainfall begins in November and lasts till July, with amounts exceeding 200 mm $month^{-1}$. These high rainfall amounts are associated to intense cloudiness, reducing solar radiation for the crops. Consequently, soybean and maize potential yields are reduced, reaching, respectively, around 3800 kg ha^{-1} and 7900 kg ha^{-1} (Figures S4 and S6 in the Supplementary material). On the other hand, YG_w in this region is low, which favors the soybean-maize succession. This favorable climate condition in the state of Pará led to an increase in the soybean and maize off-season harvested areas of 210% and 548%, respectively, between 2010 and 2016 (IBGE, 2019). However, rainfall has a high inter-annual variability in this state (SOMBROEK, 2001), with several dry spells along the growing season, mainly associated with the warm phase of El Niño Southern Oscillation (DINIZ et al., 2015).

In southern Brazil, the lowest yield and net revenue were obtained when soybean sowing was delayed (Figure 9). The results obtained demonstrated that solar radiation and air temperature seasonality were responsible for potential yield reduction, corroborating with the results of Waha et al. (2012). Moreover, during the autumn and winter, early agronomic frosts can occur (Alvares et al., 2017), generating strong yield losses for maize off-season. The occurrence of the agronomic frosts in the region is an issue that has been addressed for many years (CESAR DEMARCHI; LUÍS PIROLI, 2015). According to Arakaki and Minuzzi (2015), to avoid problems with agronomic frosts on maize off-season it strongly recommended that soybean sowing takes place in late September or early October, which is in agreement with the results obtained here. Furthermore, the average of agronomic frost days can exceed 8 days per month, in June and July, in south Brazil (ALVARES; SENTELHAS; STAPE, 2017), therefore, it is recommended that the maize be harvested before this period.

The economic analysis revealed that the soybean-maize succession is a risky production system and its success depends heavily on the choice of the best sowing date (Figure 9). In Brazil, the farmers which produce soybean-maize succession face with a high cost of production, and a volatile selling price (NARIK, 2012). The consequences of the prices volatility are well documented in the literature and include economic and political instability as well as the changes of consumers and producers behaviors, as is shown by Pereira et al. (2012). Fertilizers, seeds, pesticides and transportation costs are the main reasons for the high production costs. The cost of pesticides, for example, represents 19.4% for the total cost for soybean, whereas for maize it represents 12.1% (CONAB, 2019). The cost with fertilizer and transport, represent about 22.4 and 4.1%, respectively, of the total cost for soybean-maize succession (CONAB, 2019). These costs could be reduced through the adoption of crop management techniques capable of increasing soil fertility without the need to apply large quantities of chemical fertilizers (GHOSH, 2004); adoption of more rational pest and disease management, such as integrated pest management systems (DE GROOTE et al., 2010); and adoption of public logistic policies for improving grain transport.

The results of this study illustrate the climatic impacts on soybean-maize succession yields and net revenues, as a function of different sowing dates. However, non-climatic factors, such as farming size, labor and machinery availability were not considered. These factors definitely determines whether sowing can be completed or not in the planned time (ASSENG et al., 2013; KUCHARIK, 2006). So, we consider that researches that integrate climate and non-climate impacts on sowing dates should be encouraged in Brazil, in order to improve the determination of the risks linked to soybean-maize succession. Based on the results of this study, the climatic impacts on soybean-maize succession can be minimized by choosing the best sowing date. The optimal sowing date varies according to the Brazilian region. For the central Brazil, the higher net revenue is obtained when soybean sowing is anticipated towards the end of September or early October, which increases YG_w for soybean but reduces it for maize off-season and for the total crop system. It is also recommended to sow soybean on the end of September or early October in southern Brazil, because the delay can generate damages to maize off-season due to low temperatures and solar radiation. In northern Brazil, represented by Altamira, PA, it is recommended to sow soybean from late November, in order to minimize yield gaps and net revenue losses by water deficit in soybean crop.

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Supplementary material

Table 1. Silt, sand, clay, carbon, and nitrogen contents (%), and pH of soils in the 29 Brazilian locations where soybean and maize off season yields were simulated.

State	Location	Silt (%)	Clay (%)	Sand (%)	pH	Carbon (%)	Nitrogen (%)
BA	Cocos (COC)	10	41	49	5.9	0.20	0.02
BA	Luís E. Magalhães (LEM)	9	22	69	5.7	0.27	0.01
GO	Chapadão do Céu (CHA)	9	37	54	5.4	0.70	0.08
GO	Rio Verde (RIV)	17	26	57	5.3	4.80	0.44
GO	Formosa (FOR)	24	45	31	5.3	1.21	0.12
MA	São R. das Mangabeiras (SRM)	13	32	55	5.5	0.43	0.06
MG	Uberaba (UBE)	5	27	68	5.5	0.35	0.03
MG	Buritis (BUR)	5	22	73	5.7	0.26	0.02
MS	Ponta Porã (POP)	15	59	26	5.0	1.47	0.11
MS	Rio Brilhante (RIB)	8	52	40	5.0	1.97	0.14
MS	S. Gabriel do Oeste (SGO)	37	24	39	5.2	1.60	0.09
MS	Coxim (COX)	7	27	66	5.2	1.18	0.11
MT	Rondonópolis (RON)	46	27	27	5.30	0.59	0.06
MT	Primavera do Leste (PRL)	12	32	56	5.6	1.50	0.09
MT	Nova Xavantina (NOX)	18	32	50	6.4	0.19	0.03
MT	Campo N. do Parecis (CNP)	7	30	63	5.6	0.80	0.06
MT	Sorriso (SOR)	10	56	34	5.2	3.20	0.30
MT	Querência (QUE)	8	49	43	5.5	2.10	0.20
PA	Altamira (ALT)	12	27	61	5.3	1.55	0.13
PI	Uruçuí (URU)	26	24	50	5.1	0.99	0.08
PR	Campo Mourão (CAM)	17	76	7	5.4	2.83	0.25
PR	Londrina (LON)	9	49	42	5.32	0.50	0.05
RO	Vilhena (VIL)	8	39	53	5.6	2.90	0.10
RO	Rio Crespo (RIC)	34	37	29	6.2	1.40	0.10
SP	Taquarituba (TAQ)	10	55	35	4.9	0.66	0.06
SP	Ibirarema (IBI)	17	64	19	6.0	2.74	0.27
SP	Barretos (BAR)	18	61	21	5.5	2.39	0.16
TO	Figueirópolis (FIG)	18	49	33	5.3	0.75	0.04
TO	Bom J. do Tocantins (BJT)	15	39	46	5.3	0.26	0.02

Table 2. Crop models´ performance for simulating soybean yield at the calibration and validation phases. Adapted from Battisti et al. (2017).

Models	RMSE (kg ha^{-1})	d	R^2
		Calibration	
FAO	650	0.91	0.79
DSSAT	548	0.93	0.79
APSIM	550	0.90	0.69
		Validation	
FAO	752	0.77	0.21
DSSAT	511	0.89	0.54
APSIM	732	0.79	0.43

RMSE = Root mean error square; d = Wilmott agreement index; R^2 = coefficient of determination.

Table 3. Crop models´ performance for simulating maize off season yield at the calibration and validation phases. Adapted from Duarte (2018) (*) and Bender (2017) (**).

Models	RMSE (kg ha^{-1})	d	R^2
		Calibration	
FAO*	1459	0.72	0.28
DSSAT**	576	0.86	0.69
APSIM**	1205	0.76	0.31
		Validation	
FAO*	2008	0.71	0.28
DSSAT**	337	0.93	0.77
APSIM**	1554	0.81	0.49

RMSE = Root mean error square; d = Wilmott agreement index; R^2 = coefficient of determination.

Table 4. Production cost for cultivating soybean and maize off-season in several producing regions of Brazil.

State	Weather station	Production costs (R$ ha^{-1})	
		Soybean	Maize off-season
BA	Luís E. Magalhães (LEM)	1765	2203
GO	Chapadão do Céu (CHA)	2776	2829
MA	São R. das Mangabeiras (SRM)	2786	2203
MG	Uberaba (UBE)	2766	3388
MS	Ponta Porã (POP)	3182	2647
MT	Primavera do Leste (PRL)	3292	2441
MT	Campo N. do Parecis (CNP)	2807	2157
MT	Sorriso (SOR)	2498	2908
PA	Altamira (ALT)	2786	2907
PI	Uruçuí (URU)	2786	3094
PR	Campo Mourão (CAM)	2292	3000
PR	Londrina (LON)	3405	2203
RO	Vilhena (VIL)	2807	2203
SP	Barretos (BAR)	2848	1884
TO	Figueirópolis (FIG)	2786	1884

The other locations, which do not have estimated production cost by CONAB (2019), the values used were the same from their respective states or from the nearest municipality.

Table 5. Monthly variation of soybean and maize sales prices (R$ per bags of 60 kg), in Brazil, considering three scenarios: pessimistic, average and optimistic. Adapted from CEPEA (2018).

Months	Soybean sales price scenarios			Maize sales price scenarios		
	pessimistic	average	optimistic	pessimistic	average	optimistic
January	61.7	68.1	74.6	26.6	32.8	39.1
February	61.1	66.4	71.8	28.3	34.1	39.9
March	61.1	66.6	72.1	28.5	35.9	43.3
April	58.1	66.8	75.5	24.3	33.7	43.1
May	59.4	69.2	79.1	22.6	33.6	44.7
June	60.4	71.4	82.4	22.0	32.3	42.6
July	62.7	71.2	79.8	21.6	30.2	38.9
August	62.6	68.7	74.7	20.0	29.2	38.5
September	61.9	69.5	77.1	22.2	29.8	37.4
October	62.9	70.1	77.3	23.2	30.7	38.4
November	66.0	71.3	76.6	26.2	31.4	36.6
December	65.9	71.7	77.4	27.0	32.1	37.1

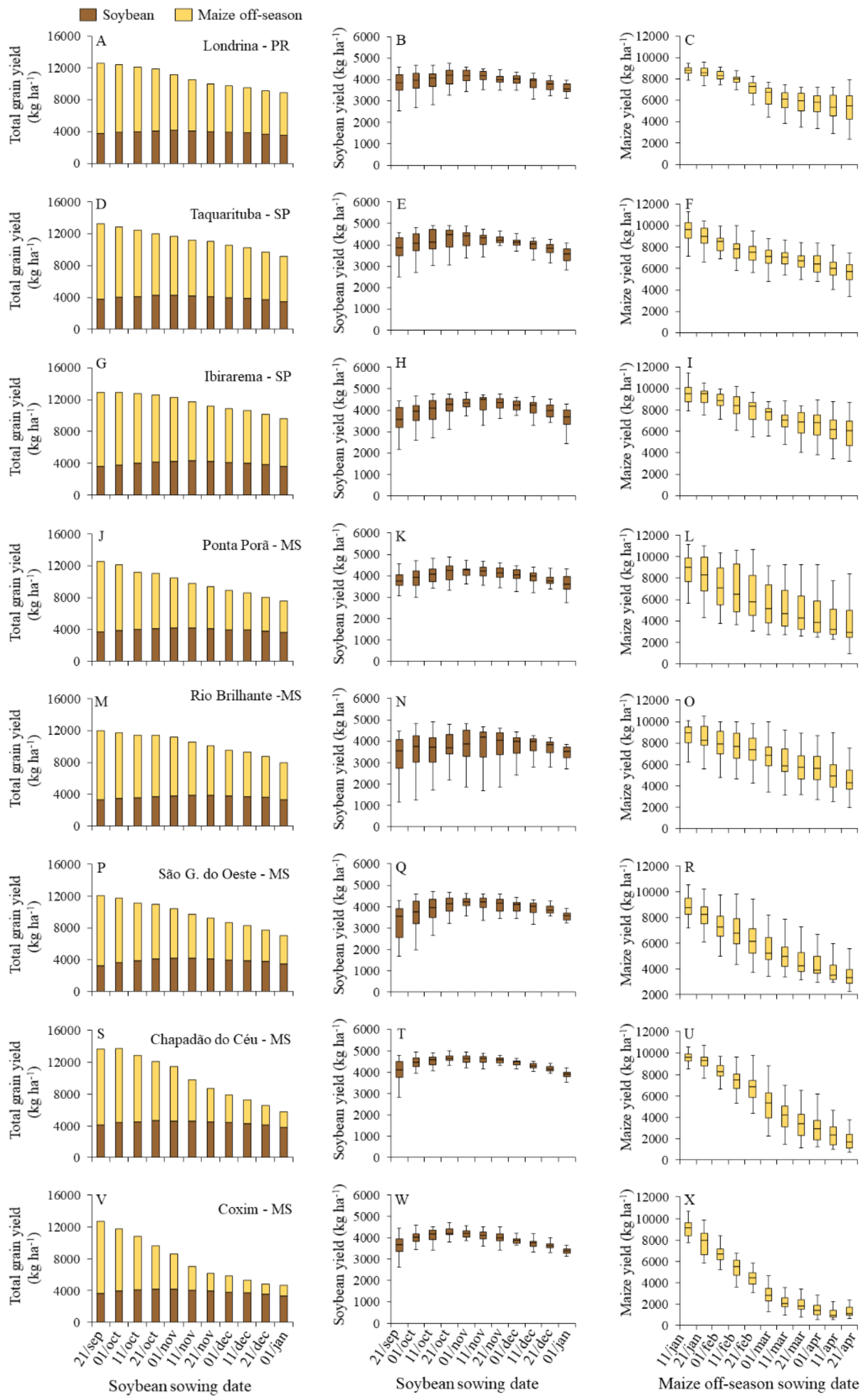

Figure 1. Total average grain yield for the succession soybean and maize crops (left), inter-annual variability of soybean (center) and maize off-season (right) water-limited yields for different sowing dates and locations in Brazil: Londrina (A, B and C), Taquarituba (D, E and F), Ibirarema (G, H and I), Ponta Porã (J, K and L), Rio Brilhante (M, N and O), São Gabriel do Oeste (P, Q and R), Chapadão do Céu (S, T and U) and Coxim (V, W and X).

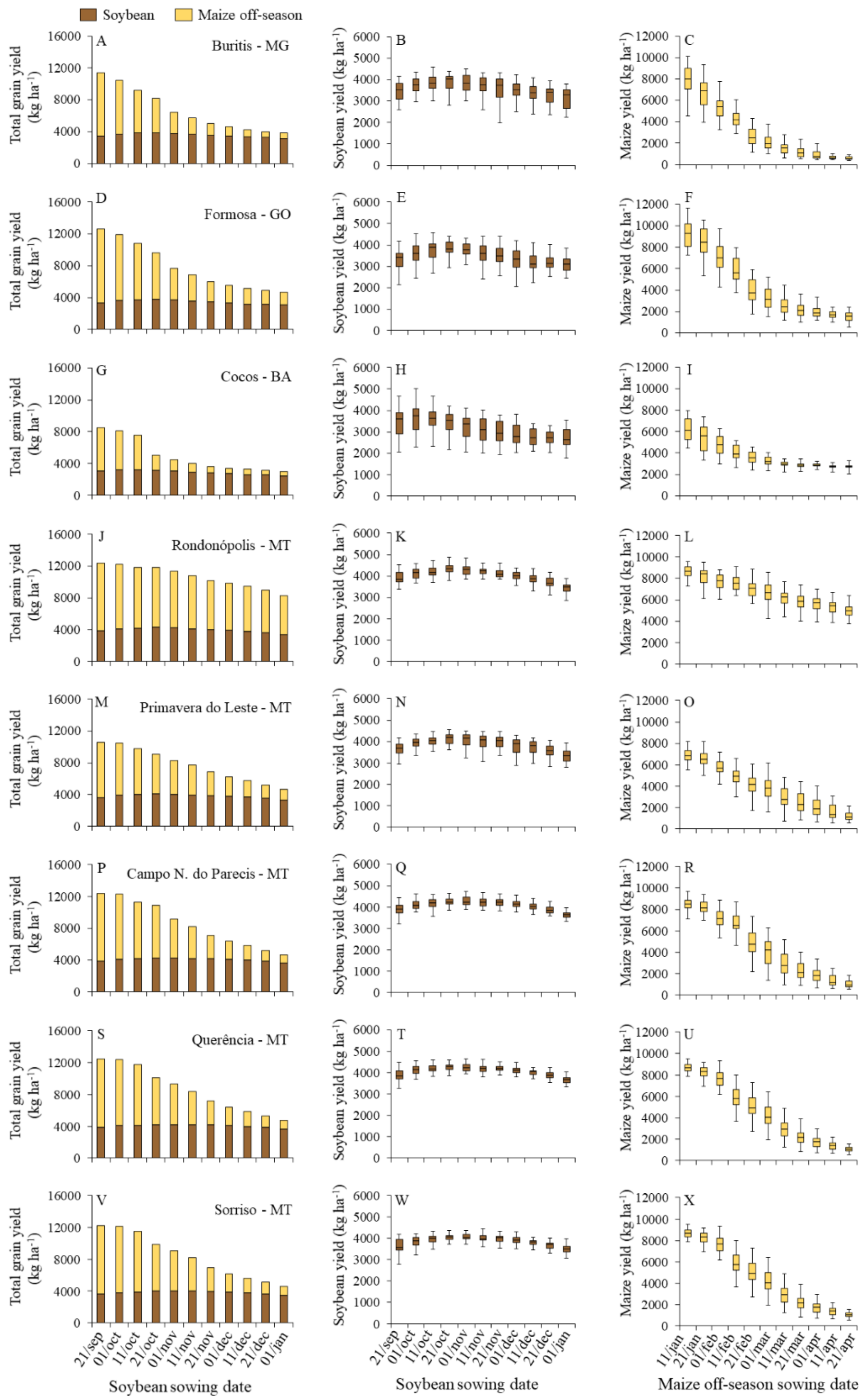

Figure 2. Total average grain yield for the succession soybean and maize crops (left), inter-annual variability of soybean (center) and maize off-season (left) water-limited yields for different sowing dates and locations in Brazil: Buritis (A, B and C), Formosa (D, E and F), Cocos (G, H and I), Rondonópolis (J, K and L), Primavera do Leste (M, N and O), Campo Novo do Parecis (P, Q and R), Querência (S, T and U) and Sorriso (V, W and X).

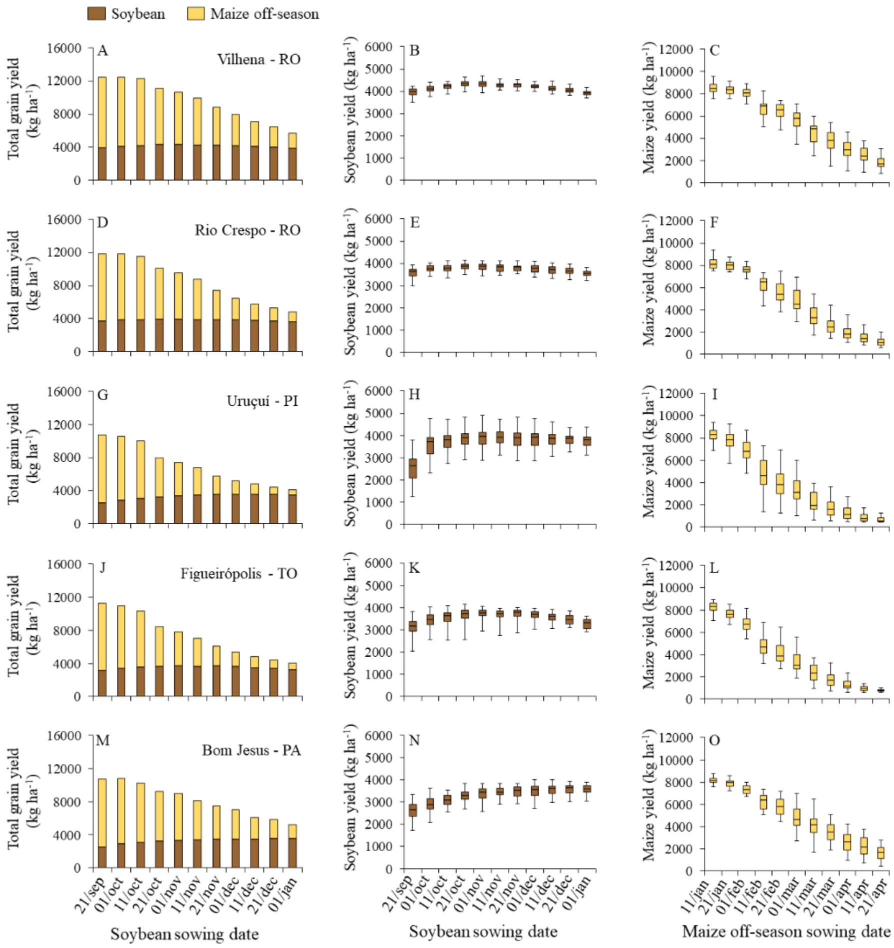

Figure 3. Total average grain yield for the succession soybean and maize crops (left), inter-annual variability of soybean (center) and maize off-season (right) water-limited yields for different sowing dates and locations in Brazil: Vilhena (A, B and C), Rio Crespo (D, E and F), Uruçuí (G, H and I), Figueirópolis (J, K and L), Bom Jesus do Tocantins (M, N and O).

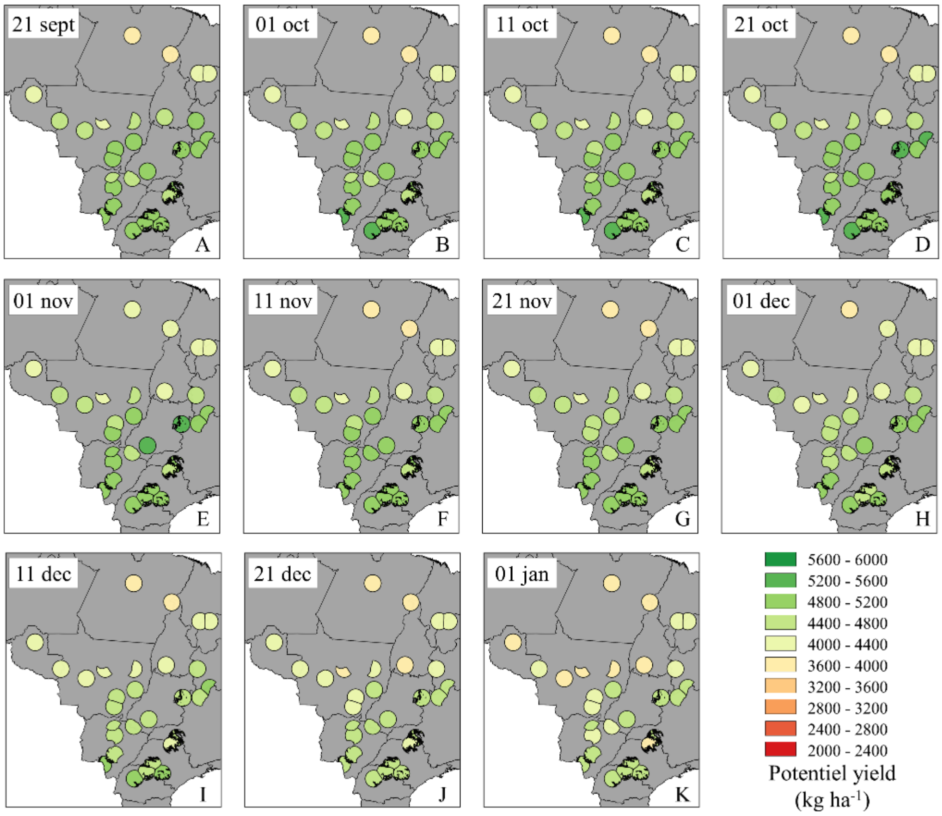

Figure 4. Spatial and temporal variation of soybean potential yield in Brazil, in different sowing dates.

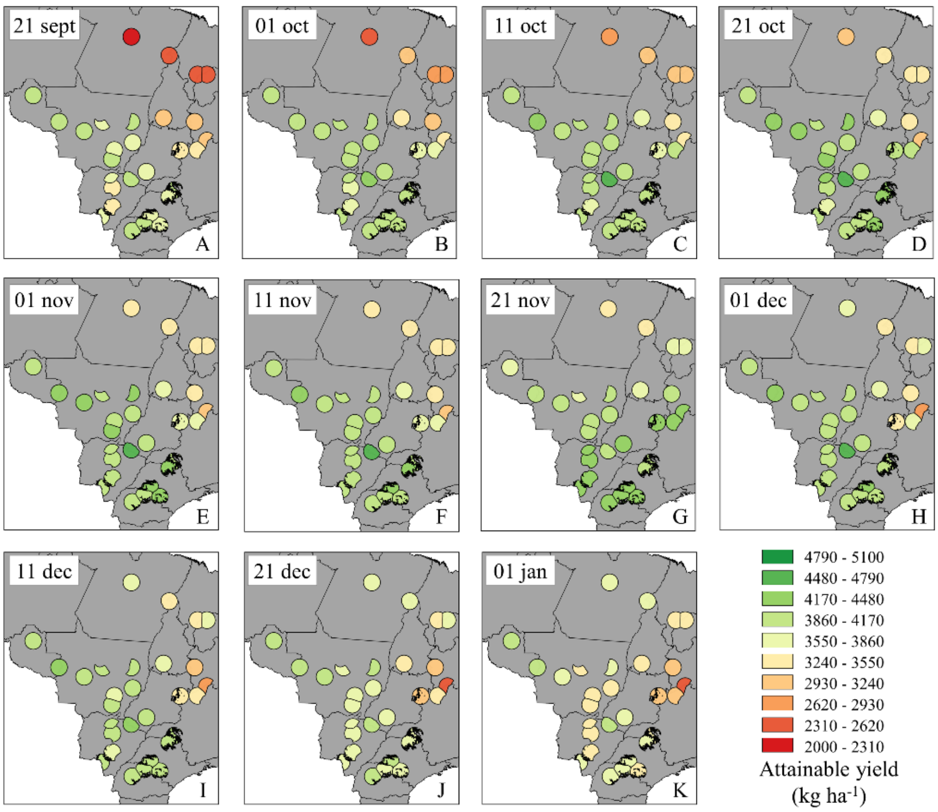

Figure 5. Spatial and temporal variation of soybean water-limited yield in Brazil, in different sowing dates.

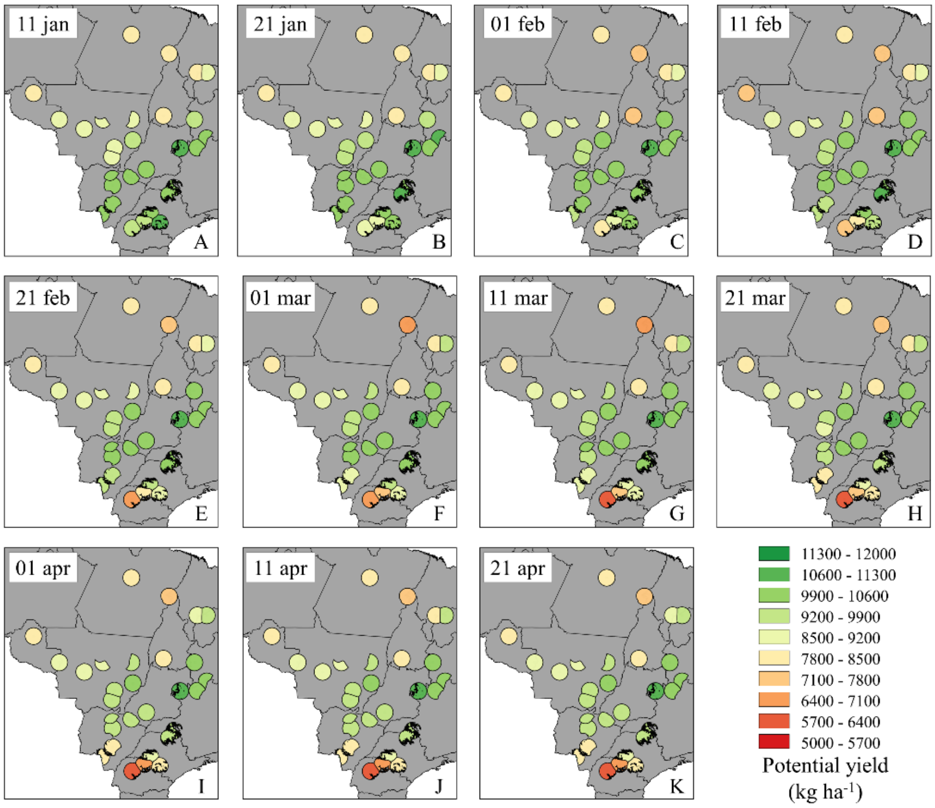

Figure 6. Spatial and temporal variation of maize off-season potential yield in Brazil, cultivated in succession to soybean in different sowing dates.

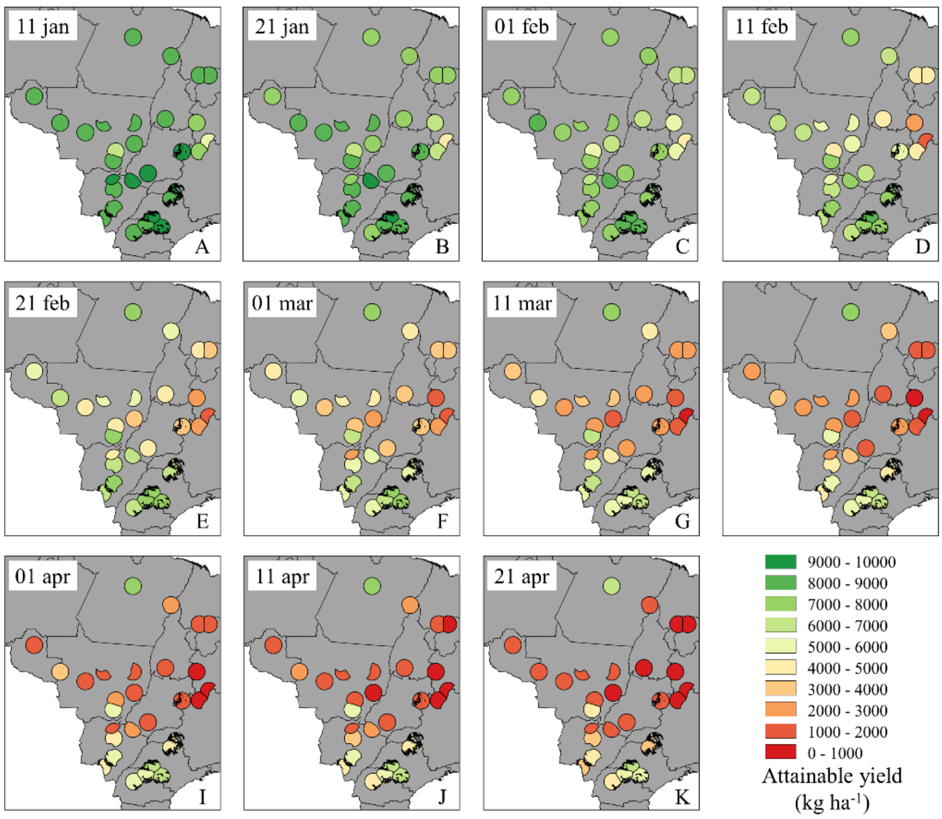

Figure 7. Spatial and temporal variation of maize off-season water-limited yield in Brazil, cultivated in succession to soybean in different sowing dates.

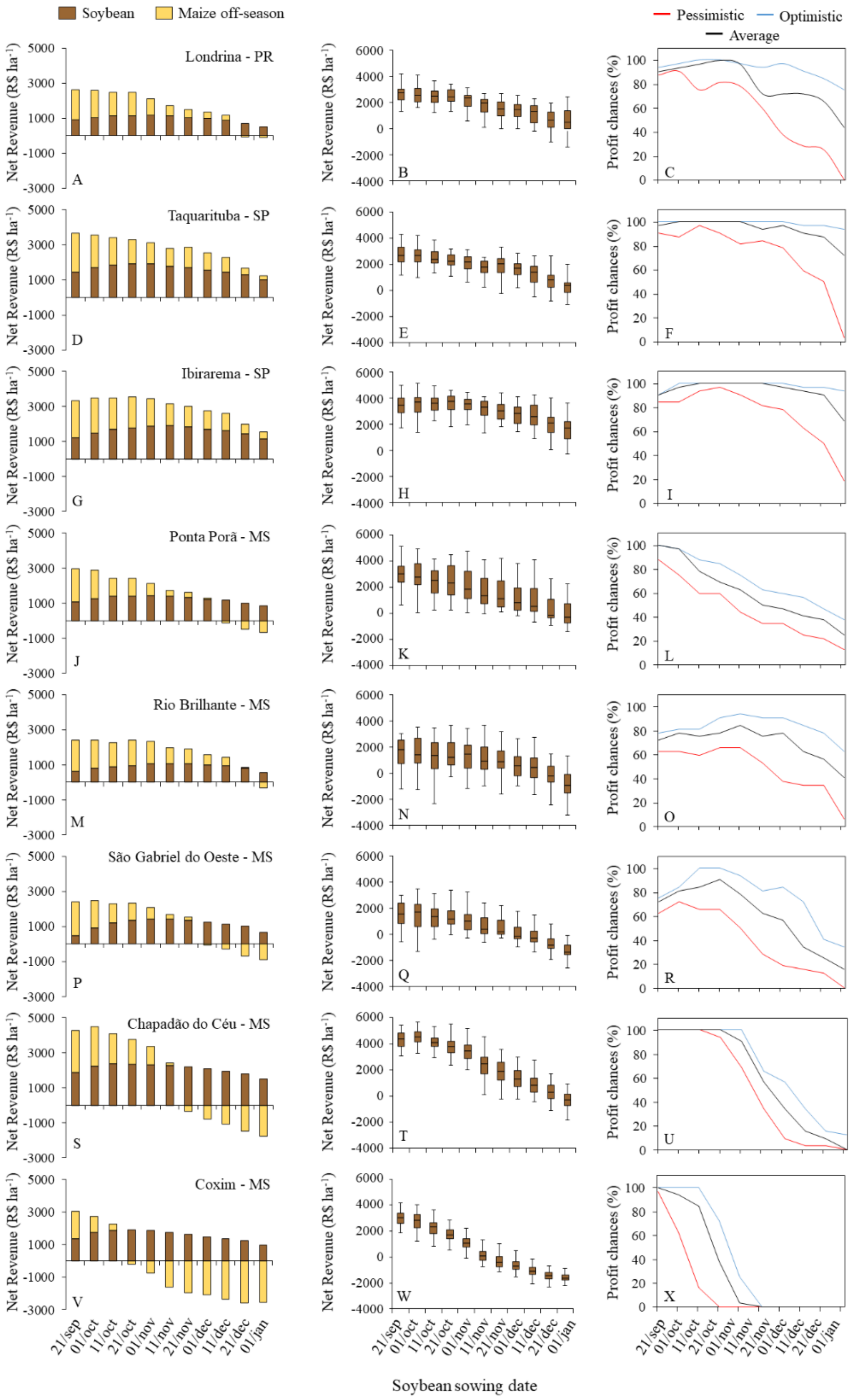

Figure 8. Net revenue for soybean and maize off-season crops in succession (left), its inter-annual variation (center), and profit chances (right) in optimistic (high sales price), average (average sales price) and pessimistic (low sales price) scenarios for both crops, in different sowing dates and locations of Brazil: Londrina (A, B and C), Taquarituba (D, E and F), Ibirarema (G, H and I), Ponta Porã (J, K and L), Rio Brilhante (M, N and O), São Gabriel do Oeste (P, Q and R), Chapadão do Céu (S, T and U) and Coxim (V, W and X).

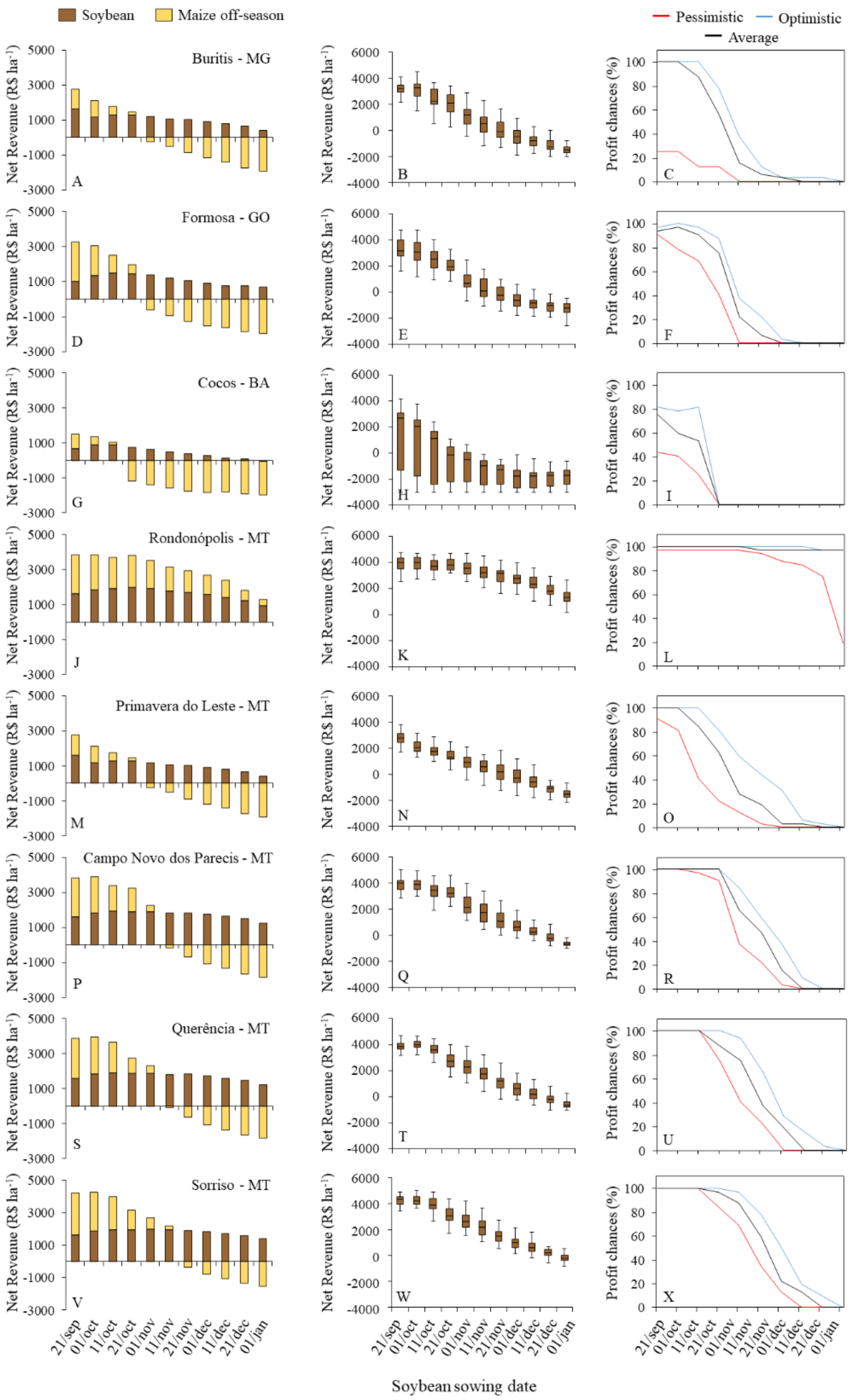

Figure 9. Net revenue for soybean and maize off-season crops in succession (left), its inter-annual variation (center), and profit chances (right) in optimistic (high sales price), average (average sales price) and pessimistic (low sales price) scenarios for both crops, in different sowing dates and locations of Brazil: Buritis (A, B and C), Formosa (D, E and F), Cocos (G, H and I), Rondonópolis (J, K and L), Primavera do Leste (M, N and O), Campo Novo do Parecis (P, Q and R), Querência (S, T and U) and Sorriso (V, W and X).

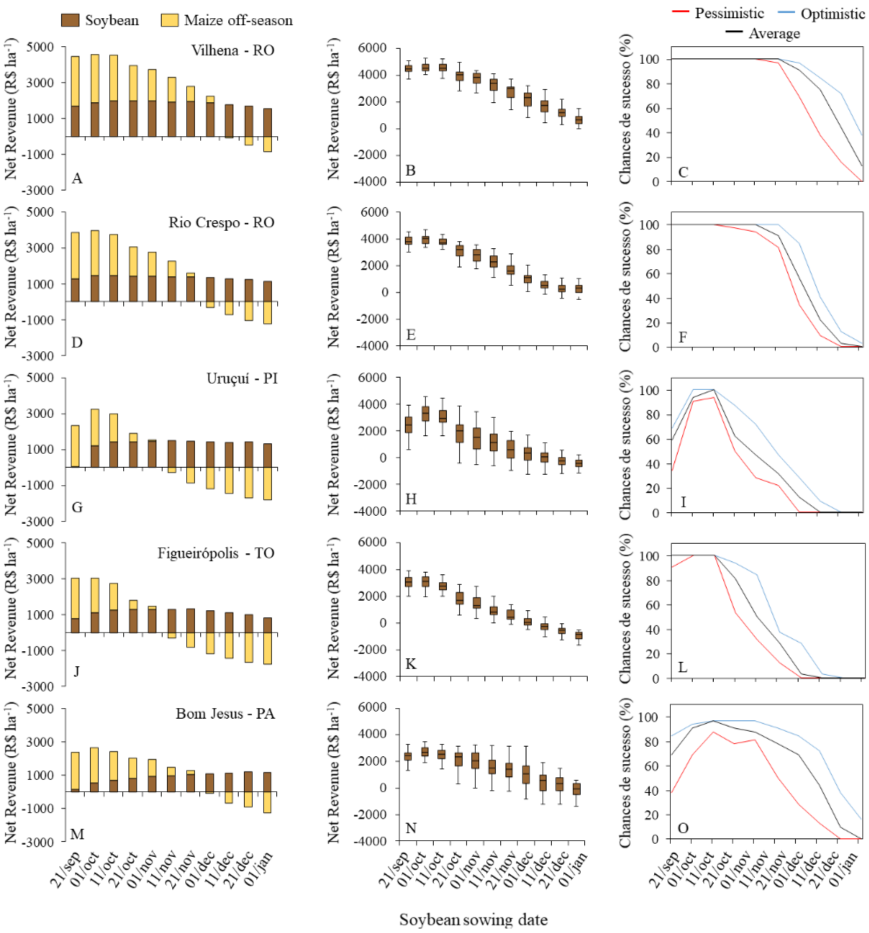

Figure 10. Net revenue for soybean and maize off-season crops in succession (left), its inter-annual variation (center), and profit chances (right) in optimistic (high sales price), average (average sales price) and pessimistic (low sales price) scenarios for both crops, in different sowing dates and locations of Brazil: Vilhena (A, B and C), Rio Crespo (D, E and F), Uruçuí (G, H and I), Figueirópolis (J, K and L), Bom Jesus do Tocantins (M, N and O).

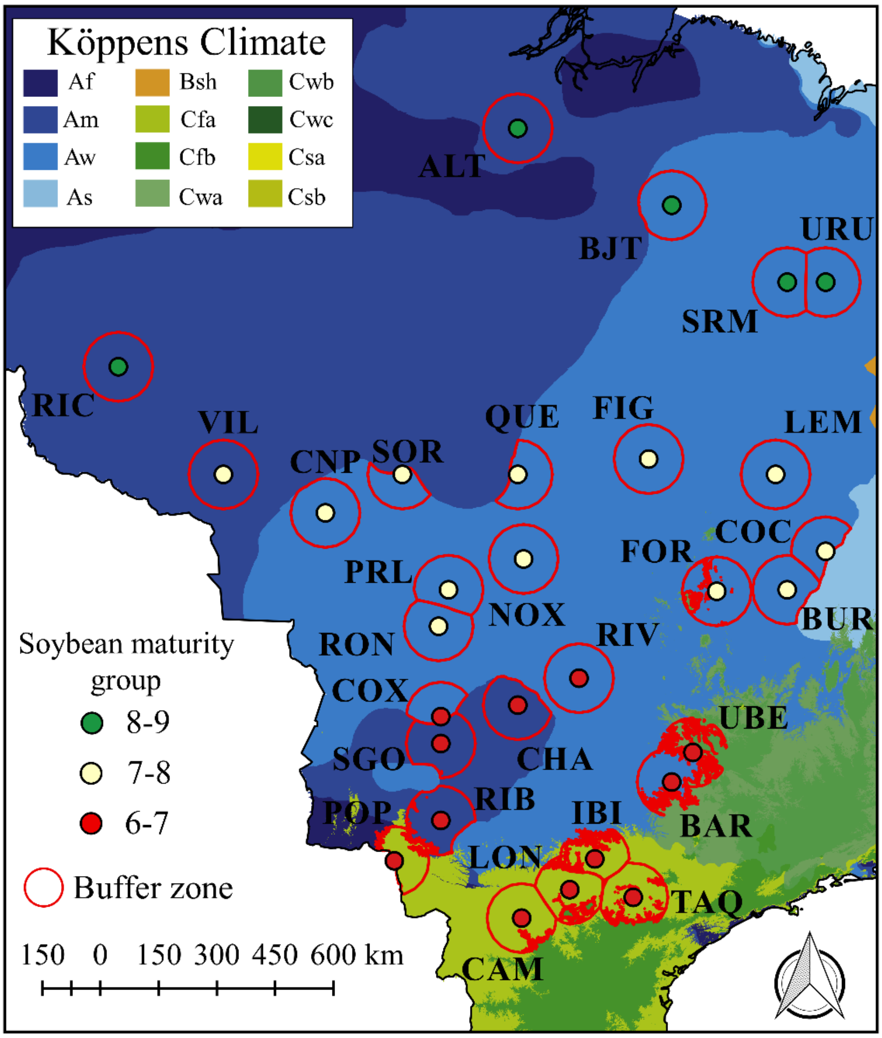

Figure 11. Weather stations (WS) and associated buffer zones selected for simulating yield water-limited and yield gap by water deficit for the soybean-maize succession in Brazil, considering different soybean maturity groups. The map presents the Köppen climate classification proposed by Alvares et al. (2013).

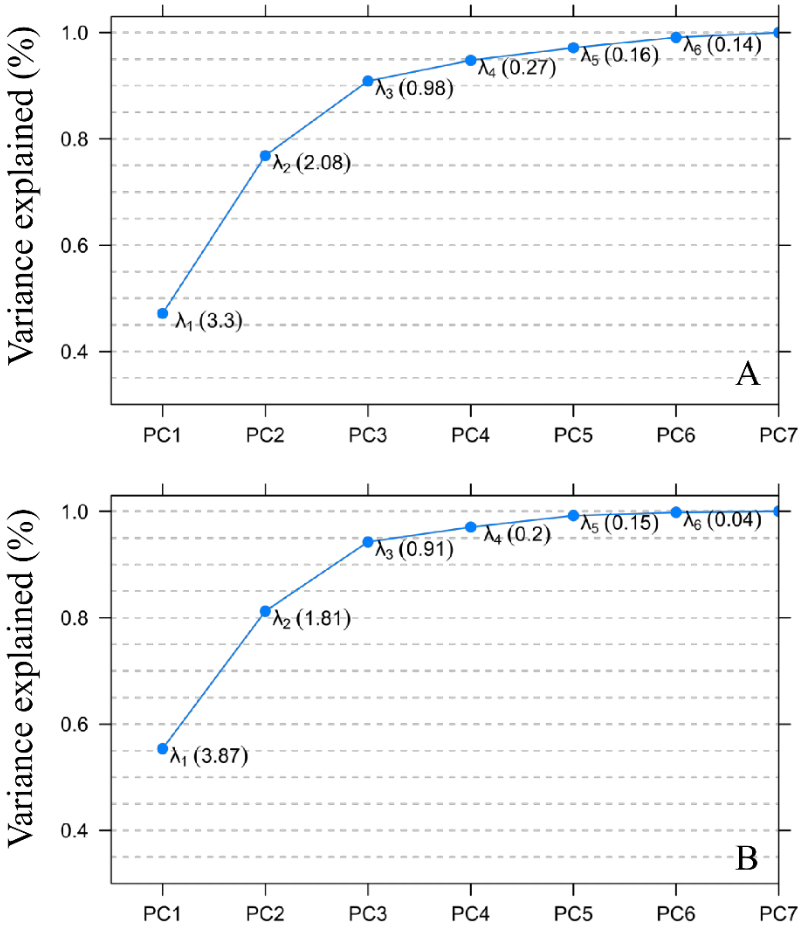

Figure 12. The results of scree plot (accumulated explained variance and the eigenvalues for each principal component presented in parenthesis) of the principal component analyses for soybean (A) and maize off-season (b).

Table 6. The matrix of the data pre-standardized used in the Principal components presented in Figure 8A, for soybean in Brazil. ETa/ETc: dimensionless; SR: solar radiation (MJ m^{-2} day^{-1}); RH: relative humidity (%); Rain (mm day^{-1}); Ta: air temperature (°C); Yp: potential yield (kg ha^{-1}); Yw: water-limited yield (kg ha^{-1}). The data are average of the growing season in different sowing dates and locations.

Location	Sowing date	ETa/ETc	SR	Rain	RH	Ta	Yp	Yw
Campo Mourão - PR	21 September	0.82	16.89	5.39	86.13	22.41	4997.09	3764.67
	21 October	0.83	17.53	5.90	86.93	23.19	5066.74	4066.10
	21 November	0.84	17.15	6.00	88.25	23.49	4821.25	3988.78
	21 December	0.86	16.28	5.43	89.14	23.27	4516.14	3804.38
Barretos - SP	21 September	0.79	20.08	5.68	70.57	24.73	4698.55	3706.42
	21 October	0.89	20.02	7.29	74.90	24.84	4821.24	4324.93
	21 November	0.90	19.76	7.78	77.31	24.93	4596.57	4165.69
	21 December	0.89	19.23	6.62	77.90	24.85	4201.76	3795.79
Uberaba - MG	21 September	0.81	19.72	6.42	72.21	23.57	4906.59	3807.21
	21 October	0.89	19.52	8.29	76.61	23.59	4957.02	4244.93
	21 November	0.91	19.44	8.81	78.75	23.60	4783.75	3936.63
	21 December	0.90	19.16	8.09	79.26	23.52	4596.89	3607.58
Rio Verde - GO	21 September	0.83	18.76	6.35	71.48	24.50	5091.50	3737.92
	21 October	0.91	18.61	7.74	76.57	24.21	5135.22	4144.70
	21 November	0.92	18.48	8.16	78.62	24.11	4939.64	4040.43
	21 December	0.91	18.40	7.92	78.80	24.07	4518.05	3686.38
Nova Xavantina - MT	21 September	0.83	18.60	6.46	76.70	26.30	4900.59	3725.24
	21 October	0.91	18.20	8.46	81.66	25.88	4971.04	4162.66
	21 November	0.92	18.00	8.61	83.61	25.69	4784.87	3950.25
	21 December	0.91	18.08	7.40	83.70	25.69	4461.83	3593.92
Luis Eduardo Magalhães - BA	21 September	0.69	19.65	4.86	66.60	28.09	4890.61	2940.23
	21 October	0.80	19.49	5.93	72.96	27.62	4721.56	3423.45
	21 November	0.79	19.57	5.81	75.89	27.15	4650.26	3222.78
	21 December	0.78	19.75	5.19	76.58	26.80	4335.22	3012.24
São R. das Mangabeiras - MA	21 September	0.68	18.30	3.98	69.95	27.52	4193.78	2475.53
	21 October	0.82	17.44	5.11	76.06	26.92	4232.51	3217.12
	21 November	0.87	17.26	5.70	79.72	26.60	4233.14	3436.18
	21 December	0.89	17.31	5.57	81.60	26.54	4170.19	3396.90
Altamira - PA	21 September	0.63	17.70	3.67	77.90	28.09	3974.15	2130.72
	21 October	0.77	16.60	5.79	80.54	27.62	3901.31	3089.15
	21 November	0.89	16.09	8.16	83.11	27.15	3861.19	3598.56
	21 December	0.97	15.83	11.88	85.24	26.80	3801.00	3696.22
	Mean	0.85	18.34	6.70	78.60	25.42	4585.35	3621.68
	Sd	0.08	1.23	1.67	5.46	1.68	388.71	499.17

Table 7. The matrix of the data pre-standardized used in the Principal components presented in Figure 8B, for maize off-season in Brazil. ETa/ETc: dimensionless; SR: solar radiation (MJ m^{-2} day^{-1}); RH: relative humidity (%); Rain (mm day^{-1}); Ta: air temperature (°C); Yp: potential yield (kg ha^{-1}); Yw: water-limited yield (kg ha^{-1}). The data are average of the growing season in different sowing dates and locations.

Location	Sowing date	ETa/ETc	SR	Rain	RH	Ta	Yp	Yw
Campo Mourão - PR	11 January	0.89	14.67	5.20	89.79	22.09	9386.39	8758.90
	11 February	0.91	12.94	4.45	90.75	20.44	7459.36	7301.98
	11 March	0.91	11.38	4.07	91.57	18.66	6239.97	5433.39
	11 April	0.90	10.57	3.47	91.81	17.25	5799.24	4218.77
Barretos – SP	11 January	0.84	18.52	5.36	75.78	24.20	10279.42	8758.90
	11 February	0.73	17.40	3.57	73.94	23.14	10615.21	7301.98
	11 March	0.64	16.23	2.09	70.97	21.97	10006.68	5433.39
	11 April	0.54	15.83	0.94	66.52	21.15	9697.26	4218.77
Uberaba – MG	11 January	0.85	18.68	6.22	77.09	22.91	10375.97	9019.62
	11 February	0.74	17.72	4.18	75.33	21.86	10563.56	7025.39
	11 March	0.64	16.70	2.50	72.41	20.70	10030.34	5172.52
	11 April	0.53	16.53	0.86	67.60	19.89	9633.47	4237.86
Rio Verde – GO	11 January	0.86	18.21	6.03	75.98	23.74	10062.57	9150.82
	11 February	0.70	17.53	4.35	72.61	23.07	10394.32	6054.66
	11 March	0.59	16.80	2.57	67.64	22.30	9983.76	2637.71
	11 April	0.48	16.72	0.64	61.10	21.80	9794.17	1404.76
Nova Xavantina – MT	11 January	0.83	18.22	5.72	81.78	25.52	10391.05	8547.06
	11 February	0.66	17.99	3.77	79.26	24.92	10921.26	5155.01
	11 March	0.53	17.73	1.98	75.43	24.13	10985.47	1783.69
	11 April	0.42	17.86	0.39	69.62	23.54	10899.57	989.24
Luis Eduardo Magalhães – BA	11 January	0.75	19.56	3.93	74.77	26.80	8558.72	7245.36
	11 February	0.57	19.11	2.66	71.51	26.92	9820.84	2881.58
	11 March	0.44	18.70	1.49	66.65	27.06	9733.57	1171.26
	11 April	0.31	18.92	0.27	60.40	27.26	9854.67	639.13
São R. das Mangabeiras – MA	11 January	0.86	17.74	4.90	80.81	26.67	8349.40	8153.69
	11 February	0.68	18.19	3.57	78.11	26.71	7900.29	4880.49
	11 March	0.53	18.69	2.24	73.19	26.64	8192.23	2664.09
	11 April	0.38	19.59	0.60	66.49	26.63	8413.89	1015.26
Altamira – PA	11 January	0.98	15.81	10.71	85.74	26.80	8208.67	8026.96
	11 February	0.94	16.02	9.64	85.26	26.92	8052.73	7703.69
	11 March	0.86	16.53	7.50	83.84	27.06	7853.26	7409.16
	11 April	0.74	17.50	4.01	81.59	27.26	7968.33	7027.64
	Mean	0.70	17.02	3.75	76.10	23.94	9263.30	5356.96
	Sd	0.18	2.13	2.52	8.51	2.84	1346.80	2747.54

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3. SOYBEAN-MAIZE OFF-SEASON DOUBLE CROP SYSTEM IN BRAZIL AS AFFECTED BY EL NIÑO SOUTHERN OSCILLATION PHASES

ABSTRACT

El Niño Southern Oscillation (ENSO) is one of the most important atmospheric-oceanic phenomena, responsible for climate variability in several Brazilian regions, which affects agriculture, mainly soybean - maize off-season succession. Therefore, the ENSO impacts on soybean - maize off-season double crop system can affect global food security, since Brazil is a major player as producer of these two crops, with a total production that represents 27% and 6% of world's soybean and maize production, respectively. In order to understand the risks associated to this crop system, the aim of this study was to assess the influence of ENSO phenomenon on the spatial and temporal soybean and maize off-season yield variabilities, considering simulations with three different crop models (FAO-AZM, DSSAT and APSIM) in a multi-model approach, and to determine the best sowing windows for this production system for each ENSO phase (El Niño, La Niña and Neutral) in different Brazilian producing regions. Previously calibrated and validated models were used to simulate soybean yields for 29 locations in 12 states, with sowing dates ranging from late September to early January of each growing season for a period of 34 years (1980-2013). The maize off-season sowing was done just after the soybean harvest, ranging from late January to early May. ENSO phases affected soybean and maize yields across the country, which can be minimized by choosing the best sowing window for soybean. In northern Brazil, El Niño negatively impacts soybean and maize off-season yields, making the succession of these crops risk, with the best sowing window being very short. Similar result was found for southern and central Brazil during La Niña years. On the contrary, cropping soybean and maize off-season in succession during El Niño years in center-south of and during La Niña years up north have higher chances of success.

Keywords: Crop simulation models, ENSO impacts, Food security, Multi-model approach

3.1. Introduction

Studies associating the climatic effect on agricultural economic outcomes are of great importance for assessing risks, since climate variability and anomalies are responsible for crop yield losses in all regions around the world (CARLETON; HSIANG, 2016; FAROOQ et al., 2009; LIANG et al., 2017). Historically, major crop failures resulted from anomalous low precipitation (KRISHNA KUMAR et al., 2004; WOLI et al., 2012). However, worldwide trends of temperature increase since 1981 have lowered maize and wheat yields by 3.8 and 5.5% (LOBELL; FIELD, 2007), causing annual losses of 40 megatons or US$ 5 billion in grain production (LOBELL; SCHLENKER; COSTA-ROBERTS, 2011). Similarly, such weather conditions also decreased crop yields in Africa and South America (TITO; VASCONCELOS; FEELEY, 2018; WHEELER; VON BRAUN, 2013). In Brazil, water deficit and extreme temperatures are the most important limitation factors for obtaining high yields in soybean (Battisti et al., 2018; Nóia Júnior and Sentelhas, 2019; Sentelhas et al., 2015) and maize (Bender, 2017; Andrea et al., 2018; Duarte, 2018; Nóia Júnior et al., 2018a).

In the recent decades, the Brazilian farmers have been able to increase grain production by cultivating a second crop, mainly maize off-season. The maize off-season is sown from January to April, after harvesting the summer crop, usually soybean. This double crop system is called as soybean–maize succession. Brazilian farmers, researchers and government have invested in the maize off-season expansion, and it has experienced continuous increase in both area and yield, surpassing the yield of maize cultivated as a summer crop (summer maize), and accounting for 70% of Brazilian maize production (CONAB, 2019). However, the maize off-season when cultivated lately has more restrictive climatic conditions during the reproductive phases of its cycle (Andrea et al., 2018; Soler et al., 2007).

To minimize the climate impacts on the maize off-season, Brazilian farmers are anticipating soybean sowing to September or early October and using short-cycle cultivars, allowing maize to be sowed in January when the climatic conditions and soil water availability are still favorable for crop establishment and growth (GARCIA et al., 2018). However, the accumulated rainfall in September in most of Brazilian producing regions is still low (ALVARES et al., 2013), increasing the risks of crop failure for early soybean sowings. Therefore, the anticipation of soybean-maize off-season sowings will favor maize but disfavor soybean, due to the greater risks of losses by water deficit (NÓIA JÚNIOR; SENTELHAS, 2019). On the other hand, the sowing delay will favor soybean and disfavor maize, due to the gradual reduction of solar radiation, photoperiod, temperature and soil water availability along the cycle. Considering that, the determination of the best soybean-maize off-season sowing date is one of the most important management aspects of this crop system in Brazil.

The complex interaction of rainfall, solar radiation, air temperature, and other meteorological parameters with plant and soil characteristics make challenging the determination of the best sowing date for soybean-maize succession in the different Brazilian producing regions, mainly when the effects of El Niño Southern Oscillation (ENSO), Pacific Decal Oscillation (PDO), and other phenomena are considered (BLAIN et al., 2009; DA ROCHA et al., 2014; ERASMI et al., 2014). The ENSO phenomenon alters the rainfall regime, causing serious problems for Brazilian agriculture depending on its phase (El Niño or La Niña), such as floods and droughts. During El Niño events there is a higher chance of abnormal floods in the states of southern Brazil and intense droughts in the states of North and Northeast regions of the country; on the other hand under La Niña conditions the opposite is observed, while the central part of the country is classified as a transitional regions (GRIMM, 2003; MOURA et al., 2019; NÓIA JÚNIOR et al., 2018b; PENALBA; RIVERA, 2016). For example, the strong El Niño of 2015/16 caused a general soybean and maize off-season yield reductions of 4% and 31%, respectively, mainly associated to the yield losses observed in the states of the Northeast region, like Bahia, Maranhão and Piauí (IBGE, 2019). Considering that ENSO is the main driver of climate variability in Brazil (GELCER et al., 2013; SOLER; SENTELHAS; HOOGENBOOM, 2009), our hypothesis is that the best sowing window for soybean-maize off-season succession may change as function of the phases of this phenomenon (El Niño, La Niña and Neutral), having varying results in the different Brazilian regions.

In order to test our hypothesis, three calibrated and validated soybean and maize crop simulation models were used to simulate soybean-maize succession yields in Brazil, aiming to determine the influence of ENSO phases on the spatial and temporal yield variability of soybean-maize succession and, therefore, to determine the best sowing window for soybean-maize off-season succession in different producing regions and for each phase of this phenomenon.

3.2. Material and methods

Study steps

Water-limited yield (Yw), which is defined by the interaction between the genotype, in a given plant population, with solar radiation, photoperiod, air temperature, atmospheric carbon dioxide concentration, and amount and distribution of rainfall during the growing season, was estimated for soybean and maize off-season crops, when cultivated in succession. Therefore, Yw is the yield obtained under rainfed conditions and considering optimum crop management. The study comprised different steps: to obtain and to consist weather and soil data; to simulate the Yw using a multi-model approach; to classify the years of simulation by its ENSO phase; to perform a descriptive analysis; and to determine the best sowing window for the soybean-maize off-season succession, based on specific criteria. All steps described above are presented in Figure 1.

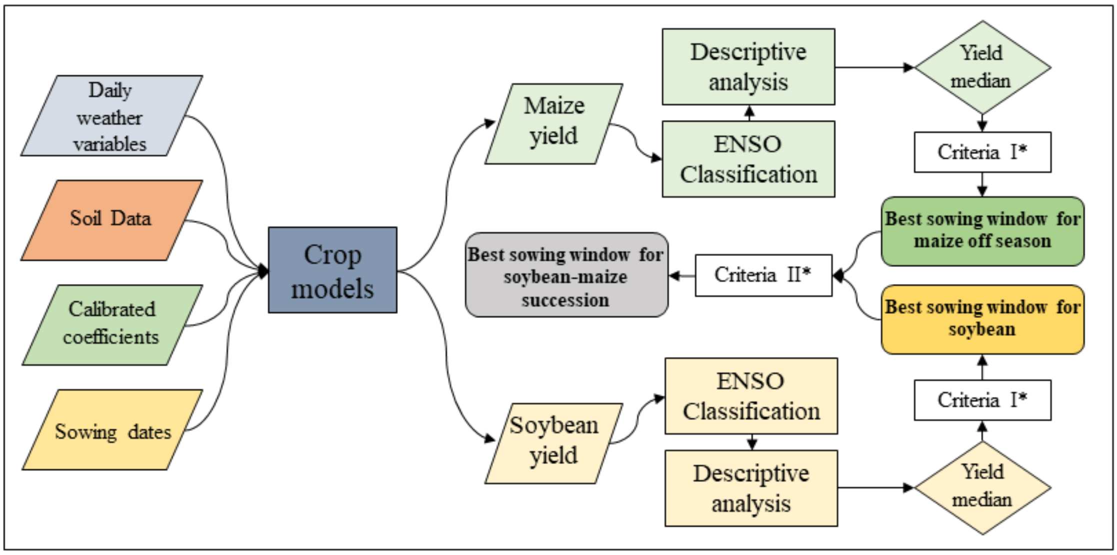

Figure 1. Flowchart of the procedures for estimating soybean and maize off-season yields and to define the best sowing window. *The criteria I and II used to determine the best sowing window are presented in the subsection 2.5 (Criteria to determine the optimal window sowing).

Sites, climate and soil data

According to IBGE (2019), Brazil has 1259 municipalities cropped with soybean-maize succession. They are distributed in 12 states: Paraná (PR), São Paulo (SP), Minas Gerais (MG), Mato Grosso do Sul (MS), Mato Grosso (MT), Goiás (GO), Rondônia (RO), Pará (PA), Tocantins (TO), Piauí (PI), Maranhão (MA) and Bahia (BA), being more than 90% of these areas concentrated in four different Köppen´s climatic zones (ALVARES et al., 2013): Tropical monsoon (Am), Tropical humid with dry winter (Aw), Subtropical Humid without dry season and hot summer (Cfa) and Subtropical Humid with dry winter and hot summer (Cwa). Based on that, 29 weather stations were selected to represent the soybean-maize succession growing areas in the 12 states and four climatic zones mentioned above (Figure 2). The soybean and maize Yw were estimated for all assessed locations, following the protocols previously described by Grassini et al. (2015) and van Bussel et al. (2015).

The predominant soil types of each site was selected using the soil map from IBGE (2014) (see Table S1 in the supplementary material). Information about sand, clay, and silt contents, pH, bulk density and organic carbon and nitrogen contents for each soil type (see Table S2 in the supplementary material), were taken from RADAMBRASIL (1974). The soil water holding capacity was then estimated using pedo-transfer functions developed by Reichert et al. (2009) for Brazilian soils.

Long-term (1980–2013) weather data were collected from the Brazilian Institute of Meteorology (INMET) and Integrated Agrometeorological Information Center of São Paulo (CIIAGRO). The missing weather data were filled out with data from Daily Gridded weather database (XAVIER; KING; SCANLON, 2015), which has presenting an excellent performance for replacing actual data when the purpose is to estimate water-limited yield, as reported by Battisti et al. (2018) for soybean, and by Duarte (2018) and Bender and Sentelhas (2018) for maize crop.

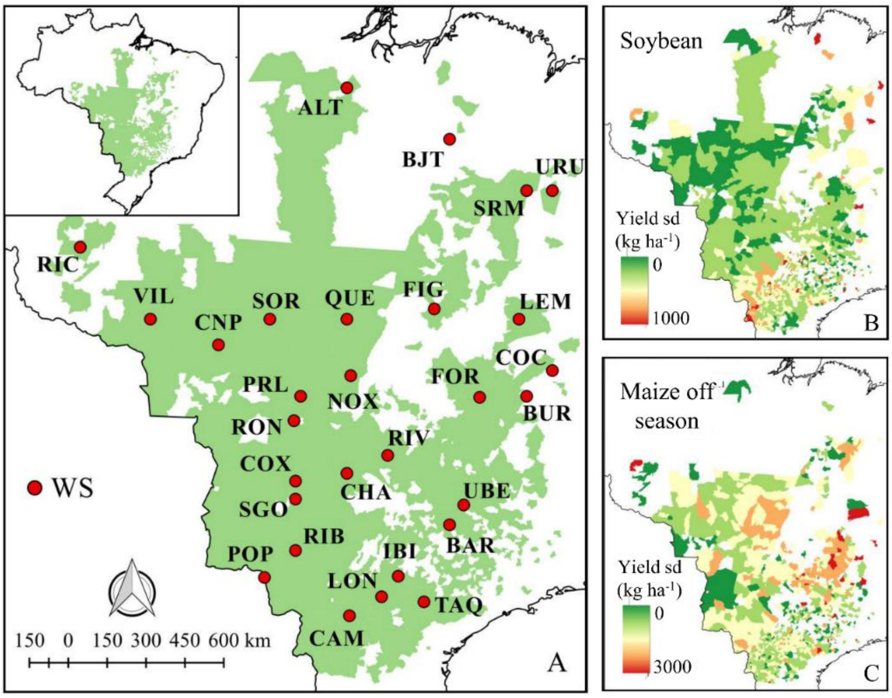

Figure 2. Weather stations (WS) assessed for estimating soybean-maize off-season yields, when cultivated in succession in Brazil. The areas in light green in A correspond to the regions where soybean-maize off-season in succession are produced. B and C represent, respectively, soybean and maize off-season yield standard deviations (sd, kg ha^{-1}), based on recent years (2006-2016) at the municipality level (IBGE, 2019), indicating the interannual variability of the studied crops in Brazil. Location codes for each weather station are presented in Table S1 in the supplementary material.

Crop simulation models

Recent studies have suggested the use of multi-models approach (ensemble) as a way to improve accuracy and reduce uncertainties in studies about the effect of climate on crop yield (Asseng et al., 2013; Martre et al., 2015; Battisti et al., 2017; Duarte, 2018). According to Battisti et al. (2017), the mean standard estimation errors of five soybean crop models in Brazil was around 550 kg ha^{-1}, which was reduced to 256 kg ha^{-1} when their ensemble was used. For maize, Duarte (2018) showed that the RMSE of the FAO, APSIM and DSSAT models for maize (in-season and off-season) can be reduced by about 60% when using their ensemble rather than the results of a single one. Considering that, this study simulated soybean and maize crop growth, development and yield with three models for each crop, as follows: FAO – Agroecological Zone model (FAO) (BATTISTI; SENTELHAS; BOOTE, 2017; KASSAM, 1977; RAO; SARMA; CHANDER, 1988); Agricultural Production Systems Simulator v. 7.7 (APSIM) (HOLZWORTH et al., 2014; KEATING et al., 2003); Crop System Model – CROPGRO – Soybean v.4.6.1 and Cropping System Model – CERES – Maize both presented in the software Decision Support System for Agrotechnology Transfer (DSSAT) (BOOTE et al., 2003; JONES et al., 2003). The multi-model ensemble was obtained from the arithmetic mean of the yields simulated for each crop with the three above-mentioned models. Further information about the performance of the individual models can be found in Nóia Júnior and Sentelhas (2019), Battisti et al. (2017), Duarte (2018) and Bender (2017).

Calibration and validation of these models for simulating water-limited (Yw) yields under Brazilian conditions were done by Battisti et al. (2017) for soybean and by Duarte (2018) and Bender (2017) for maize. Detailed descriptions of calibrated coefficients used by each model are presented in the supplementary material, Tables S3 and S4.

Cultivar and sowing dates

Yw were simulated for 11 sowing dates for soybean and maize off-season, in succession, starting with soybean sowing at September 21st and finishing at January 1st, with an interval of 10 days between two of them. Maize sowing was simulated immediately after the soybean harvest, as commonly practiced in the farms in Brazil. Harvesting was performed when the crops reached their optimum maturity point, simulated by each crop simulation model, mainly according the degree days approach modulated by photoperiod when required. During the simulations, soybean presented a mean cycle of 114 days, whereas maize off-season had mean cycle of 136 days. For running these models, the initial soil water content was simulated based on the water balance initiated six months before sowing, considering the prior crop as fallow.

The 29 locations used in the present study are in different latitudes, thus, in order to keep the soybean crop cycle around 115 days throughout Brazilian territory, three soybean maturity group (6.5, 7.5 and 8.5) were selected, based on recommendations of Battisti et al. (2017). More details about soybean maturity groups can be found in Figure S7 in the Supplementary material.

El Niño Southern Oscillation classification

To classify the crop seasons according to the ENSO phases, the system presented by National and Atmospheric administration (NOOA) was used (See Table S5 in the Supplementary Material). This system considers the Pacific Ocean sea surface temperature anomaly in relation to the normal (SSTA) at Niño 3.4 region. A given growing season, starting in July of year one and ending in June of year 2, is classified as La Niña when SSTA is equal or below to -0.5°C for 5 consecutive 3-month averages. Similar criterion is used to classify an event as El Niño, however, in this case the SSTA should be equal or above +0.5°C for 5 consecutive 3-month averages. A Neutral year occurs when SSTA remains between -0.5 and +0.5°C (NOOA, 2018).

Criteria to determine the best sowing window

According to MAPA (2018), the best sowing window for soybean and maize off-season in Brazil occurs when average of the ratio between actual and maximum crop evapotranspiration (ETa/ETc) during the flowering and grain filling crop phases are higher than 0.60 and 0.55, respectively, in at least 80% of the years.

As the soybean and maize off-season yields were simulated, they were used as criterion for defining the best sowing window, since yield encompasses the influence of all climatic factors on crop growth. The relationships between the ETa/ETc (average of the entire crop cycle) and soybean and maize yields (Figure S2 in the Supplementary Material) indicated ETa/ETc of 0.55 and 0.60, respectively, as those that corresponds to the median yields. Regarding the frequency of the years with ETa/ETc above the given limit to consider the sowing date as recommended, MAPA uses 80%; however, this criterion is based only on ETa/ETc and during the reproductive crop phase. As the final yields integrate the influence of all climatic variables on the crop growth, a frequency of 60% of growing seasons with yield above median, for each location, sowing date and ENSO phase, was considered for determining if a given sowing date is recommended or not. Based on that, the following criteria were established:

Criterion I: The best sowing window for soybean and maize off-season in Brazil occurred when the final yield (ensemble of three models, for each growing season, ENSO phase and location) is higher than the median yield (ensemble of three models, for each location and considering the 34 growing seasons), in at least 60% of the years;

Criterion II: The best sowing date for soybean-maize off-season succession occurred when criterion 1 was met for both crops (Figure 1).

Data analysis

ENSO effects on soybean and maize yields

Soybean and maize yields from the 29 locations, with their respective latitudes, and 34 growing seasons were grouped according to the ENSO classification (La Niña, Neutral and El Niño). For each ENSO phase, location and sowing date, the soybean and maize off-season average yields were subtracted from their respective general average (location and sowing date), resulting in the yield anomaly. Such anomaly allowed to identify the level of impact generated by ENSO phases on a given sowing date, latitude and crop. A positive anomaly corresponds to a yield increment under such ENSO phase, whereas a negative one corresponds to a yield decrement.

Principal Component Analysis – ENSO phases x climate variables x water limited yields

The statistical analyses were carried out using the software R (R CORE TEAM, 2017). To obtain an integrated assessment of the ENSO phases on climate variables and the soybean and maize off-season yields, the data were subject to a principal component analysis (PCA). The PCA was carried out by using the differences of the variables used in each ENSO phase, sowing date and location and the average of the variables for each sowing date and location. The PCA method reduces the dimensionality of data with a large number of measured variables by transforming these to a new, considerably smaller set of variables called Principal Components (PCs). Each crop (soybean and maize off-season) was submitted to a PCA. The data were standardized by dividing the difference between each data point and the arithmetic mean of the variable of interest by standard deviation of the variable, so that the results were not influenced by the magnitude of the variable units. The variables used in PCA analysis were: solar radiation (SR); air temperature (Ta); air relative humidity (RH); rainfall (Rain); ratio between actual and maximum crop evapotranspiration (ETa/ETc); and the simulated water-limited yield for maize and soybean crops. The weather data used in PCA analysis were collected from the Brazilian Institute of Meteorology (INMET) and Integrated Agrometeorological Information Center of São Paulo (CIIAGRO). These variables were averaged/summed by ENSO phases, crop, growing season for each sowing date and location. Two PCs were selected considering all variables, following the criterion indicated by Kaiser (1974), which is based on the presence of PCs with eigenvalues greater than 1 (Figure S8 in the supplementary material). Further information about principal component analysis can be found in Demšar et al. (2013) and Yeater et al. (2015).

3.3. Results

Soybean and maize off-season yields as affected by location, sowing date and ENSO phase

Soybean and maize off-season yields were greatly affected by sowing date and ENSO phases, which impacted them differently across the country (Figures 3, 4, and 5). For the south-central Brazil, the highest soybean yields were obtained when sowing occured from the end of October to the middle of November. When soybean sowing occurs at this time, there is also a minimization of the ENSO phenomenon effects on the average soybean yield, as presented in Figure 3. Nevertheless, the inter-annual variability of soybean yield (Figure 5) are reduced in El Niño years.

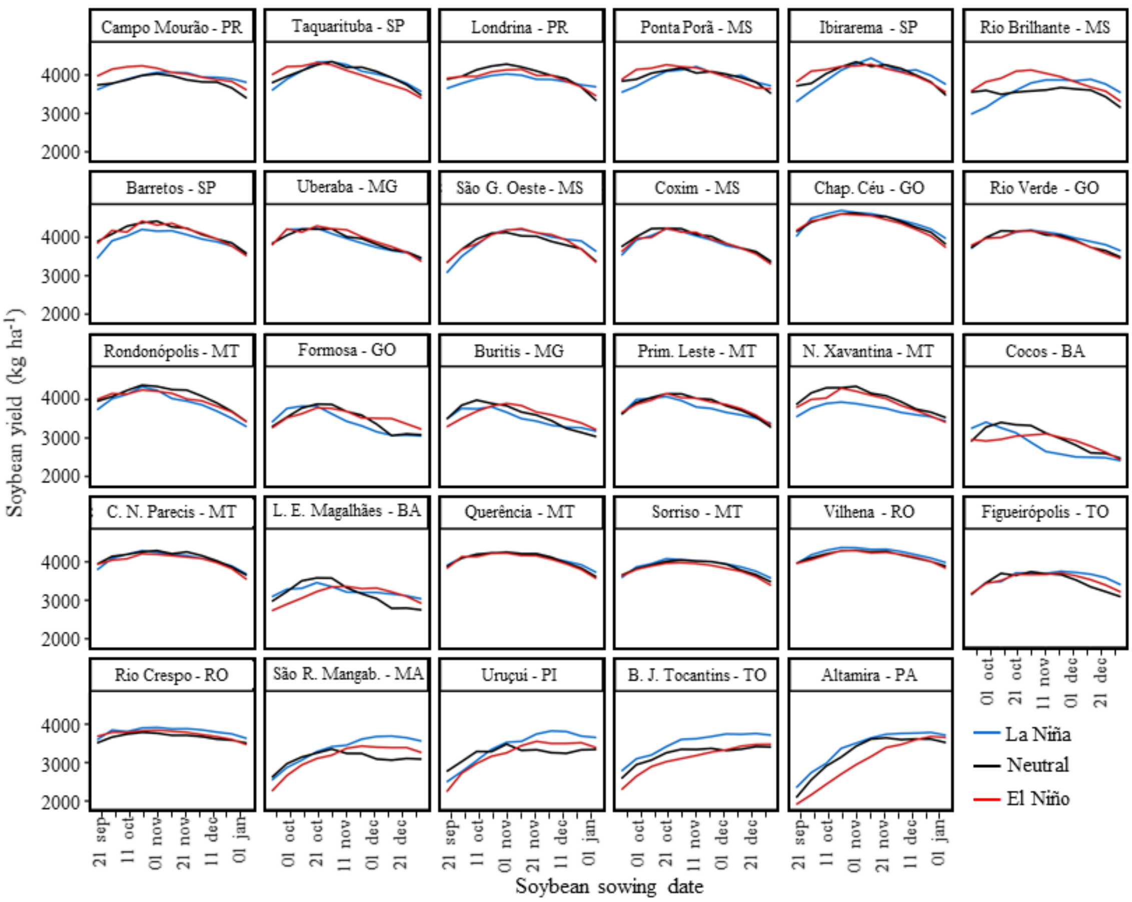

Figure 3. Average soybean grain yield for different sowing dates and locations in Brazil, considering the three phases of El Niño Southern Oscillation (ENSO): El Niño, Neutral and La Niña. The yield data presented are the ensemble of three crop simulation models.

The sowing anticipation to September and its delay to November and December caused soybean yield losses, which can exceed 500 kg ha^{-1}. In Southern Brazil (e.g. Campo Mourão and Taquarituba), La Niña years can further intensify the losses (Figure 3). On the other hand, in the El Niño years, the highest soybean yield was obtained when the sowing was done in early October, and yield losses caused by sowing anticipation were reduced.

For northern Brazil (e.g. Uruçuí and Altamira), the maximum soybean yields were obtained with the late sowings, from middle of November (Figure 3). For this region, the highest yield was obtained in La Niña years. In El Niño years, the yield losses caused by early sowing were intensified and the soybean yield was smaller.

In Brazil, the maximum maize off-season yield was obtained when sowing was carried out in early January (Figure 4). Therefore, the delay of soybean sowing resulted in higher maize yield losses. The maize yield was reduced linearly with the sowing delay, with a rate of decrease ranging between -9.10 kg ha^{-1} per day of delay in Altamira, PA, during La Ninã phase, and -11.89 kg ha^{-1} per day of delay in El Niño phase (See Table S6 in the Supplementary Material). In southern Brazil (e.g. Campo Mourão), the maize yield losses by the sowing delay was minimized during El Niño years and intensified in La Niña years. On other hand, in northern Brazil (e.g. Uruçui), the highest maize yield was obtained in La Niña years.

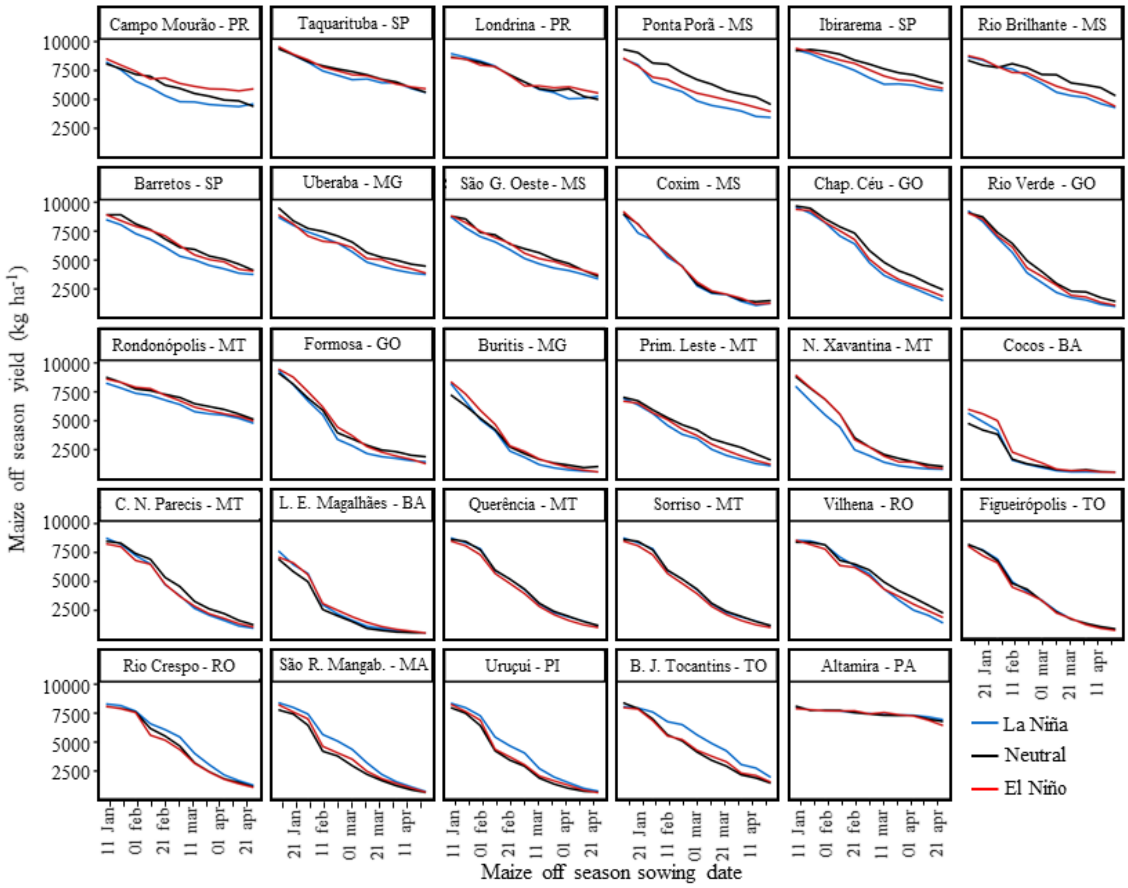

Figure 4. Average maize off-season grain yield for different sowing dates and locations in Brazil, considering the three phases of El Niño Southern Oscillation (ENSO): El Niño, Neutral and La Niña. The yield data presented are the ensemble of three crop simulation models.

In Bahia State (e.g. Cocos and Luis Eduardo Magalhães), the soybean yield, sowed until the middle of November, was favored by years of La Niña. From November to January, the highest soybean yield was obtained in El Niño years. In this region, the El Niño phenomenon, also provided higher average maize yields. It was also observed that in some locations of Mato Grosso state, such as Querência and Campo Novo Parecis, the impacts of ENSO phases are not clearly noticed for the assessed crops. The box plots showing the variability of soybean and maize off-season yields for the assessed locations are presented in Figure 5 and Figures S3 to S6 in the Supplementary Material.

Another way to show the influence of ENSO phases effects on soybean and maize off-season yields in Brazil is by their yield anomalies, which represent difference between the average yield of each sowing date and location for a given ENSO phase from the general average yield for the respective sowing date and location. The yield anomalies differed according to the region, mainly due to latitude effect, and sowing date (Figure 6). The La Niña phase was related to reduced soybean yields in high latitudes (≥ 18° S), especially when the soybean sowing occurred from late September to middle November. The earlier was soybean sowing, the greater were yield losses caused by La Niña (> 300 kg ha^{-1}). La Niña effects on soybean yield was minimized when the sowing was carried out from November to January. The maize off-season yield was also reduced during La Niña years in high latitudes. Losses caused by La Niña on maize yield at high latitudes were close to 1000 kg ha^{-1}, when the maize off-season sowing occurred from the end of February to the end of March.

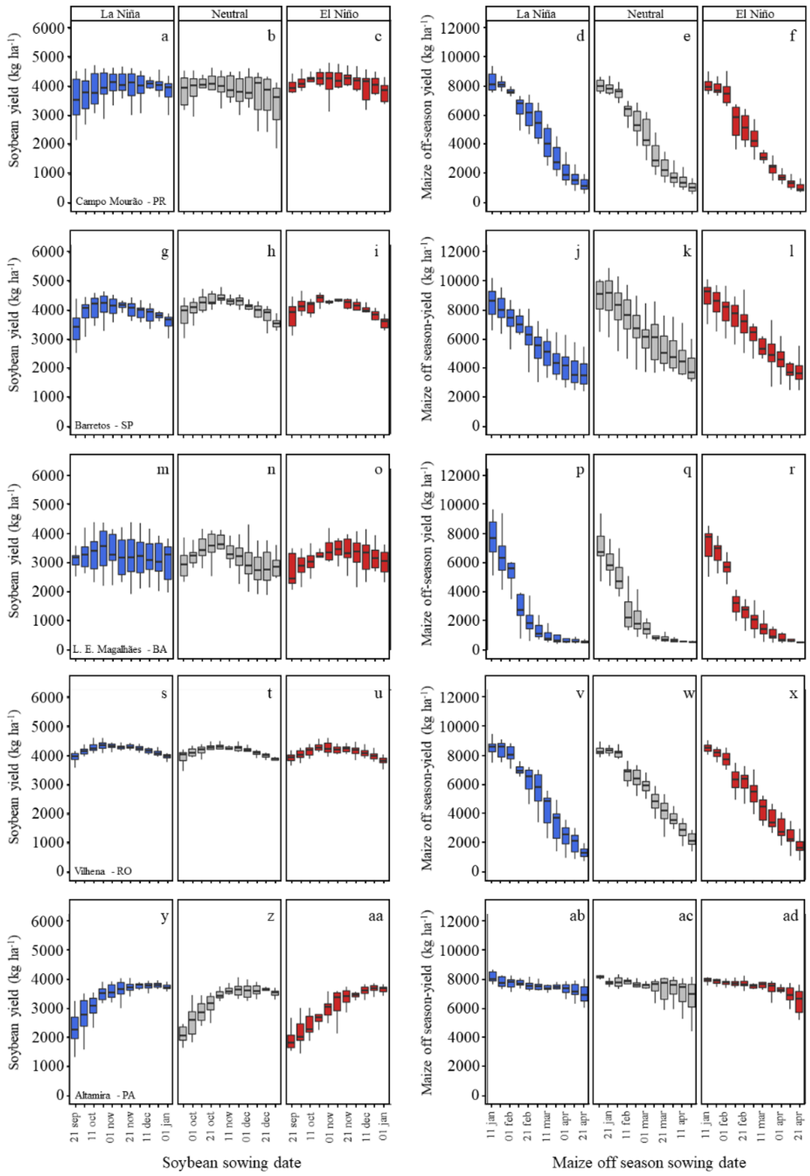

Figure 5. Box plots of soybean and maize off-season water-limited yields for different ENSO phases (1980-2013), sowing dates and locations in Brazil: Campo Mourão – PR (a, b, c, d, e and f), Barretos – SP (g, h, i, j, k and l), Luis Eduardo Magalhães - BA (m, n, o, p, q and r), Vilhena – RO (s, t, u, v, w and x) and Altamira – PA (y, z, aa, ab, ac and ad). The Yw data presented are the ensemble of three crop simulation models. The results for the other 24 locations are presented in the Supplementary material (Figures S3, S4. S5 and S6).

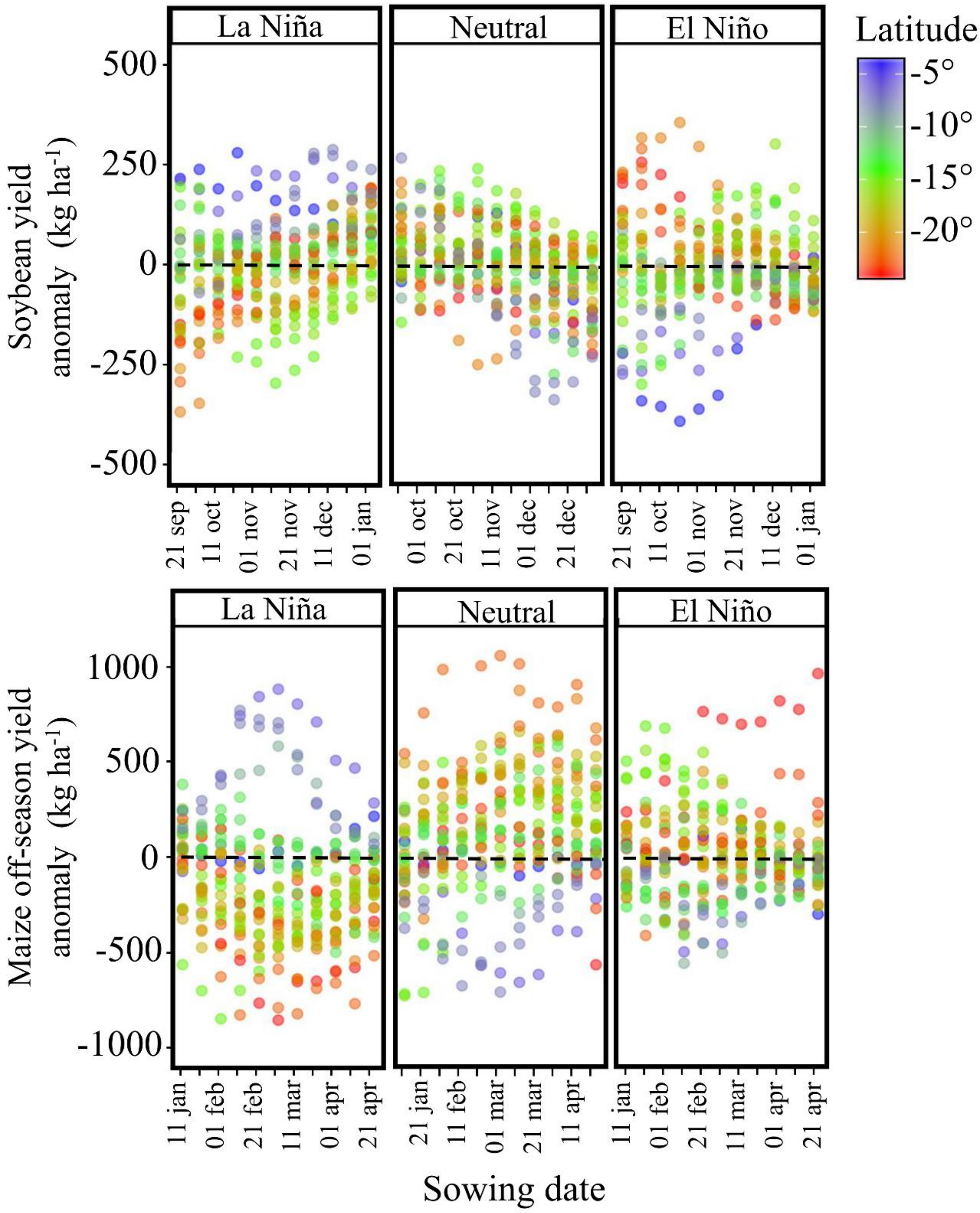

Figure 6. Soybean and maize off-season yield anomalies during La Niña, Neutral and El Níño years in relation to the general yield average for each sowing date and location, represented by its latitudes, in Brazil. The soybean and maize off-season yield anomalies were obtained by subtracting the average yield of each sowing date and location of a given ENSO phase from the general average yield for the respective sowing date and location.

In low latitudes (≤10° S), the highest soybean and maize yields were obtained in La Niña years (Figure 6). Yield gains exceeded 250 kg ha^{-1} for soybean and 500 kg ha^{-1} for maize. For soybean, the sowing date did not change the La Niña effect; however, for maize, yield gains were higher when this crop was sowed between February and end of March. The El Niño phenomenon in Brazil caused opposite effects to La Niña, favoring soybean and maize yield at high latitudes, and reducing it at low latitudes.

During Neutral years (Figure 6), the soybean yield was high in almost all latitudes when the crop was sowed till early November, and decreased when sowed from mid-November to January. For maize off-season, the Neutral years negatively affected the yields in low latitudes and favored it in high latitudes.

Relationship among ENSO phases and climate conditions, soybean and maize yields in different locations and sowing dates

The multivariate approach allowed an integrated assessment of the ENSO phases, in different sowing dates, on soybean and maize off-season yields in contrasting Brazilian regions. For that, solar radiation (SR), air temperature (Ta), relative air humidity (RH), rainfall (Rain) and the ratio between actual and maximum crop evapotranspiration (ETa/ETc), during the both crop cycles were assessed individually and in an integrated way (Figure 7).

In Campo Mourão, for example, the first principal component (PC1) is associated to the contrast between SR and weighted average Rain and ETa/ETc, whereas the PC2 includes the contrast between Ta and the weighted average of RH and Yw. Thus, from the analysis of PC1 it is clear that the sowing dates located in the first (top right) and second (bottom right) quadrants present the highest Rainfall and ETa/ETc and the lowest SR. On the other hand, by analyzing the PC2, the sowing dates presented in the first and fourth (top left) quadrants are those with the highest Ta and lowest Yw and RH. According to the principal component analysis, PC1 and PC2 explain, respectively, 45.79% and 28.19% of the data variance. By these results it is noticed that the greatest differences between the ENSO phases impacts on soybean, in Campo Mourão and in Barretos, occurred when this crop was sowed between late September and early October, since the points related to these sowing dates are more at the extremes of each quadrant (Figures 7A and 7C). For these sowing dates, the amount of rainfall was reduced in La Niña years (e.g. in Campo Mourão the points associated to the sowing dates are located in the fourth quadrant in the opposite direction of rainfall), which contributed to the reduction of ETa/ETc (which is highly positive correlated with Rainfall) and increase of SR (which has a high negative correlation with Rain and ETa/ETc), intensifying soybean yield losses by water deficit. During El Niño years, there was a higher amount of rainfall during the growing season, which resulted in higher RH, ETa/ETc and Yw. For Campo Mourão, the delay in the soybean sow reduced the differences between yield obtained in different ENSO phases. The ENSO effects on maize off-season was very similar to what was observed for soybean in Campo Mourão and Barretos (Figures 7B and 7D).

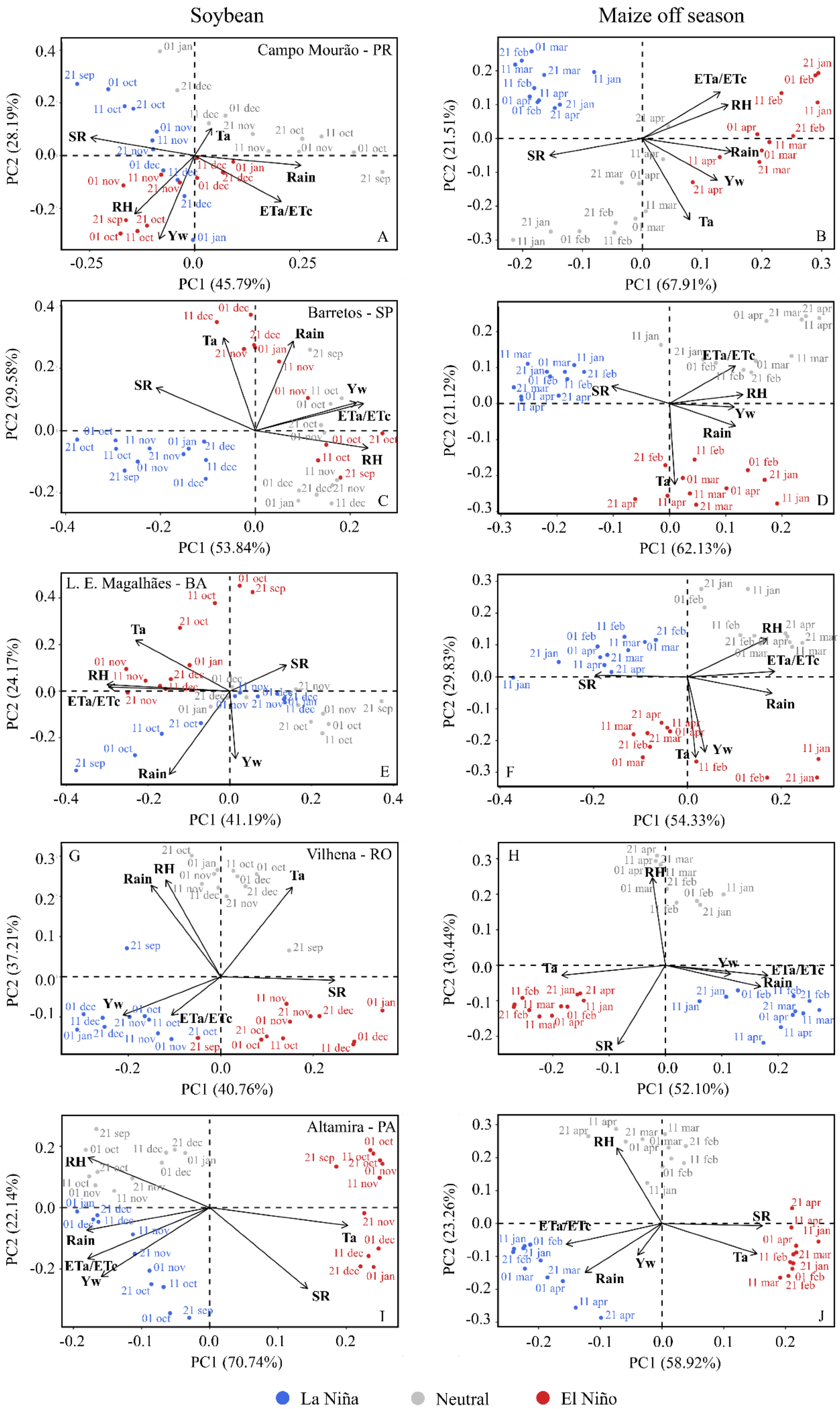

Figure 7. Biplot of the loadings of the original variables in the first two canonical variables for the ENSO effects on soybean (left) and maize off-season (right), in different locations in Brazil, when cultivated in succession in different sowing dates. The percentage of total variance explained by each canonical variable is indicated in parentheses. The first quadrant, in the upper left-hand corner, includes negative values of x and positive values of y. The fourth quadrant is the upper right-hand corner of the graph, the section where both x and y are positive. The second quadrant, in the lower right-hand and the third quadrant is the lower right-hand.

For soybean in Luis Eduardo Magalhães, the PC1 explained 41.19% of the data variance and is characterized by a contrast between SR and the weighted average ETa/ETc and RH, whereas the PC2 explained 24.17% of variance and is expressed by the contrast between the weighted average of Rainfall and Yw and Ta (Figure 7E). From this analysis, a high positive correlation between Yw and Rainfall was observed, indicating that ENSO phases affect rainfall in this location and, consequently, impacts the soybean yield. An anticipation of soybean sowing to late September or early October is favored during La Niña events, which is associated with more rainfall in the beginning of the wet season in this site. When the soybean was sowed in November or latter, the differences between the impacts caused by the distinct ENSO phases were reduced.

For maize off-season in Luis Eduardo Magalhães, the PC1 explained 54.33% of the data variance and expressed the contrast between weighted average Yw and Ta, whereas the PC2 explained 29.83% of variance and was characterized by the contrast between SR and weighted average ETa/ETc and Rain (Figure 7F). These results show that the maize yield was favored by El Niño years. Also, the PC analysis depicts that the highest amount of rainfall occurs from October to December during La Niña years, whereas it happens from January to April during El Niño years (Figure S1 in the Supplementary Material).

La Niña events also favored the soybean and maize off-season yields in Vilhena and Altamira (Figures 7G, 7H, 7I and 7J). PC1 and PC2 explained 77.97% and 92.88% of soybean data variance for Vilhena and Altamira, respectively. For Altamira, PC1 is the contrast between the weighted average of SR and Ta and the weighted average of Rain and ETa/ETc, and PC2 is the contrast between SR and the weighted average of RH and Yw. For maize off-season, 82.54% of data variance is explained by the PC1 and PC2 in Vilhena and 82.18% in Altamira. In Altamira, the PC1 is characterized by the contrast between ETa/ETc and the weighted average of SR and Ta, whereas the PC2 is the contrast between RH and the weighted average of Rain, Yw and Ta. The angles between the arrows give us an estimate of the correlation between the variables (i.e. if the angle between tow arrows is 90°, then the correlation is roughly equal cos 90° or zero. This is exact when $R^2 = 0$). From the correlation between the arrows and the characterization of PCs, it is noted that in both locations, the highest amounts of rainfall occurred during La Niña years, which contributed to increase ETa/ETc as well as Yw. On the other hand, during El Niño years Ta and SR increased as a result of less rainy days, which together resulted in reduction of soybean and maize yields.

ENSO effects on the best sowing window for soybean-maize succession

Considering the criteria presented in the subsection *Criteria to determine the best sowing window date*, the best sowing windows for soybean, maize off-season and soybean-maize off-season succession, varied according to ENSO phases and across Brazilian regions (Figure 8 and 9). For soybean, during La Niña years, it was noticed that there was an elongation of the best sowing window in the regions located in northern Brazil (e.g. Altamira), and a shortening of that in southern Brazil. On the other hand, during El Niño years, the elongation of the best sowing window occurred in southern Brazil, and the opposite occurred in the locations at the north (Figure 8).

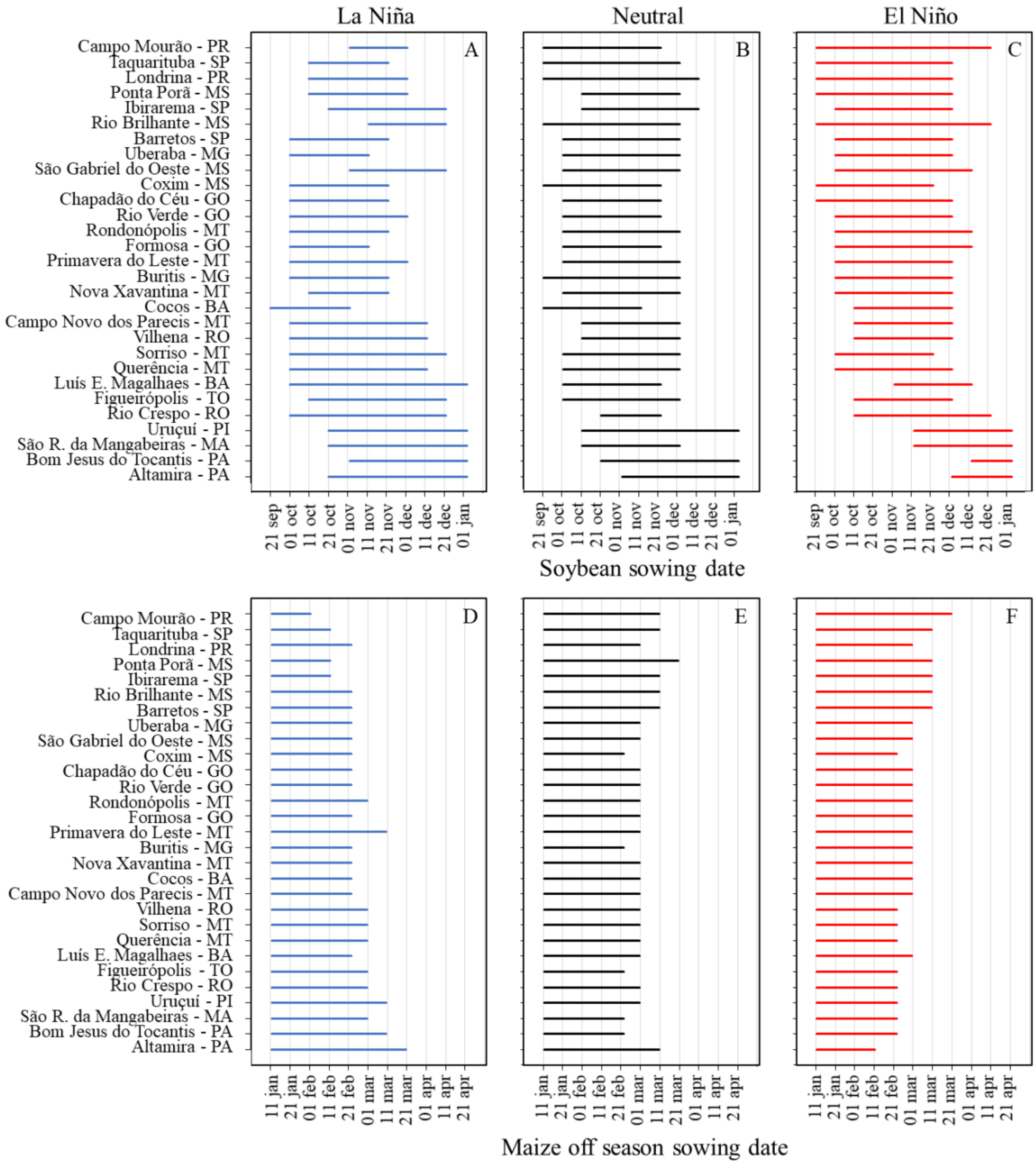

Figure 8. Best sowing windows for soybean during the La Niña (A), Neutral (B) and El Niño (C) years, and for maize off-season during the La Niña (D), Neutral (E) and El Niño (F) years, in different Brazilian locations. The criteria used to determine the best sowing dates are presented in Material and Methods (subsection 2.5).

In southern Brazil, the soybean sowing anticipation to late September or early October is not recommended during La Niña years, whereas during Neutral and El Niño years the sowing at this time was favored, mainly during El Niño events (Figure 8A, 8B and 8C). Compared to Neutral years, the shortening of the optimal sowing window, occurred in La Niña, reaching 30 days (Figure 8B). On the other hand, during El Niño years number of days favorable for sowing was increased by 30 days. In Northern Brazil, La Niña events favored the anticipation of the soybean sowing to late October, and compared to Neutral phase, the best sowing window increased by about 20 days, while in El Niño phase it was shortened by about 30 days (Figure 8A, 8B and 8C).

For maize off-season, sowing should be carried out until the end of February in almost all locations (Figure 8D, 8E and 8F). However, similar to the results found for soybean, during La Niña years there was a shortening of the best sowing window in about 30 days in the south of Brazil, and an elongation of about 20 days in the north, when compared to Neutral years. During El Niño years, the best sowing window was shorter in the north of Brazil, about 20 days, and longer in the south, about 20 days, in relation to the Neutral years.

The best sowing window for soybean-maize succession was also affected by ENSO phase and varied across Brazilian regions (Figure 9). In Neutral years (Figure 9B), the best sowing window for this crop system was longer in the south and shorter in the locations up north. The same results were observed for El Niño years (Figure 9C). However, during the years of La Niña (Figure 9A), the best sowing window was longer in the central part of the country and shorter in the extreme north and south (Figure 9A). The results presented in Figure 8 also show that in some locations of southern Brazil the cultivation of soybean-maize off-season succession is not recommended during La Niña events, like in São Gabriel do Oeste, Rio Brilhante, Ibirarema and Campo Mourão (Figure 9A). The same was observed for El Niño years in the northern Brazil, which include the locations of Uruçuí, São Raimundo das Mangabeiras, Bom Jesus do Tocantins and Altamira (Figure 9C).

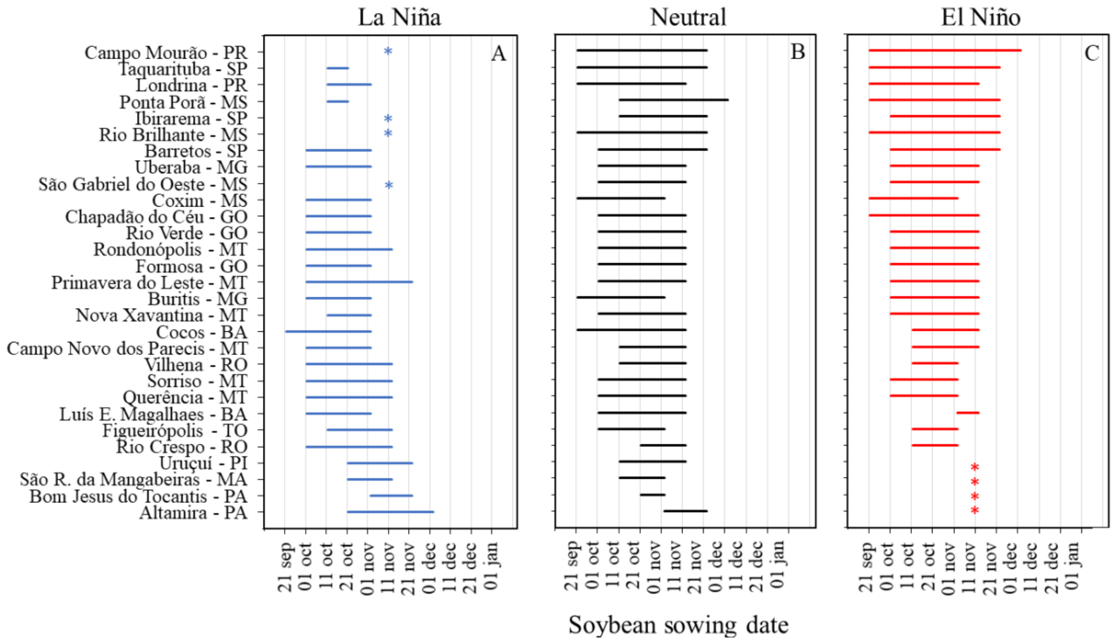

Figure 9. Best sowing windows for soybean-maize off-season succession during La Niña (A), Neutral (B) and El Niño (C) years, in different Brazilian locations. The criteria used to determine the best sowing date are presented in in Material and Methods (subsection 2.5). * indicates that no optimal sowing date was found for the soybean-maize off-season succession. The maize off-season sowing was simulated immediately after the soybean harvest, and thus, only the soybean sowing dates are presented in x-axis.

3.4. Discussion

The results obtained in this study showed that, in general, the highest soybean yields in Central-South Brazil are obtained when the sowing is done between the end of October and mid-November (Figures 3 and 5), corroborating with the results from Battisti et al. (2013). In the same region, the highest maize off-season yields were obtained when this crop was sowed from early January to February (Figures 4 and 5), which was also indicated by Soler et al. (2007). Thus, to obtain high soybean yields (sowing from end October to mid-November), the maize sowing should be delayed to mid-February, which would cause maize yield losses. On the other hand, to obtain high maize yield (sowing occurring in January), the soybean sowing must be anticipated to early September, causing soybean yield losses. Therefore, the decision about which soybean sowing date to consider is presently the biggest dilemma faced by the farmers every growing season. This problem becomes greater when soybean - maize off-season succession is considered and, also, when different ENOS events occur.

Aiming to improve the farmers knowledge about these aspects in different Brazilian regions, a multi-model approach for 29 locations spread in the different regions of the country and considering historical weather series of 34 years, were assessed.

Results from the present study revealed that ENSO impacts on the yields vary among locations, crop (maize and soybean), sowing dates and ENSO phases (Figures 3, 4, 5 and 6). In Southern Brazil, the yield losses caused by the anticipation of soybean sowing date to early September were higher during La Niña years. During El Niño events, these impacts were reversed, with some locations (e.g. Campo Mourão) showing the highest yields when soybean was sowed in early October.

The La Niña events contributed to the reduction of rainfall amount and increase of solar radiation in Southern Brazil (Figure 7), which is also confirmed by Anderson et al. (2018). High solar radiation availability generates an increase of the maximum crop evapotranspiration (ETc), while the reduction of rainfall affects the actual crop evapotranspiration (ETa), reducing the ETa/ETc ratio and, consequently, impairing crop yield. The effects of El Niño events were the opposite than those observed during La Niña events. The maximum rates of ETc in soybean occurred during its flowering and grain filling phases, and when the soybean sowing is anticipated to late September and early October, these phases occur during November and December, which are the months with the maximum precipitation anomalies caused by ENSO (ANDERSON et al., 2018), and consequently, the maximum differences of ENSO phases impacts on soybean yield occurred when soybean sowing is anticipated.

When the soybean sowing was carried out from mid-November to January, in Southern Brazil, the differences between the ENSO phases was minimized. However, at this time it is noticed that the soybean yield was reduced during El Niño years (Figure 7), even though with largest rainfall amounts. The lower soybean yield during El Niño years is correlated to an excess of rainfall, which reduced solar radiation availability, lowering potential yield, as also observed by Cunha et al. (2001). Many authors correlated high soybean yields in Southern Brazil with El Niño years (ALBERTO et al., 2006; BERLATO; FONTANA, 2001; IIZUMI et al., 2014), but they fixed the soybean sowing date. In the present study, several sowing dates were assessed and, therefore, it is the first attempt to show that the positive effect of El Niño on soybean yield in Southern Brazil depends on sowing date.

In Northern Brazil, in the states of Tocantins, Maranhão, Piauí and Pará, there is a gain in soybean and maize off-season yields during La Niña years. During El Niño events, there is a reduction of rainfall amounts and an increase of solar radiation availability and air temperature, which increase water deficits for soybean and maize crops, reducing their yields (Figure 7). According to Nóia Júnior et al. (2018a), the high temperatures reduces the photosynthesis of C3 (soybean) and C4 (maize) plants mainly due to stomatal closure and carboxylation rates reduction, and it is more intense when the plants are subjected to water deficit, as confirmed by Santos et al. (2018) during El Niño years in Northern Brazil.

The lowest soybean and maize yields in Brazil were obtained in the state of Bahia (i.e. Luis Eduardo Magalhães and Cocos), as shown in Figures 3 and 4. Droughts are not unusual in this region , where the probability of long periods of droughts is one year in nine, being most of them connected with the ENSO phenomenon (AWANGE; MPELASOKA; GONCALVES, 2016). Also, in this region, soybean yield is favored by La Niña events, when sowing occurred until November. When soybean sowing is performed lately, from November, the El Niño events favored both soybean and maize yields. However, maize yield decreases linearly with the sowing delay, and thus the possibility of anticipating the soybean sowing in La Niña years is positive since higher maize yields can be also obtained. Therefore, the best sowing date for soybean – maize off-season succession during La Niña years are those between late September and early October (Figure 9).

The best sowing window for soybean – maize off-season succession varied according to locations and ENSO phases (Figure 9). The best sowing window was prolonged during El Niño phase in Central-South and shortened in the Northern Brazil. The opposite occurred in during La Niña years.

From the best of our knowledge, these results are the first to determine the ENSO impacts on soybean and maize off-season yields when cultivated in succession and on the best sowing window for this crop system in several Brazilian locations. Understanding the contrasting effects of ENSO on the two main grain crops in Brazil is very useful to reduce the possible impacts on yields, total food production and investments. Furthermore, these results provide information that strengthens decision making of farmers, government, insurance companies, input industry and all sectors involved in the soybean – maize off-season succession production. Even considering that this study presents relevance and innovative results, other researches should consider the use of crop management strategies to minimize the negative impacts of ENSO events, such as deep soil preparation (BATTISTI; SENTELHAS, 2017), use of drought tolerant cultivars (BATTISTI et al., 2017), biostimulators (ARNAO; HERNÁNDEZ-RUIZ, 2014), among others, as well as to reinforce the positive impacts by adopting crop strategies that improve yields when weather conditions, mainly rainfall, are favorable, such as choosing high-performance cultivars, intensify soil fertilization and pests/diseases control (DENG et al., 2006; KOESTER et al., 2016). These strategies can assure in a short-term higher food availability, contributing for the food security in the country.

Many Brazilian farmers sow soybean from the middle of October, to minimize the effects of climate variability on the crop (CRUZ; FILHO; FILHO, 2018). However, our results show that, in some locations, and depending on the ENSO phase, sowing date could be anticipated to the end of September which would allow obtaining higher maize off-season yields (NÓIA JÚNIOR; SENTELHAS, 2019). Thus, we consider that the results presented by the present study could be more easily applied to the reality of the Brazilian farmers, if the uncertainties regarding the prediction of the ENSO phase were reduced. Although the ability to predict ENSO has improved significantly in the past three decades (CHEN; CANE, 2008; XUE et al., 2013; ZHU et al., 2015), the model errors are still a challenge (ZHENG; HU; L'HEUREUX, 2016; ZHU et al., 2016). Also, research that aim at reducing these uncertainties should be encouraged, so that farmers could benefit from the access to this information in advance, carrying out better agricultural planning and decision making.

3.5. Conclusions

The impacts of ENSO phases can be minimized by choosing the best sowing window for soybean and maize off-season as single crops or as crops in succession. The ENSO impacts varied according to the crop (soybean and maize), sowing date, location and ENSO phases (El Niño, Neutral and La Niña). In northern Brazil, El Niño events negatively impact soybean and maize off-season yields, reducing the period of the best sowing window of both crops and also for their cultivation in succession. Similar results were found for central south Brazil during La Niña years. The soybean and maize off-season yield are favored during El Niño years in Central-South Brazil, and during La Niña years in Northern Brazil.

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Supplementary material

Table 1. Weather stations (WS), their locations, associated codes, geographical coordinates, Koppen's climate classification (ALVARES et al., 2013) and soil type.

State	Location	Latitude (degrees)	Longitude (degrees)	Elevation (meters)	köppen's climatic	Soil classification
BA	Cocos (COC)	-14.10	-44.50	500	Aw	Oxisol
BA	Luís Eduardo Magalhães (LEM)	-12.40	-46.41	603	Aw	Oxisol
GO	Chapadão do Céu (CHA)	-18.50	-52.50	840	Am	Ultisol
GO	Rio Verde (RIV)	-17.80	-50.91	774	Aw	Oxisol
GO	Formosa (FOR)	-15.54	-47.33	935	Aw	Oxisol
MA	São Raim. das Mangabeiras (SRM)	-7.53	-46.03	259	Aw	Oxisol
MG	Uberaba (UBE)	-19.73	-47.95	737	Cwa	Oxisol
MG	Buritis (BUR)	-15.52	-46.40	894	Aw	Oxisol
MS	Ponta Porã (POP)	-22.55	-55.71	650	Cfa	Oxisol
MS	Rio Brilhante (RIB)	-21.77	-54.52	324	Am	Oxisol
MS	S. Gabriel do Oeste (SGO)	-19.42	-54.55	646	Am	Oxisol
MS	Coxim (COX)	-18.51	-54.73	251	Aw	Oxisol
MT	Rondonópolis (RON)	-16.45	-54.56	284	Aw	Ultisol
MT	Primavera do Leste (PRL)	-15.83	-54.38	450	Aw	Oxisol
MT	Nova Xavantina (NOX)	-14.70	-52.35	316	Aw	Oxisol
MT	Campo Novo do Parecis (CNP)	-13.78	-57.83	525	Aw	Oxisol
MT	Sorriso (SOR)	-12.55	-55.72	379	Aw	Oxisol
MT	Querência (QUE)	-12.62	-52.22	361	Aw	Oxisol
PA	Altamira (ALT)	-3.21	-52.21	74	Am	Oxisol
PA	Bom Jesus do Tocantins (BJT)	-5.36	-49.13	95	Aw	Oxisol
PI	Uruçuí (URU)	-7.44	-44.34	399	Aw	Oxisol
PR	Campo Mourão (CAM)	-24.04	-52.40	616	Cfa	Oxisol
PR	Londrina (LON)	-23.30	-51.15	610	Cfa	Ultisol
RO	Vilhena (VIL)	-12.73	-60.15	615	Am	Oxisol
RO	Rio Crespo (RIC)	-9.75	-62.75	157	Am	Oxisol
SP	Taquarituba (TAQ)	-23.19	-49.38	561	Cfa	Oxisol
SP	Ibirarema (IBI)	-22.74	-50.38	484	Cfa	Ultisol
SP	Barretos (BAR)	-20.55	-48.54	534	Aw	Oxisol
TO	Figueirópolis (FIG)	-12.10	-49.10	291	Aw	Ultisol

Table 2. Silt, sand, clay, carbon, and nitrogen contents (%), and pH of soils in the 29 Brazilian locations where soybean and maize off season yields were simulated.

State	Location	Silt (%)	Clay (%)	Sand (%)	pH	Carbon (%)	Nitrogen (%)
BA	Cocos (COC)	10	41	49	5.9	0.20	0.02
BA	Luís E. Magalhães (LEM)	9	22	69	5.7	0.27	0.01
GO	Chapadão do Céu (CHA)	9	37	54	5.4	0.70	0.08
GO	Rio Verde (RIV)	17	26	57	5.3	4.80	0.44
GO	Formosa (FOR)	24	45	31	5.3	1.21	0.12
MA	São R. das Mangabeiras (SRM)	13	32	55	5.5	0.43	0.06
MG	Uberaba (UBE)	5	27	68	5.5	0.35	0.03
MG	Buritis (BUR)	5	22	73	5.7	0.26	0.02
MS	Ponta Porã (POP)	15	59	26	5.0	1.47	0.11
MS	Rio Brilhante (RIB)	8	52	40	5.0	1.97	0.14
MS	S. Gabriel do Oeste (SGO)	37	24	39	5.2	1.60	0.09
MS	Coxim (COX)	7	27	66	5.2	1.18	0.11
MT	Rondonópolis (RON)	46	27	27	5.30	0.59	0.06
MT	Primavera do Leste (PRL)	12	32	56	5.6	1.50	0.09
MT	Nova Xavantina (NOX)	18	32	50	6.4	0.19	0.03
MT	Campo N. do Parecis (CNP)	7	30	63	5.6	0.80	0.06
MT	Sorriso (SOR)	10	56	34	5.2	3.20	0.30
MT	Querência (QUE)	8	49	43	5.5	2.10	0.20
PA	Altamira (ALT)	12	27	61	5.3	1.55	0.13
PI	Uruçuí (URU)	26	24	50	5.1	0.99	0.08
PR	Campo Mourão (CAM)	17	76	7	5.4	2.83	0.25
PR	Londrina (LON)	9	49	42	5.32	0.50	0.05
RO	Vilhena (VIL)	8	39	53	5.6	2.90	0.10
RO	Rio Crespo (RIC)	34	37	29	6.2	1.40	0.10
SP	Taquarituba (TAQ)	10	55	35	4.9	0.66	0.06
SP	Ibirarema (IBI)	17	64	19	6.0	2.74	0.27
SP	Barretos (BAR)	18	61	21	5.5	2.39	0.16
TO	Figueirópolis (FIG)	18	49	33	5.3	0.75	0.04
TO	Bom J. do Tocantins (BJT)	15	39	46	5.3	0.26	0.02

Table 3. Crop models´ performance for simulating soybean yield at the calibration and validation phases. Adapted from Battisti et al. (2017).

Models	RMSE (kg ha^{-1})	d	R^2
		Calibration	
FAO	650	0.91	0.79
DSSAT	548	0.93	0.79
APSIM	550	0.90	0.69
		Validation	
FAO	752	0.77	0.21
DSSAT	511	0.89	0.54
APSIM	732	0.79	0.43

RMSE = Root mean error square; d = Wilmott agreement index; R^2 = coefficient of determination.

Table 4. Crop models´ performance for simulating maize off season yield at the calibration and validation phases. Adapted from Duarte (2018) (*) and Bender (2017) (**).

Models	RMSE (kg ha^{-1})	d	R^2
		Calibration	
FAO*	1459	0.72	0.28
DSSAT**	576	0.86	0.69
APSIM**	1205	0.76	0.31
		Validation	
FAO*	2008	0.71	0.28
DSSAT**	337	0.93	0.77
APSIM**	1554	0.81	0.49

RMSE = Root mean error square; d = Wilmott agreement index; R^2 = coefficient of determination.

Table 5. Three-month ENSO classification according to the Oceanic Niño Index (INO) and the classification of the growing season according to the NOAA (2018) criteria. A given growing season, starting in July of year one and ending in June of year 2, is classified as La Niña when SSTA is equal or below to -0.5°C for 5 consecutive 3-month averages. The same criteria is used to classify an event as El Niño, however, in this case the SSTA should be equal or above +0.5°C for 5 consecutive 3-month averages. A Neutral year occurs when SSTA remains between -0.5 and +0.5°C.

Growing season	JJA	JAS	ASO	SON	OND	NDJ	DJF	JFM	FMA	MAM	AMJ	MJJ	Classification
1980/81	0.3	0.0	-0.1	0.0	0.1	0.0	-0.3	-0.5	-0.5	-0.4	-0.3	-0.3	Neutral
1981/82	-0.3	-0.2	-0.2	-0.1	-0.2	-0.1	0.0	0.1	0.2	0.5	0.7	0.7	Neutral
1982/83	0.8	1.1	1.6	2.0	2.2	2.2	2.2	1.9	1.5	1.3	1.1	0.7	El Niño
1983/84	0.3	-0.1	-0.5	-0.8	-1.0	-0.9	-0.6	-0.4	-0.3	-0.4	-0.5	-0.4	La Niña
1984/85	-0.3	-0.2	-0.2	-0.6	-0.9	-1.1	-1.0	-0.8	-0.8	-0.8	-0.8	-0.6	La Niña
1985/86	-0.5	-0.5	-0.4	-0.3	-0.3	-0.4	-0.5	-0.5	-0.3	-0.2	-0.1	0.0	Neutral
1986/87	0.2	0.4	0.7	0.9	1.1	1.2	1.2	1.2	1.1	0.9	1.0	1.2	El Niño
1987/88	1.5	1.7	1.6	1.5	1.3	1.1	0.8	0.5	0.1	-0.3	-0.9	-1.3	El Niño
1988/89	-1.3	-1.1	-1.2	-1.5	-1.8	-1.8	-1.7	-1.4	-1.1	-0.8	-0.6	-0.4	La Niña
1989/90	-0.3	-0.3	-0.2	-0.2	-0.2	-0.1	0.1	0.2	0.3	0.3	0.3	0.3	Neutral
1990/91	0.3	0.4	0.4	0.3	0.4	0.4	0.4	0.3	0.2	0.3	0.5	0.6	Neutral
1991/92	0.7	0.6	0.6	0.8	1.2	1.5	1.7	1.6	1.5	1.3	1.1	0.7	El Niño
1992/93	0.4	0.1	-0.1	-0.2	-0.3	-0.1	0.1	0.3	0.5	0.7	0.7	0.6	Neutral
1993/94	0.3	0.3	0.2	0.1	0.0	0.1	0.1	0.1	0.2	0.3	0.4	0.4	Neutral
1994/95	0.4	0.4	0.6	0.7	1.0	1.1	1.0	0.7	0.5	0.3	0.1	0.0	El Niño
1995/96	-0.2	-0.5	-0.8	-1.0	-1.0	-1.0	-0.9	-0.8	-0.6	-0.4	-0.3	-0.3	La Niña
1996/97	-0.3	-0.3	-0.4	-0.4	-0.4	-0.5	-0.5	-0.4	-0.1	0.3	0.8	1.2	Neutral
1997/98	1.6	1.9	2.1	2.3	2.4	2.4	2.2	1.9	1.4	1.0	0.5	-0.1	El Niño
1998/99	-0.8	-1.1	-1.3	-1.4	-1.5	-1.6	-1.5	-1.3	-1.1	-1.0	-1.0	-1.0	La Niña
1999/00	-1.1	-1.1	-1.2	-1.3	-1.5	-1.7	-1.7	-1.4	-1.1	-0.8	-0.7	-0.6	La Niña
2000/01	-0.6	-0.5	-0.5	-0.6	-0.7	-0.7	-0.7	-0.5	-0.4	-0.3	-0.3	-0.1	La Niña
2001/02	-0.1	-0.1	-0.2	-0.3	-0.3	-0.3	-0.1	0.0	0.1	0.2	0.4	0.7	Neutral
2002/03	0.8	0.9	1.0	1.2	1.3	1.1	0.9	0.6	0.4	0.0	-0.3	-0.2	El Niño
2003/04	0.1	0.2	0.3	0.3	0.4	0.4	0.4	0.3	0.2	0.2	0.2	0.3	Neutral
2004/05	0.5	0.6	0.7	0.7	0.7	0.7	0.6	0.6	0.4	0.4	0.3	0.1	El Niño
2005/06	-0.1	-0.1	-0.1	-0.3	-0.6	-0.8	-0.8	-0.7	-0.5	-0.3	0.0	0.0	La Niña
2006/07	0.1	0.3	0.5	0.7	0.9	0.9	0.7	0.3	0.0	-0.2	-0.3	-0.4	El Niño
2007/08	-0.5	-0.8	-1.1	-1.4	-1.5	-1.6	-1.6	-1.4	-1.2	-0.9	-0.8	-0.5	La Niña
2008/09	-0.4	-0.3	-0.3	-0.4	-0.6	-0.7	-0.8	-0.7	-0.5	-0.2	0.1	0.4	La Niña
2009/10	0.5	0.5	0.7	1.0	1.3	1.6	1.5	1.3	0.9	0.4	-0.1	-0.6	El Niño
2010/11	-1.0	-1.4	-1.6	-1.7	-1.7	-1.6	-1.4	-1.1	-0.8	-0.6	-0.5	-0.4	La Niña
2011/12	-0.5	-0.7	-0.9	-1.1	-1.1	-1.0	-0.8	-0.6	-0.5	-0.4	-0.2	0.1	La Niña
2012/13	0.3	0.3	0.3	0.2	0.0	-0.2	-0.4	-0.3	-0.2	-0.2	-0.3	-0.3	Neutral

Table 6. Yield rate of decrease for maize off-season (kg ha^{-1} day^{-1}) in the different locations and ENSO phases. The yield rate presented are the b value of a linear regression (y = a + bx); where y is the yield (kg ha^{-1}) and x are different sowing dates.

State	Location	Rate of yield decrease (kg ha^{-1} day^{-1})		
		El Niño	Neutral	La Niña
BA	Cocos (COC)	-58.57	-42.84	-51.34
BA	Luís Eduardo Magalhães (LEM)	-68.78	-64.36	-71.61
GO	Chapadão do Céu (CHA)	-84.41	-79.36	-87.45
GO	Rio Verde (RIV)	-85.72	-83.57	-87.01
GO	Formosa (FOR)	-86.88	-75.12	-81.04
MA	São Raim. das Mangabeiras (SRM)	-80.02	-76.66	-83.86
MG	Uberaba (UBE)	-48.14	-49.44	-52.55
MG	Buritis (BUR)	-80.12	-64.91	-75.29
MS	Ponta Porã (POP)	-44.09	-48.04	-50.56
MS	Rio Brilhante (RIB)	-42.85	-28.65	-46.35
MS	S. Gabriel do Oeste (SGO)	-51.48	-51.79	-52.25
MS	Coxim (COX)	-82.87	-80.79	-80.43
MT	Rondonópolis (RON)	-37.85	-34.57	-34.27
MT	Primavera do Leste (PRL)	-59.12	-55.42	-61.77
MT	Nova Xavantina (NOX)	-85.49	-82.30	-73.52
MT	Campo Novo do Parecis (CNP)	-80.10	-81.00	-86.39
MT	Sorriso (SOR)	-82.62	-83.14	-83.87
MT	Querência (QUE)	-82.62	-83.14	-83.87
PA	Altamira (ALT)	-11.89	-11.12	-9.10
PA	Bom Jesus do Tocantins (BJT)	-67.93	-73.03	-65.17
PI	Uruçuí (URU)	-81.25	-79.23	-83.78
PR	Campo Mourão (CAM)	-26.33	-36.71	-36.90
PR	Londrina (LON)	-32.89	-39.39	-43.81
RO	Vilhena (VIL)	-70.86	-66.29	-79.89
RO	Rio Crespo (RIC)	-78.84	-79.59	-78.92
SP	Taquarituba (TAQ)	-34.96	-34.81	-35.50
SP	Ibirarema (IBI)	-36.53	-31.38	-37.25
SP	Barretos (BAR)	-51.96	-50.68	-50.11
TO	Figueirópolis (FIG)	-77.11	-79.39	-80.47

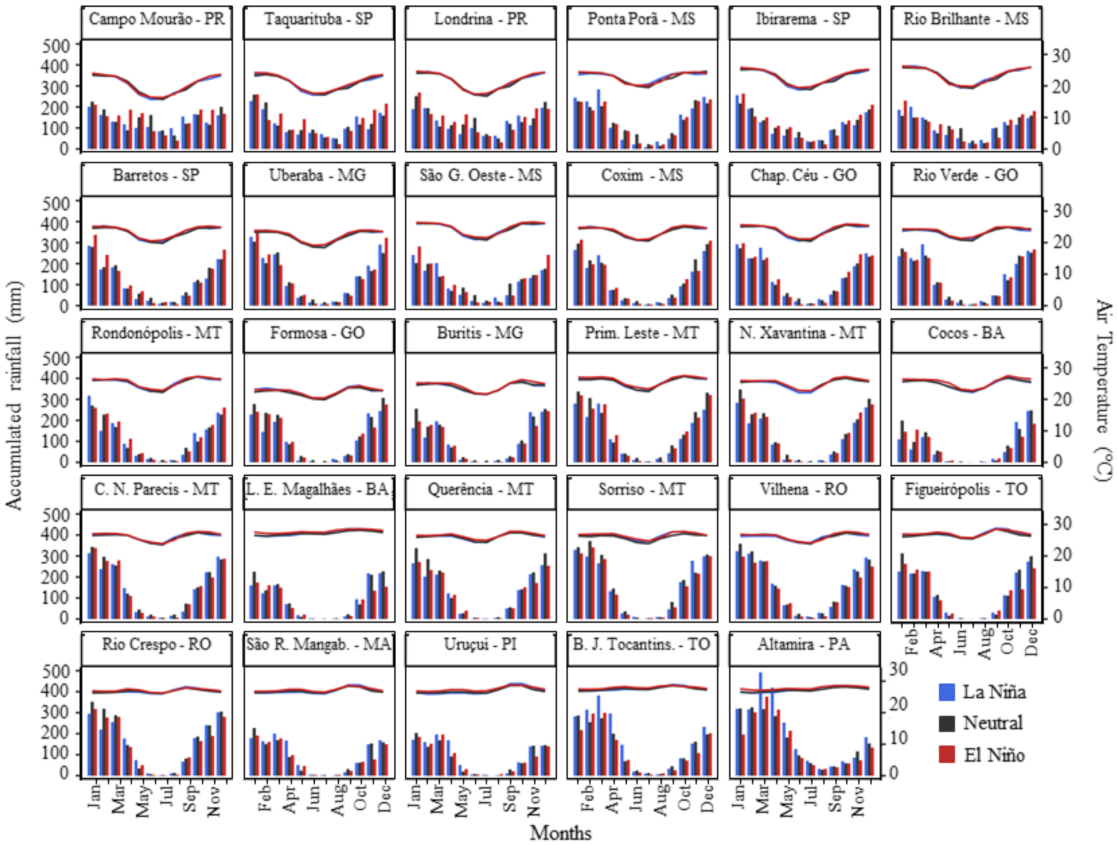

Figure 1. Average monthly rainfall and air temperature for the 29 locations used for the soybean and maize yield simulations, according to El Niño Southern Oscillation phases.

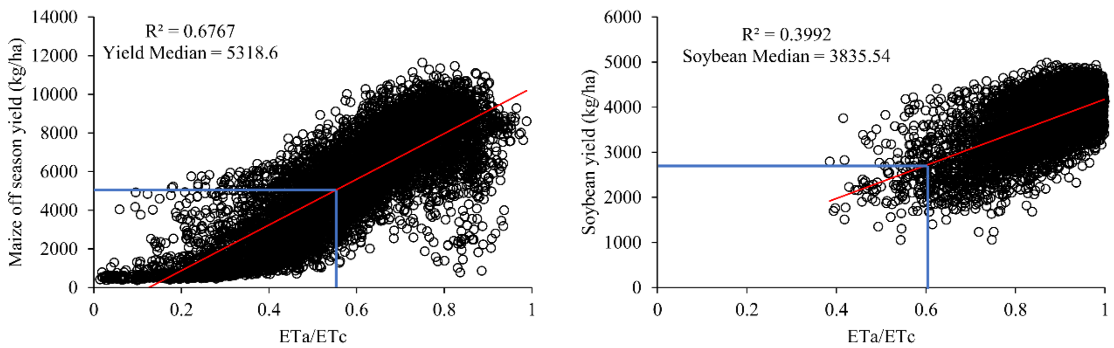

Figure 2. Relationship between ETa/ETc and maize off-season and soybean yields for 29 locations in Brazil for 34 growing seasons for each crop. Blue line indicates the ETa/ETc recommended by MAPA (2018) for determination of to the best sowing window to soybean and maize off-season in Brazil.

*Note: In the relationship between ETa/ETc and Maize yield, its noticed that the ETa/ETc ratio recommended by MAPA (2018) corresponds to a yield value close to the Yield Median. However, for soybean crop, the recommended ETa/ETc ration does not represent Yield Median. This happened because the soybean sowing dates used in the present study coincided with the rainy season in Brazil, when ETa/ETc is predominantly higher than 0.6. Therefore, we preferred to use the same criterion adopted for maize (Yield Median), since this guarantee for the users of our data higher soybean yields.

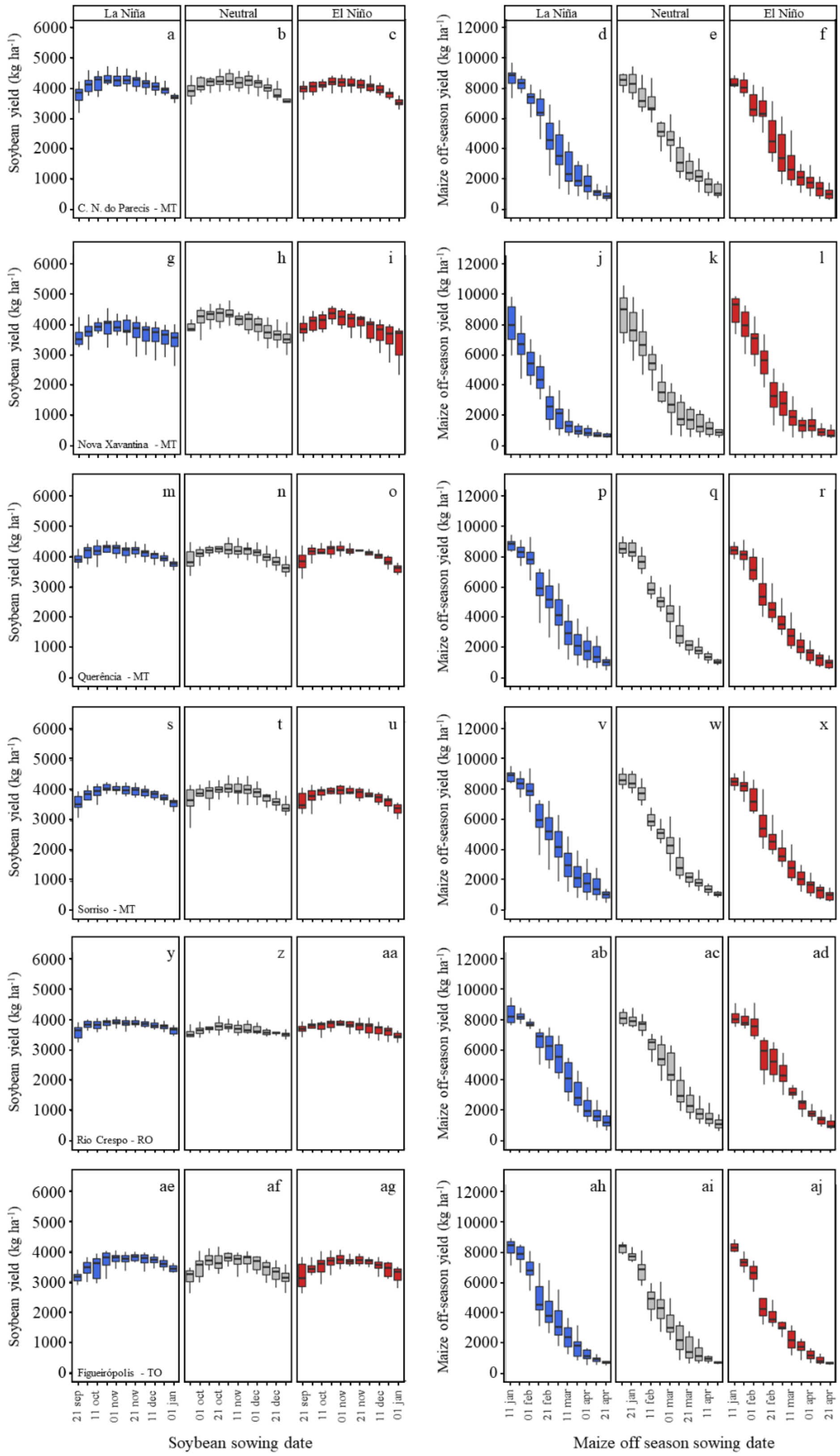

Figure 3. Box plots of soybean (left) and maize off-season (right) water-limited yields for different ENSO phases (1980-2013), sowing dates and locations in Brazil. The Yw data presented are the ensemble of three crop simulation models.

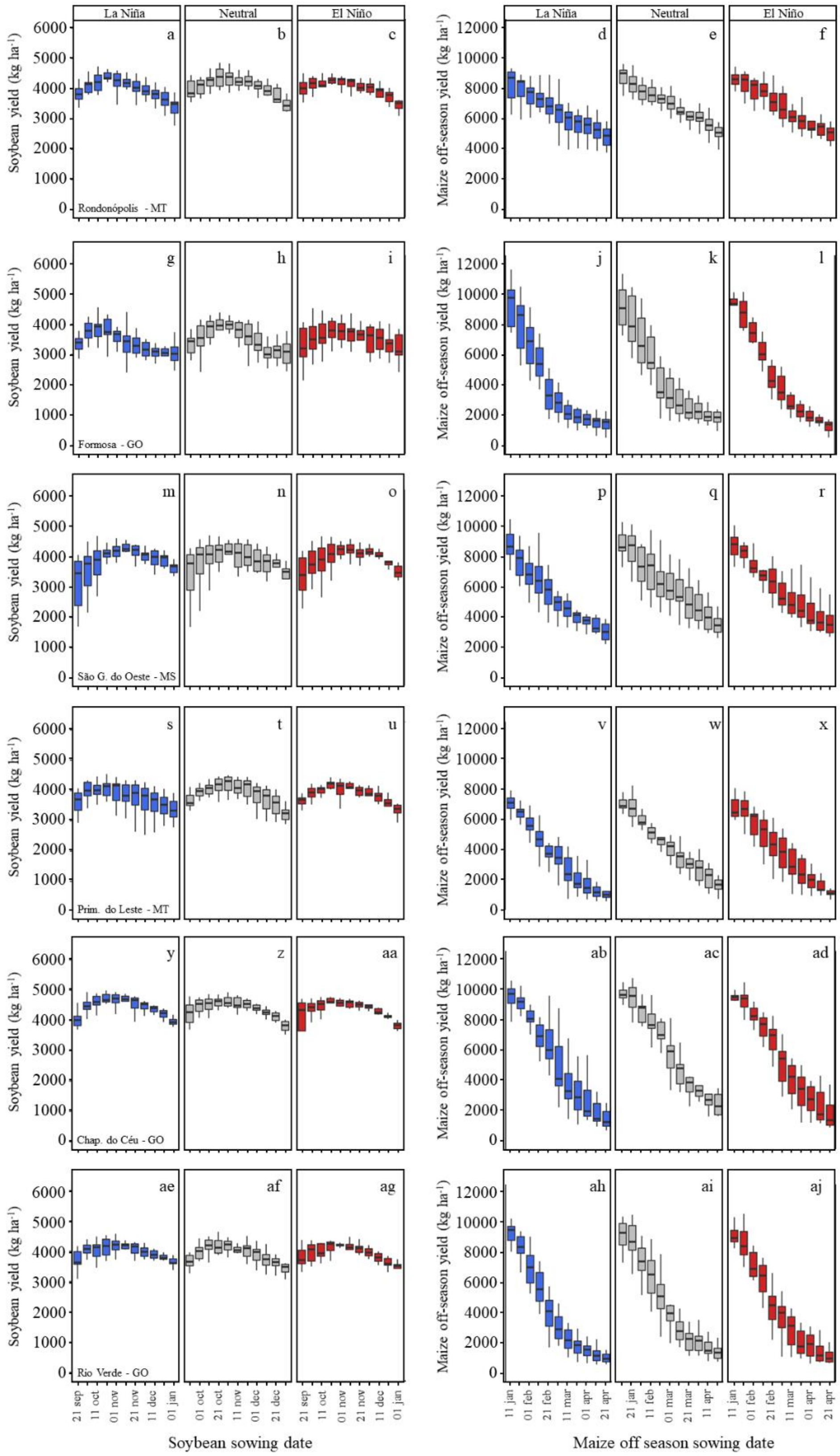

Figure 4. Box plots of soybean (left) and maize off-season (right) water-limited yields for different ENSO phases (1980-2013), sowing dates and locations (a to aj) in Brazil. The Yw data presented are the ensemble of three crop simulation models.

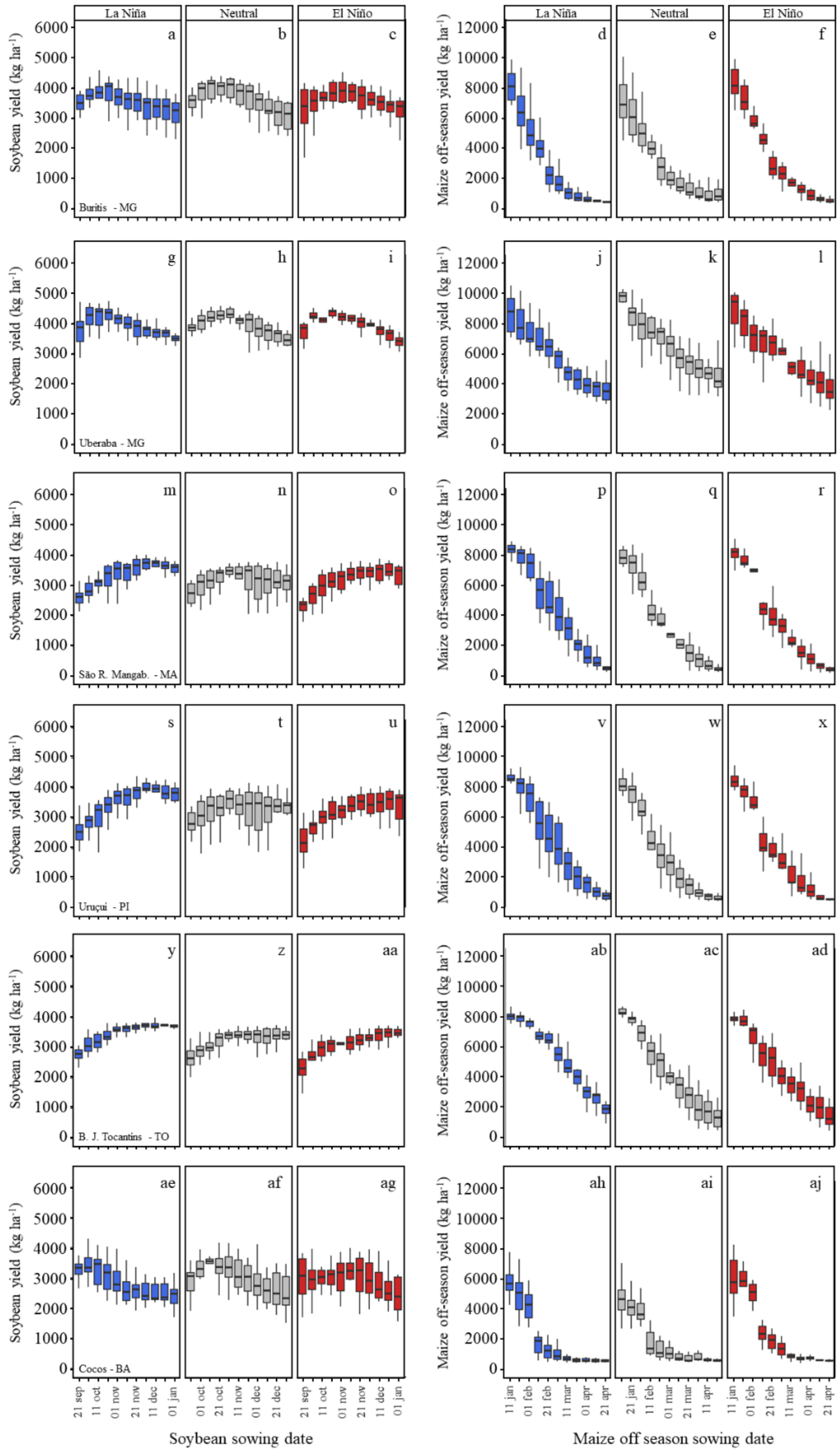

Figure 5. Box plots of soybean (left) and maize off-season (right) water-limited yields for different ENSO phases (1980-2013), sowing dates and locations (a to aj) in Brazil. The Yw data presented are the ensemble of three crop simulation models.

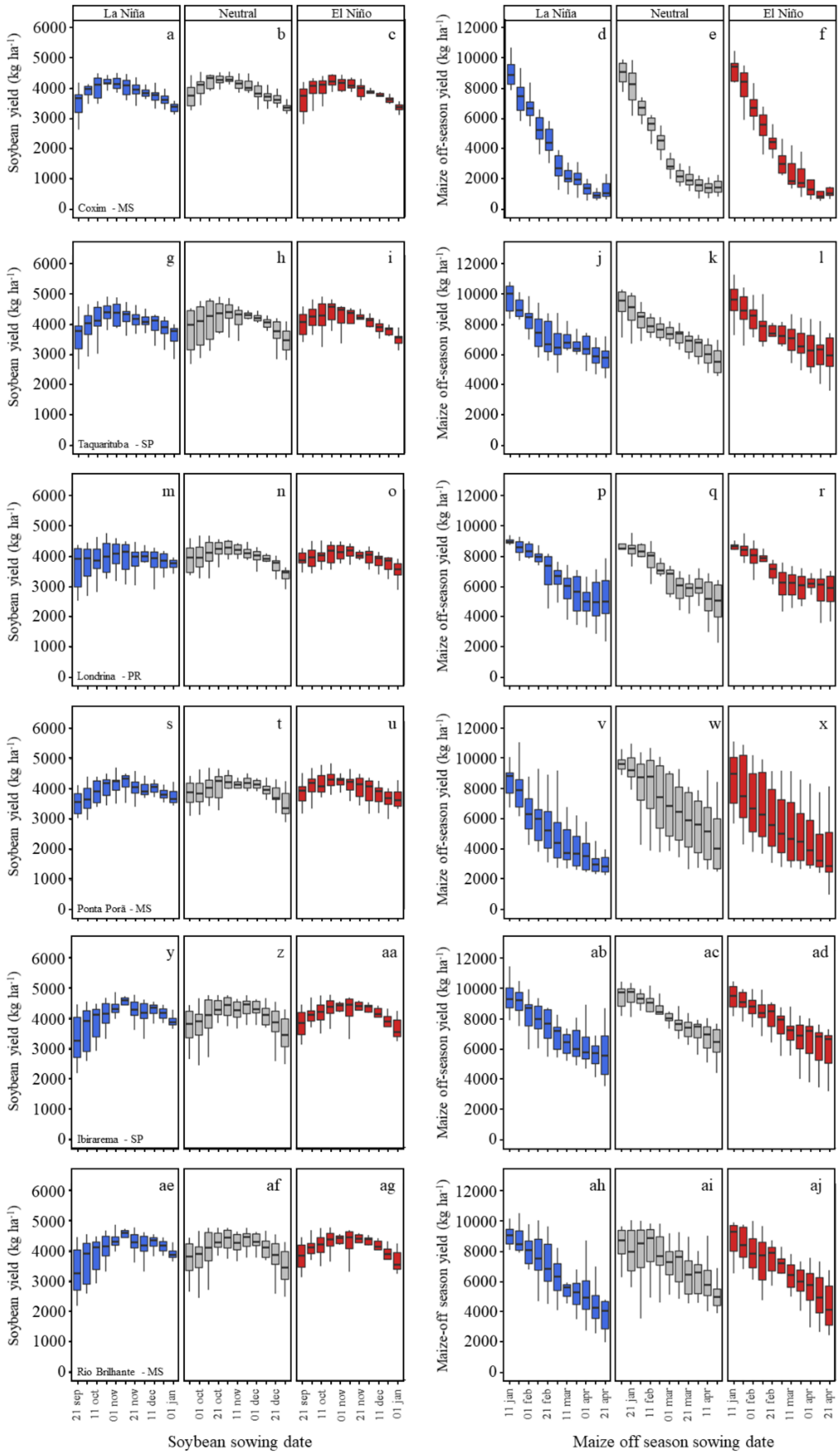

Figure 6. Box plots of soybean (left) and maize off-season (right) water-limited yields for different ENSO phases (1980-2013), sowing dates and locations (a to aj) in Brazil. The Yw data presented are the ensemble of three crop simulation models.

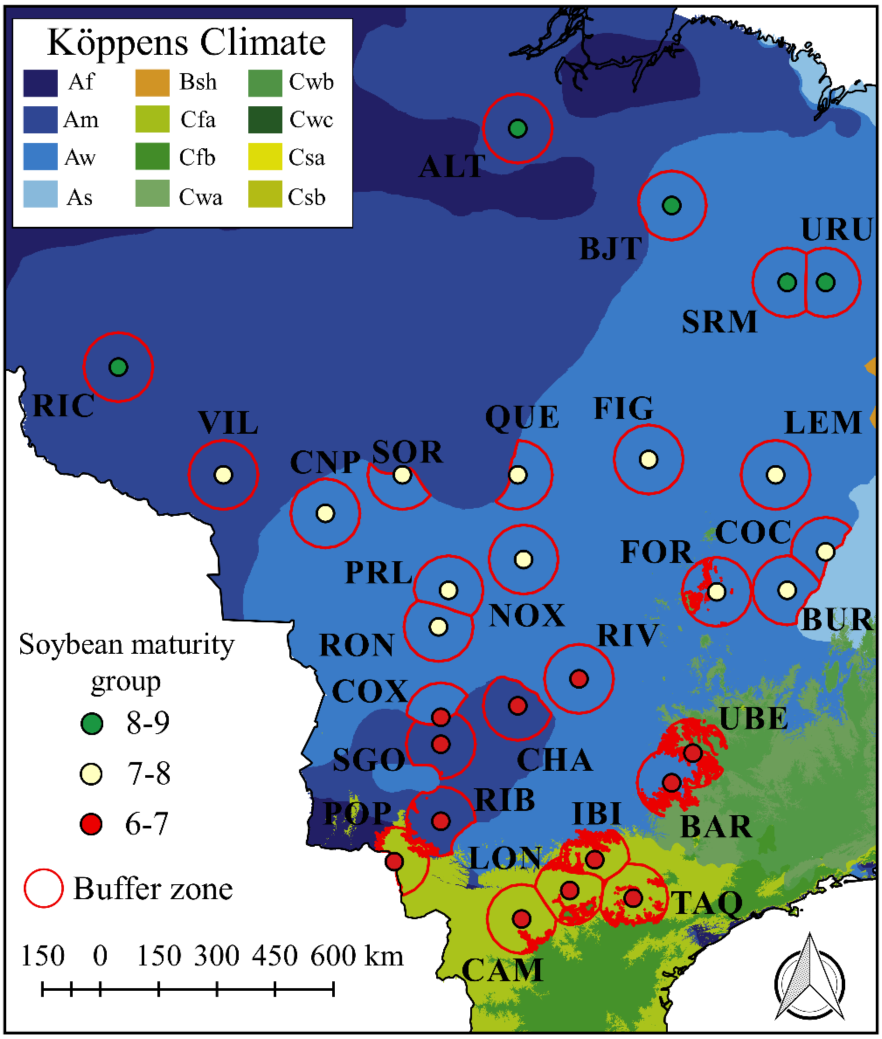

Figure 7. Weather stations (WS) and associated buffer zones selected for simulating yield water-limited and yield gap by water deficit for the soybean-maize off-season succession in Brazil, considering different soybean maturity groups. The map presents the Köppen climate classification proposed by Alvares et al. (2013).

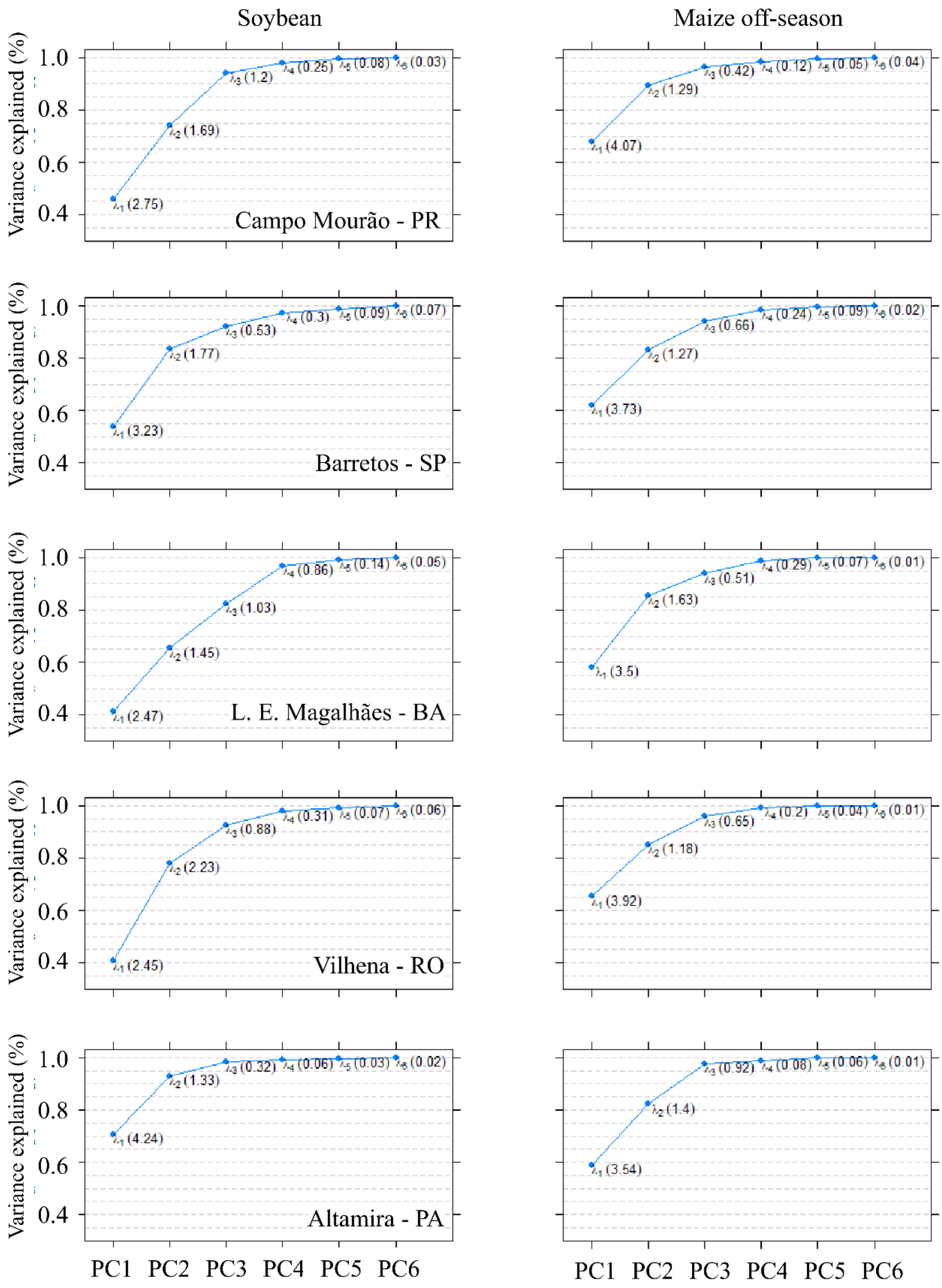

Figure 8. The results of scree plot (accumulated explained variance and the eigenvalues for each principal component presented in parenthesis) of the principal component analyses for soybean (left) and maize off-season (right).

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4. A MULTI-MODEL APPROACH FOR DETERMINING SOYBEAN – MAIZE OFF-SEASON SUCCESSION YIELD GAP IN BRAZIL

ABSTRACT

The soybean – maize off-season succession is an important Brazilian agricultural system which contributes to increase grain production without necessity of crop land expansion. In order to identify the main factors that threaten these crops, yield gap studies become pivotal to increase food security not only in Brazil but also around the world, since the country accounts for 27% and 6% of world's soybean and maize production, respectively. Therefore, the aim of the present study was to determine the magnitude of the grain and revenue yield gap (YG) for the soybean – maize-off-season succession caused by water deficit (YG_W) and by sub-optimal crop management (YG_M) and to propose strategies for closing these gaps in order to improve food security in different Brazilian regions. For that, the ensemble of three previously calibrated and validated models (FAO-AZM, DSSAT and APSIM) was used to estimate soybean and maize-off-season yields for 28 locations in 12 states for a period of 34 years (1980-2013). The municipalities of Cocos, BA, Buritis, MG and Formosa, GO, are those with the highest YGw on soybean - maize succession yield. The locations in the central region of Brazil, mainly in the state of Mato Grosso, were those with the lowest YG_M. For soybean the YG_M was the main cause of total YG in Brazil, accounting for 51.8%, whereas for maize off-season the YGw corresponded to 53.8% of the total YG.

Keywords: Crop simulation models, Multi model approach, Potential yield, Attainable yield, Actual yield, Water deficit and sub-optimal crop management

4.1. Introduction

Food security is one of the greatest challenges for humanity, presently and for the next generations. This subject becomes more critical considering the high rate of world´s population growth, which is increasing the demand for food, fiber and energy annually (EHRLICH; HARTE, 2015). Therefore, this is a problem to be addressed in a short term since recent survey of 2017 showed that more than 800 million people in several regions of the world are undernourished (FAO, 2019). Based on that, it is of high importance to determine how much the agricultural production needs to grow to support the demand now and in the future (FOLEY et al., 2011; GODFRAY et al., 2010c; GOLDEMBERG et al., 2014; TILMAN et al., 2011).

Many authors indicate that increasing agricultural efficiency by the closure of yield gaps is the main way for increasing food, fiber and energy yield and production (FISCHER, 2009; FOLEY, 2005; FOLEY et al., 2011; GODFRAY et al., 2010b). Brazilian agriculture has been able to increase its efficiency and to reduce its expansion to new areas by cultivating two or more crops in the same area throughout the year, which is known as crops succession.

In the last decade, maize has become the main alternative crop for the off-season period in Brazil (autumn-winter, called in Brazil as second crop or "safrinha") (CONAB, 2019). The maize off-season cultivation occurs after the summer crop, usually soybean, creating the most important agricultural system of crop succession in Brazil, known as soybean – maize-off-season succession. This production system has contributed to increase grain production without crop land expansion. Moreover, the cultivation of soybean - maize-off-season succession has been a great opportunity for farmers to increase their profitability if they sow these crops in the right time (NÓIA JÚNIOR; SENTELHAS, 2019a).

The Brazilian maize-off-season yield in 2017/18 growing season was nine times higher than that obtained in 1979/80, whereas maize cultivated during the main season (between spring and summer) had a yield increase of only three times for the same period. In the last growing season, maize-off-season represented about 70% of maize production in Brazil (CONAB, 2019) (See Figure S1 at supplementary material). The possibility of use of successive crop led farmers, researchers and the Brazilian government to seek new technologies to make the system feasible, which also contributed to a substantial increase in soybean yield. The Brazilian soybean yield has doubled compared to the 1979/80 growing season, and is now higher than the world average yield (FAO, 2019). However, to grow soybean - maize-off-season succession is very risky due to climate variability, especially for late sowing dates, when dry spells, mainly in the center and north of the country, and frosts in the states of Paraná, São Paulo and Mato Grosso do Sul, can reduce the yields drastically (NÓIA JÚNIOR; SENTELHAS, 2019a).

Aiming to keep the fast yield growth of soybean - maize off-season crop system, and reduce its climate-related risks, it is important to quantify the yield gain that could occur if current management techniques (i.e. weed, pest and disease management and soil fertilization) were improved and irrigation was implemented. According to Lobell et al. (2009), the yield gap (YG) analysis provide a robust quantitative framework to address these issues. Based on many studies, the following types of crop yield are considered (BATTISTI et al., 2018; DIAS; SENTELHAS, 2018; GUILPART et al., 2017; LOBELL; CASSMAN; FIELD, 2009; NÓIA JÚNIOR; SENTELHAS, 2019a; SENTELHAS et al., 2015; VAN BUSSEL et al., 2015): (i) Potential yield (Yp), which is the yield of a crop when grown in a non-limited water environment and with optimal crop management. Under such conditions, the crop growth is determined by the interaction between the genotype, in a given plant population, with atmospheric CO_2 concentration, air temperature, solar radiation, photoperiod (determining factors), which can change with the cultivar cycle and sowing date; (ii) Water-limited yield (Yw), which is the Yp penalized by the water deficit (limiting factor), but still considering optimal crop management; and Actual yield (Ya), which is yield obtained by farmers under operational conditions, considering, in addition to the above-mentioned factors, the reducing ones, associated to pests, diseases and weeds occurrence. The difference between Yp and Yw results in the yield gap caused by water deficit (YG_W), whereas the yield gap caused by sub-optimal crop management (YG_M) is obtained by the difference between Yw and Ya (SENTELHAS et al., 2015).

The determination of Yp, Yw and then YGs can be made by field experiments, yield contests, maximum farmer yields based on surveys and crop simulation models (DIAS; SENTELHAS, 2018; VAN ITTERSUM et al., 2013). By using crop simulation models, some studies investigated the magnitude of YG for soybean (BATTISTI et al., 2018; SENTELHAS et al., 2015) and maize (DA S. ANDREA et al., 2018; DUARTE, 2018) in Brazil; however a thorough assessment of potential soybean-maize succession yield across the major Brazilian producing regions is lacking.

In order to reduce the estimate yield errors, several studies have emphasized the importance of using different models, in an ensemble, aiming to reduce the uncertainties of the estimates (ASSENG et al., 2013; BATTISTI; SENTELHAS; BOOTE, 2017; DIAS; SENTELHAS, 2017; DUARTE, 2018; MARTRE et al., 2015). Battisti et al. (2017) observed that the average error of five soybean crop models in Brazil was half of the error caused by each model. Duarte (2018) found similar results for maize off-season in Brazil, which indicated that the use of the ensemble of three crop models reduced the errors by about 60% when compared with the results of a single one.

The hypothesis of the present study is that the determination of the yield gap of the most important Brazilian agricultural system (soybean – maize-off-season succession), estimated by the use of an ensemble of three calibrated and validated crop models, is a feasible way to identify the main strategies to reduce climatic risks and improve yields. Based on that, the aim of the study was to determine the magnitude of the current soybean – maize-off-season succession yield gap caused by water deficit (YG_W) and by sub-optimal crop management (YG_M) for 28 locations in 12 Brazilian states, by using three crop simulation models (FAO-AZM, DSSAT and APSIM), in a multi-model approach, and to propose possible strategies for closing the gaps and improve growers profitability.

4.2. Material and methods

Study area, weather and soil data

Brazil accounts for 27 and 6% of the total world's production of soybean and maize, respectively (FAO, 2019). The soybean – maize-off-season succession is spread in 1259 municipalities across Brazil (CONAB, 2019), which are distributed in 12 states: Paraná (PR), São Paulo (SP), Minas Gerais (MG), Mato Grosso do Sul (MS), Mato Grosso (MT), Goiás (GO), Rondônia (RO), Pará (PA), Tocantins (TO), Piauí (PI), Maranhão (MA) and Bahia (BA), with more than 90% of these areas concentrated in four different Köppen´s climatic zones (ALVARES et al., 2013): Am (Tropical monsoon); Aw (Tropical humid with dry winter); Cfa (Humid subtropical without dry season and hot summer); and Cwa (Humid subtropical with dry winter and hot summer). Based on that, 28 locations with weather stations were selected to represent the soybean – maize off-season succession growing areas in the above-mentioned states and climatic zones (Figure 1).

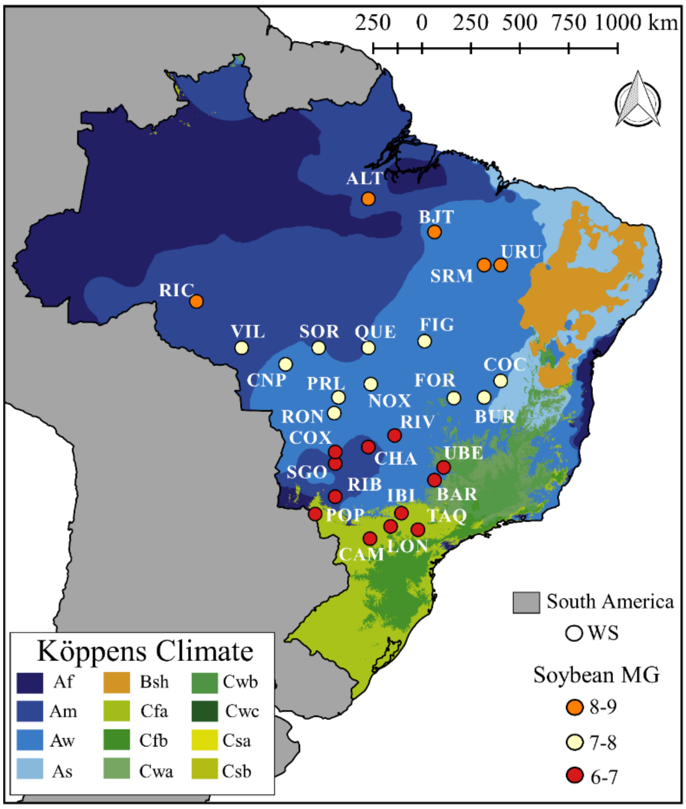

Figure 1. Locations with weather stations (WS) assessed for estimating soybean – maize-off-season yields, when cultivated in succession in Brazil. The map presents the Köppen climate classification proposed by Alvares et al. (2013) and the soybean maturity groups (colored circles) used in the simulations. Locations´ codes, latitude, longitude and altitude are presented in Table S1 (Supplementary Material).

Weather data for each location assessed in this study were obtained for the period between 1980 and 2013 from the Brazilian Institute of Meteorology (INMET) and Integrated Agrometeorological Information Center of the state of São Paulo (CIIAGRO). Missing weather data were filled out with data from Xavier gridded data base (XAVIER; KING; SCANLON, 2015), as recommended by Battisti et al. (2018) for soybean, and Duarte (2018) and Bender and Sentelhas (2018) for maize.

The predominant soil types were determined by using the soil map from IBGE (2014). Information about sand, clay, and silt contents, pH, bulk density and organic carbon and nitrogen contents for each soil type were obtained from RADAMBRASIL (1974) (Table S.2 in the Supplementary Material). The soil water holding capacity of each soil was estimated using pedo-transfer functions developed by Reichert et al. (2009).

Crop models

The soybean and maize simulation models used in the present study were: FAO – Agroecological Zone Model (BATTISTI et al., 2017a; KASSAM, 1977; RAO; SARMA; CHANDER, 1988); Agricultural Production Systems Simulator v. 7.7 (HOLZWORTH et al., 2014; KEATING et al., 2003), referred to as APSIM; and Crop Simulation Model – CROPGRO – Soybean v.4.6.1 and Cropping Simulation Model – CERES – Maize, both present in the software Decision Support System for Agrotechnology Transfer – DSSAT platform (BOOTE et al., 2003;

JONES et al., 2003). The multi-model ensemble was obtained from the arithmetic mean of the yields simulated by these three models.

The calibration and validation of the models to simulate Yp and Yw were done for soybean (BATTISTI; SENTELHAS; BOOTE, 2017) and maize off-season (BENDER, 2017; DUARTE, 2018), and are presented in Tables S3 and S4 in the Supplementary Material.

Yield gap analysis

The Yp and Yw were estimated for all assessed locations by the three crop simulation models, and the results presented are the ensemble of them. Further information about the performance of the individual models can be found in Nóia Júnior and Sentelhas (2019a), Battisti et al. (2017), Duarte (2018) and Bender (2017). The Ya averages of a 14-year series (2003-2017) for the locations under assessment were obtained from official statistics of IBGE (IBGE, 2019). For the sites where yield technological trends were observed, such trends were removed considering the procedures used by Heinemann and Sentelhas (2011). The difference between Yp and Yw resulted in the yield gap by water deficit (YG_W), whereas the yield gap by sub-optimal crop management (YG_M) was obtained by the difference between Yw and Ya.

The revenue YG was obtained by multiplying the soybean and maize off-season grain YG by their respective selling prices. In Brazil, the selling price is given in R$ per 60 kg bag. The 5-year (2013-2017) averages of soybean and maize selling prices were obtained from Securities, Commodities and Future Exchange of BOVESPA (BM&FBOVESPA), accessed from the Center for Advanced Studies in Applied Economics (CEPEA, 2018). This recent 5-year time period was selected to avoid actual price underestimations due the inflationary trend.

Initial conditions, soil dates and cultivars

For running the models for soybean and maize in succession, the initial soil water content was defined by initiating the soil water balance six months before sowing, considering the prior crop as fallow. The simulated sowing dates were those determined as the best ones by Nóia Júnior and Sentelhas (NÓIA JÚNIOR; SENTELHAS, 2019b), as presented in Figure S2 in the supplementary material.

As the 28 assessed locations are in different latitudes and the intension was to keep soybean crop cycle with 115 days throughout Brazilian territory, three soybean maturity groups (6.5, 7.5 and 8.5) were used, as recommended by Battisti et al. (2017). For maize off-season, the simulated cultivar had mean cycle of 136 days, as usual in the Brazilian farms (NÓIA JÚNIOR; SENTELHAS, 2019a).

4.3. Results

Potential, water-limited and actual yields of soybean and maize-off-season in Brazil

Simulated soybean potential yield (Yp) ranged from 3868 to 5263 kg ha^{-1}. The lowest Yp was obtained in northern Brazil (e.g. Pará, Tocantins, Maranhão and Piauí states), whereas the highest Yp was in southern Brazil (Paraná, São Paulo and Mato Grosso do Sul states) (Table 1, Figure 2A). For maize-off-season, the Yp was between 7657 and 11271 kg ha^{-1}. The highest values were obtained in Central Brazil (Bahia, Goiás, Minas Gerais states), while the lowest was in northern Brazil (Table 2, Figure 2D).

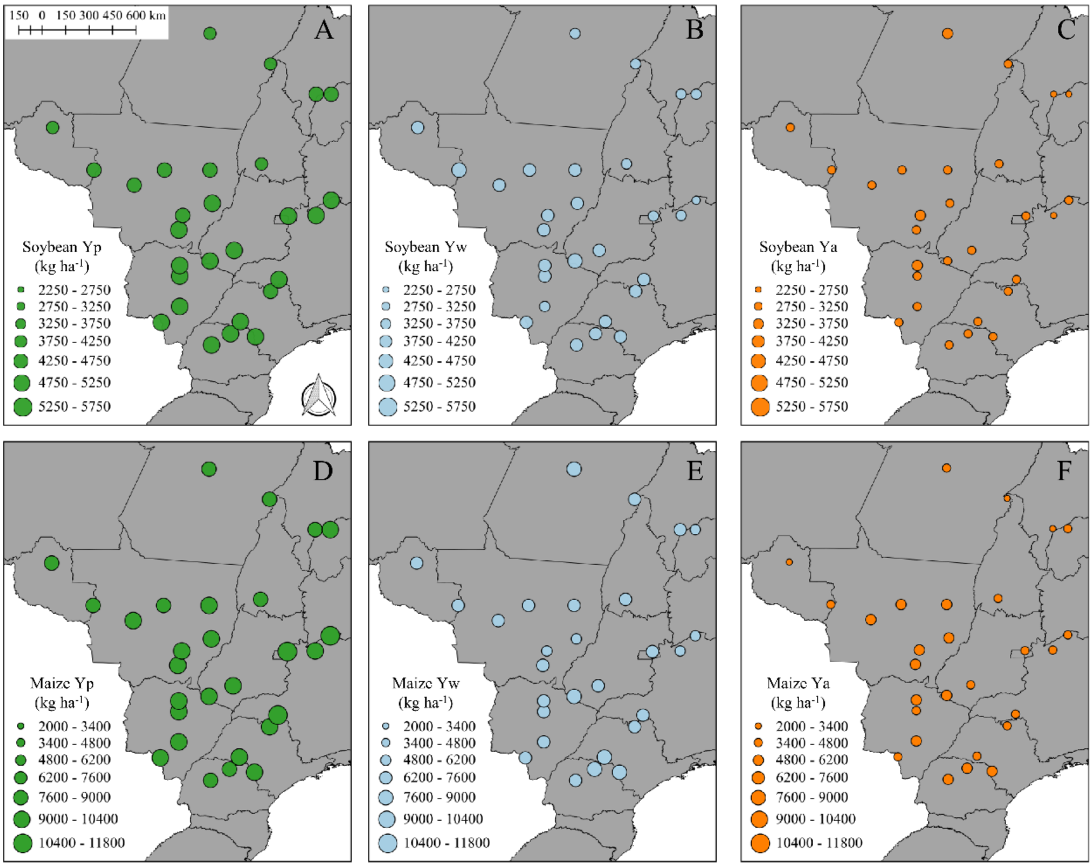

Figure 2. Potential (Yp, colored in green), water-limited (Yw, colored in light blue) actual (Ya, colored in orange) yields for soybean (A, B and C) and for maize-off-season (D, E and F), in the main growing regions in Brazil.

Table 1. Average actual (Ya), water-limited (Yw) and potential (Yp) soybean yields, and the respective yield gaps, caused by water deficit (YGw) and by sub-optimal crop management (YG_M), in different Brazilian locations. The interannual variability of soybean Ya, Yw and Ya are presented in Figure S3 at supplementary material.

Location	Yp	Yw	Ya	YGw	YG_M
			kg ha^{-1}		
Cocos (COC)	5148.6	3113.2	3045.2	2035.4	67.9
Chapadão do Céu (CHA)	4807.6	4554.6	3220.5	253.0	1334.1
Rio Verde (RIV)	5090.2	4081.6	3025.2	1008.5	1056.4
Formosa (FOR)	5147.7	3668.1	3050.8	1479.6	617.3
São Raimundo das Mangabeiras (SRM)	4260.4	3299.1	2707.0	961.2	592.1
Uberaba (UBE)	4881.4	4079.4	3047.5	802.0	1031.9
Buritis (BUR)	5063.4	3657.7	2594.1	1405.5	1063.5
Ponta Porã (POP)	5108.7	4094.6	3231.0	1014.0	863.6
Rio Brilhante (RIB)	5071.7	3682.3	3010.2	1389.3	672.1
S. Gabriel do Oeste (SGO)	4840.6	3993.8	3089.4	846.8	904.4
Coxim (COX)	4754.8	4016.3	3380.2	738.5	636.1
Rondonópolis (RON)	4803.6	4143.3	3190.5	660.3	952.7
Primavera do Leste (PRL)	4746.6	3965.4	3259.2	781.1	706.2
Nova Xavantina (NOX)	4890.9	4016.1	2981.3	874.7	1034.7
Campo Novo do Parecis (CNP)	4470.7	4189.5	3086.9	281.2	1102.6
Sorriso (SOR)	4288.6	3954.9	3197.3	333.7	757.5
Querência (QUE)	4446.8	4170.4	3156.4	276.4	1014.0
Altamira (ALT)	3868.4	3570.8	3355.1	297.6	215.6
Bom Jesus do Tocantins (BJT)	3931.7	3444.9	3044.5	486.8	400.3
Uruçuí (URU)	4275.1	3429.2	2607.0	845.9	822.2
Campo Mourão (CAM)	5163.2	4003.3	3193.4	1159.9	809.9
Londrina (LON)	4990.0	3998.4	3121.6	991.6	876.7
Vilhena (VIL)	4492.4	4274.4	3145.0	217.9	1129.3
Rio Crespo (RIC)	4207.9	4121.6	3106.8	86.3	1014.8
Taquarituba (TAQ)	5100.3	4107.4	3235.3	992.8	872.1
Ibirarema (IBI)	4943.9	4166.0	2910.0	777.9	1255.9
Barretos (BAR)	4702.0	4180.7	2897.8	521.3	1282.8
Figueirópolis (FIG)	4238.8	3633.3	2906.6	605.5	726.7
Average	4704.9	3914.7	3064.2	790.2	850.5
Standard deviation	388.0	329.7	194.6	448.3	299.0

Soybean water-limited yield (Yw) ranged from 3113 to 4554 kg ha^{-1} (Table 1, Figure 2B), while maize-off-season Yw ranged varied from 4904 to 8280 kg ha^{-1} (Table 2, Figure 2E). For soybean, the locations in Bahia, Maranhão, Piauí states and northern of Minas Gerais (i.e Cocos, Butitis, São Raimundo das Mangabeiras and Uruçuí) were those with the lowest Yw. The highest values were obtained in southern and central Brazil. For maize-off-season, Altamira, PA, was the location with the highest Yw, whereas Cocos, BA, and Buritis, MG, presented the lowest Yw.

Soybean and maize Ya varied widely across the assessed locations. The soybean Ya ranged between 2594 and 3380 kg ha^{-1} (Table 1, Figure 2C), whereas for maize-off-season Ya varied from 2290 and 5996 kg ha^{-1} (Table 2, Figure 2F). Altamira, PA, and locations in southern Brazil were those with the highest Ya for soybean, whereas the locations in Mato Grosso state were those with the highest Ya for maize-off-season. The lowest Ya was obtained in São Raimundo das Mangabeiras, MA, and Uruçuí, PI, for soybean and in Rio Crespo, RO, for maize off-season.

Table 2. Average actual (Ya), water-limited (Yw) and potential (Yp) maize off-season yields, and the respective yield gaps, caused by water deficit (YGw) and by sub-optimal crop management (YG_M), in different Brazilian locations. The interannual variability of maize off-season Ya, Yw and Ya are presented in Figure S4 at supplementary material.

Location	Yp	Yw	Ya	YGw	YG_M
	kg ha^{-1}				
Cocos (COC)	10557.0	4904.2	4250.0	5652.7	654.2
Chapadão do Céu (CHA)	10294.4	7771.7	4909.9	2522.7	2861.7
Rio Verde (RIV)	10269.7	6452.4	3707.0	3817.3	2745.3
Formosa (FOR)	11171.7	6286.3	4530.8	4885.4	1755.4
São Raimundo das Mangabeiras (SRM)	8047.9	6416.4	2978.9	1631.5	3437.4
Uberaba (UBE)	10413.8	7397.5	4575.5	3016.2	2822.0
Buritis (BUR)	10379.0	5409.6	4205.9	4969.4	1203.6
Ponta Porã (POP)	9252.7	6662.7	4728.6	2589.9	1934.1
Rio Brilhante (RIB)	9613.6	7526.3	4967.0	2087.2	2559.3
S. Gabriel do Oeste (SGO)	10193.7	7145.4	4752.0	3048.3	2393.4
Coxim (COX)	10088.1	6687.0	5753.8	3401.1	933.1
Rondonópolis (RON)	9281.6	7596.2	5996.3	1685.4	1599.8
Primavera do Leste (PRL)	9403.5	5352.1	5282.2	4051.4	69.8
Nova Xavantina (NOX)	10057.0	5497.6	4861.6	4559.4	635.9
Campo Novo do Parecis (CNP)	9033.2	6563.9	5348.3	2469.2	1215.6
Sorriso (SOR)	8860.9	6615.7	5933.0	2245.1	682.6
Querência (QUE)	9156.7	6615.7	5357.7	2541.0	1258.0
Altamira (ALT)	8014.5	7666.2	3621.4	348.3	4044.7
Bom Jesus do Tocantins (BJT)	7778.7	6979.7	3130.8	798.9	3848.9
Uruçuí (URU)	9079.7	5816.6	3501.5	3263.2	2315.0
Campo Mourão (CAM)	7657.2	6675.3	4970.1	981.8	1705.1
Londrina (LON)	8502.2	7797.3	4958.1	704.8	2839.1
Vilhena (VIL)	8674.1	7291.9	4760.0	1382.1	2531.9
Rio Crespo (RIC)	8001.1	6729.5	2290.4	1271.5	4439.0
Taquarituba (TAQ)	9626.7	7964.3	5233.3	1662.3	2731.0
Ibirarema (IBI)	9846.1	8280.5	3856.2	1565.6	4424.3
Barretos (BAR)	10388.8	7167.5	4735.5	3221.2	2432.0
Figueirópolis (FIG)	7992.9	6282.7	4480.2	1710.1	1802.5
Average	9344.2	6769.8	4559.9	2574.4	2209.9
Standard deviation	982.2	850.3	894.3	1389.3	1169.5

Yield gaps for soybean and maize off-season

The YG_W and YG_M for soybean and maize off-season varied substantially across the Brazilian regions (Figure 3). The YG_W ranged from 86 to 2035 kg ha^{-1} for soybean (Table 2, Figure 3A), and from 348 to 5652 kg ha^{-1}

for maize off-season (Tables 3, Figure 3C). The lowest YGw for soybean occurred in Mato Grosso, Pará and Rondônia states, regions where the YGw for maize off-season was also low. For maize off-season, the regions located in southern Brazil also presented small YGw. For both crops, the highest YGw occurred in Buritis, MG, Formosa, GO and Cocos, BA, regions where the rainfall seasonality is more pronounced than in the regions close to the Amazon region.

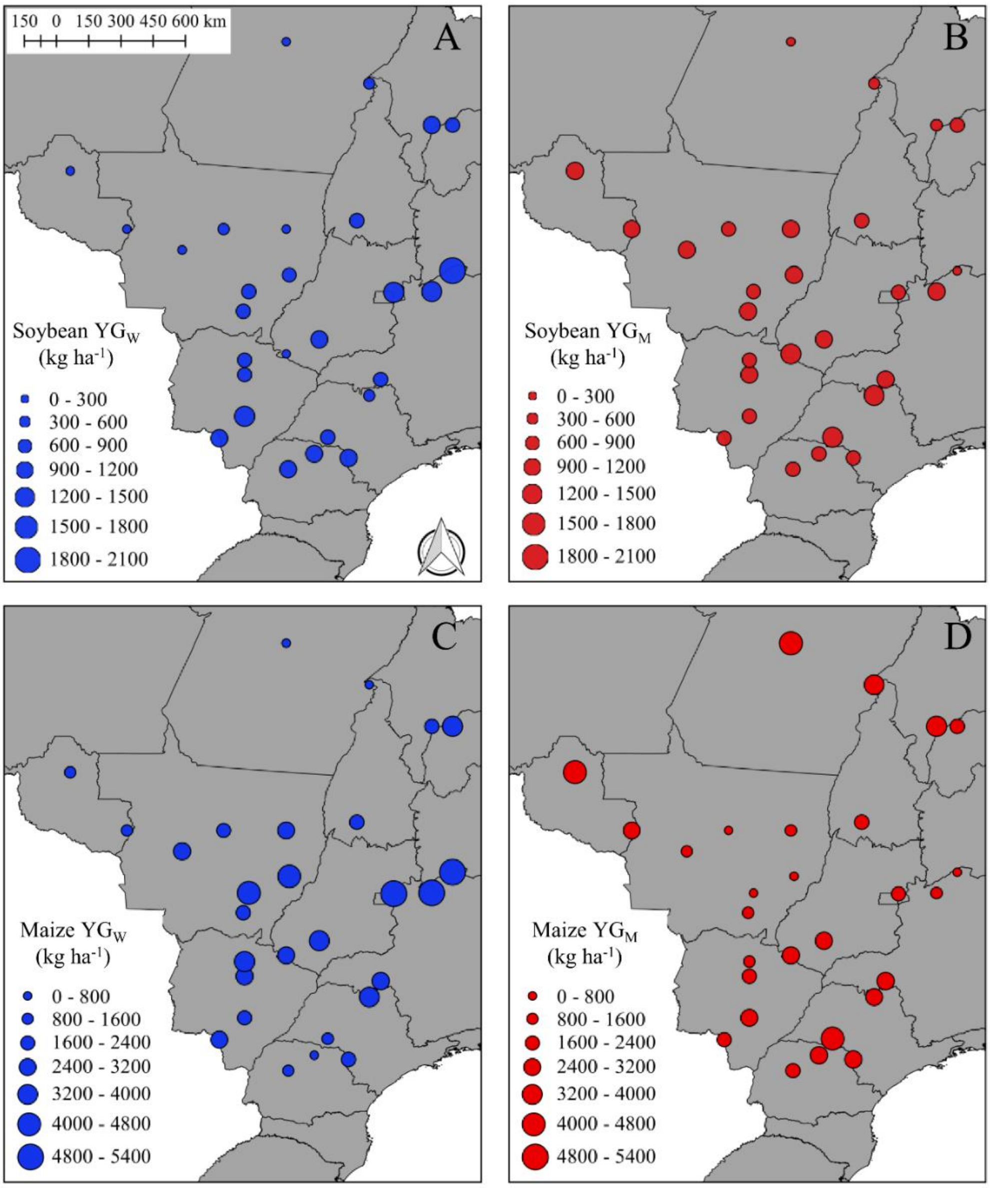

Figure 3. Yield Gap by water deficit (YG_W, blue circles) and by sub-optimal management (YG_M, red circles) for soybean (A and B) and for maize off-season (C and D), in the main growing regions of soybean-maize succession in Brazil.

Regarding YG_M, it was noticed that it ranged between 67 and 1334 kg ha^{-1} for soybean (Table 2, Figure 3B), and between 69 and 4439 kg ha^{-1} for maize off-season (Tables 2, Figure 3D). The locations in northern Brazil presented the lowest YG_M for soybean, varying between 86.3 and 961.2 kg ha^{-1}. For maize off-season, the YG_M is the lowest in the north of Mato Grosso state. Moreover, in northern Brazil, the YG_M was the highest for maize off-season, on the contrary to the results found for soybean in the same region.

Total grain and revenue gaps for soybean-maize succession

The total grain YGw for soybean-maize off-season succession ranged from 646 to 7688 kg ha^{-1}, resulting in a revenue loss between 181 and 1822 R$ ha^{-1} (Figure 4A,C). The results show that YGw for maize off-season is predominantly higher than for soybean (Figure 4A). However, as soybean has a higher selling price, the proportion of revenue losses caused by water deficit between soybean and maize off-season is not exactly the same as observed for YGw (Figure 4C). As observed in Figure 4, the locations with the highest total grain and revenue YGw were Buritis, MG, Formosa, GO and Cocos, BA.

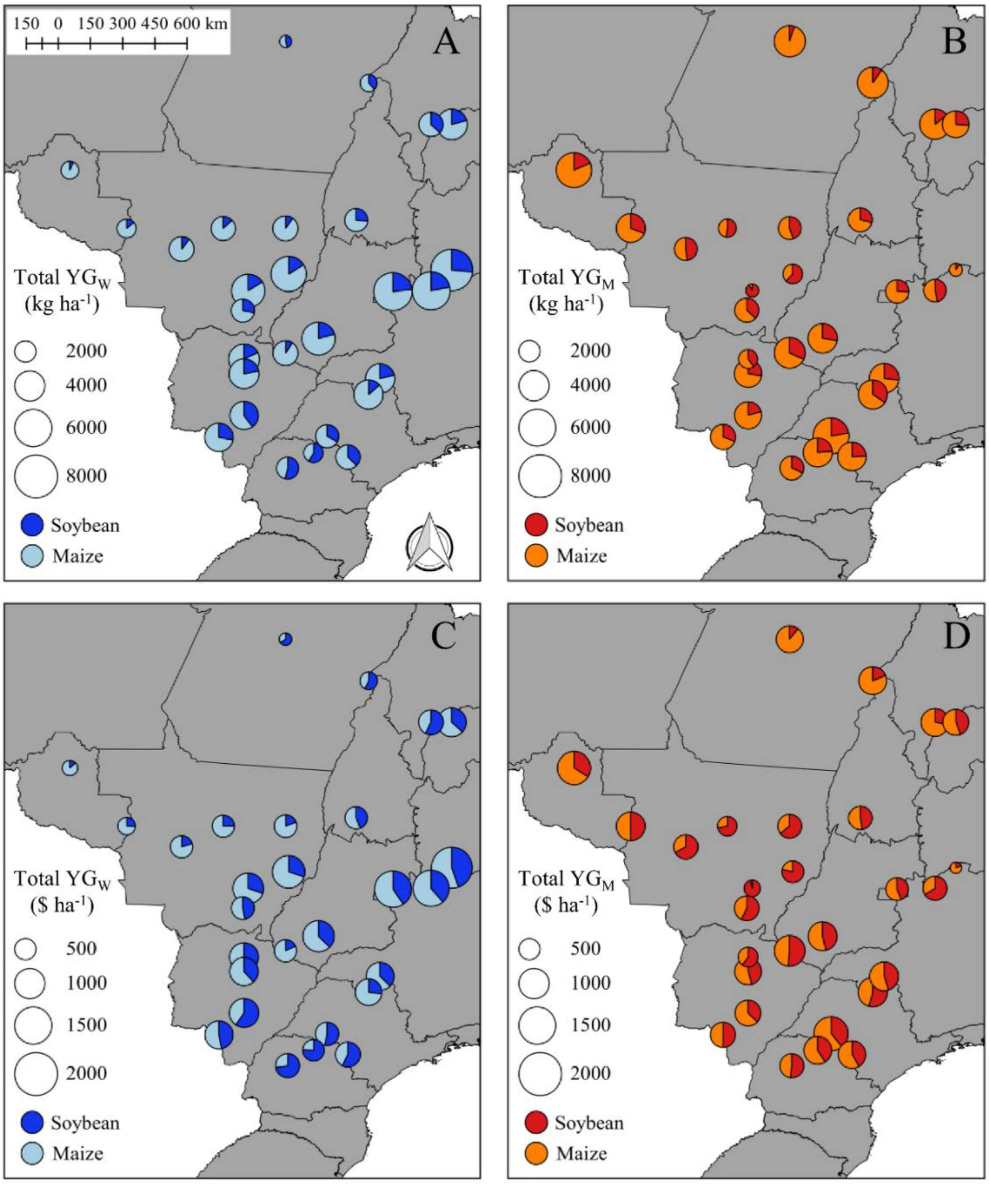

Figure 4. Total grain and revenue yield gap caused by water deficit (YGw, A and C) and by sub-optimal crop management (YG_M, B and D) for the soybean – maize off-season succession in Brazil.

The highest YG_M for soybean – maize off-season succession occurred in northern and southern Brazil, whereas the lowest YG_M were observed in the central part of the country (Figure 4B,D). In general, maize off-season YG_M accounts for 68,9% (ranging from 8,9 and 94,9%) of total YG (Figure 4B) and for 49,7% (ranging from 4,2 and 89,3%) of total revenue losses (Figure 4D).

4.4. Discussion

In the world, maize is grown in many different environments, with diverse types of soils and climates, ranging from cool to very hot and from semi-arid to wet lands (SHIFERAW et al., 2011). Such performance is a consequence of the enormous diversity of genotypes, adapted to different conditions (TŮMOVÁ et al., 2018). Because of that, this crop is a good option for locations or seasons under marginal climatic conditions (MUSSADIQ et al., 2011). In Brazil, maize has been largely cultivated as an off-season crop, usually after soybean in a cropping system known as soybean – maize off-season succession. This cultivation system is contributing to increase grain production without promoting cultivated land expansion, allowing to increase food security not only in Brazil but also in the countries that import soybean and maize from Brazil. However, to meet world's demands for food, fiber and energy, the agricultural yield is expected to grow by 60 to 120% until 2050, which has not been observed since the rates of crop yield growth in the last years are not being enough (FOLEY et al., 2011; GODFRAY et al., 2010a). In order to guide policies and researches for increasing crop yields, the studies about crop yield gaps are pivotal. In this study, the grain and revenue yield gaps for soybean-maize off-season succession in Brazil were determined, based on a multi-model approach for 28 locations spread in the different regions of the country and considering historical weather series of 34 years.

The total yield gap was separated into those caused by water deficit (YGw) and those associated to sub-optimal crop management (YG_M). The magnitude of the YGw and YG_M varied according to the crop and region. In most of the locations, the YGw was higher than the YG_M for both crops (Tables 1 and 2), which is in accordance with the results found for soybean by Sentelhas et al. (2015) and for maize off-season by Duarte (2018). In Cocos, BA, Buritis, MG, and, Formosa, GO, the YGw accounted for around 70 and 80% of total YG, for soybean and maize off-season, respectively (Tables 1 and 2). The results also showed that the YGw is more pronounced for maize off-season, accounting for 76.5% of the total grain YG, and 59.1% of the total revenue losses in the soybean – maize off-season succession in Brazil (Figure 4). Based on that, it is possible to verify that the increase of the yield and profitability of the soybean – maize off-season succession will only be possible by minimizing the effects of the water deficit on the crops growth through implementation of better agricultural practices, with the incentive of scientific researches and governmental policies.

Knowing the importance of soybean – maize off-season succession for the Brazilian economy and, also, to food security, and the importance to reduce the water deficit impacts on this crop system, some studies have been done to indicate strategies that could be used to reduce YGw. By comparing maize off-season yield under irrigated and rainfed conditions, some authors obtained an increase of at least 60% with irrigation over rainfed (BEN et al., 2016; BERGAMASCHI et al., 2006; PEGORARE et al., 2009). Besides that, currently the Brazilian irrigated area is only 6 million hectares (FAO, 2017), less than 10% of total area available for irrigation in the country, which corresponds to approximately 75 million hectares (BRAZIL, 2014). Therefore, there is a great opportunity to increase the Brazilian irrigated area in order to minimize yield gaps, not only for soybean – maize off-season succession but also for the crops. For soybean – maize off-season system, irrigation could be very positive, for example, for Cocos, BA, Buritis, MG, and, Formosa, GO, where the highest YGw for both crops occur. A key example to illustrate how positive is irrigation for minimizing YG_W is the region of Luis Eduardo Magalhães, western Bahia, where the average maize off-season yield, in the 2016/17 growing season, reached 10000 kg ha^{-1} against a national average of 5600 kg ha^{-1} (IBGE, 2019).

Although irrigation is cited by many authors as the main strategy for reducing water deficit on the soybean – maize off-season succession, this technique may not be a feasible for most regions and farmers due to water and economic restrictions. When this is a reality, other alternatives can be considered, such as: i) use of drought-tolerant cultivars (ANJUM et al., 2017; BATTISTI et al., 2017b; GOMES et al., 2013; GUAN et al., 2017; HERTEL; LOBELL, 2014); ii) improvement of root zone profile by deeper soil preparation and correction, crop rotation and control of nematodes (BATTISTI; SENTELHAS, 2017; CATUCHI et al., 2012); and iii) choice of best sowing dates for minimizing the climatic risks for soybean – maize off-season succession (BRACCINI et al., 2010; GARCIA et al., 2018; NÓIA JÚNIOR; SENTELHAS, 2019a, 2019b).

The total national average YG_M estimated for soybean – maize off-season succession in Brazil was about 3060 kg ha^{-1}, being 27.8% from soybean and 71.2% from maize off-season. Regarding the revenue losses caused by YG_M, the national average was 734 $ ha^{-1}, being 46.3% from soybean crop (Tables 1 and 2). The YG_M is higher than the YGw in some regions for both crops, such as Londrina, PR, and Vilhena, RO, which occurs mainly for maize off-season, corroborating with the results by Andrea et al. (2018). In general, southern and northern Brazil are the locations with the highest YG_M for soybean – maize off-season succession, whereas in Central Brazil are those with the smallest ones (Figure 4).

The overall crop management constraints for soybean – maize off-season succession in Brazil are associated to some aspects related to: low soil cover during the growing season, which can cause grater soil degradation (PACHECO et al., 2013); low use of fertilizers in the maize off-season crop (MAR et al., 2003; SORATTO et al., 2010); anticipation of soybean sowing to middle/late September and early October, when rainfall is highly variable and losses by water deficit normally occurs (GARCIA et al., 2018); use early soybean cultivars with lower potential yield (FOLONI et al., 2014; NORA et al., 2017); absence of rotation with other crops in the system, favoring the persistence of pests (e.g. *Spodoptera frugperda* and *Helicoverpa zea*) and diseases (e.g. *Puccinia polysora* and *Stenocarpella macrospora*) (CECCON et al., 2004; MICHELOTTO et al., 2017) of difficult control; low efficiency of chemical weeds control, mainly for species as *Digitaria horizontalis, Panicum maximum and Eleusine indica* (DUARTE; SILVA; DEUBER, 2007; LÓPEZ-OVEJERO et al., 2016).

The average Ya for soybean and maize off-season in Brazil were, respectively, 3064 and 4560 kg ha^{-1} (Tables 1 and 2); however, the results found in the present study showed that these yields could reach, in average, 4555 kg ha^{-1} for soybean (+48.6%) and 6770 kg ha^{-1} for maize off-season (+48.5%) by implementing optimal crop management practices. The results also showed that by closing the yield gap by water deficit, using some of the strategies above-listed, the yields of soybean and maize off-season, could reach, in average, 4705 kg ha^{-1} and 9344 kg ha^{-1}, respectively. Therefore, the use of better practices in the studied succession system could close the yield gaps of soybean and maize in Brazil, contributing for improving food security both in Brazil and around the world.

4.5. Conclusions

The multi-model approach allowed to determine the soybean – maize off-season succession yield gap in Brazil and its main causes (water deficit and sub-optimal crop management). This study demonstrated that the YGs for the soybean – maize off-season succession system in Brazil vary across the country, between crops and with the main causes also changing between locations. For soybean, the YG_M was the main cause of total YG in Brazil, accounting for 51.8%, whereas for maize off-season the YGw corresponded to 53.8% of the total YG.

In Cocos, BA, Buritis, MG and Formosa, GO, the YG is mainly caused by water deficit, whereas in northern MT, PA, RO, TO and, also, in the states of PR and SP were observed the lowest water deficit impacts on this crop system. When considering the sub-optimal crop management as the cause for YG, the lowest losses were also observed in the locations of MT, followed by other ones in central part of the country.

In summary, the results of the present study indicate opportunities on how to increase soybean and maize off-season yields in different Brazilian producing regions.

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Supplementary materials

Table 1. Locations, and they respective states, from where the weather stations (WS) were selected, their codes, geographical coordinates, Köppen's climate classification (ALVARES et al., 2013) and soil classification, according to Brazilian soil classification system (IBGE, 2019).

State	Location	Latitude (degrees)	Longitude (degrees)	Altitude (meters)	Köppen's climatic	Soil classification
BA	Cocos (COC)	-14.40	-44.40	520	Aw	Oxisol
GO	Chapadão do Céu (CHA)	-18.80	-52.60	821	Am	Ultisol
GO	Rio Verde (RIV)	-17.80	-50.91	774	Aw	Oxisol
GO	Formosa (FOR)	-15.54	-47.33	935	Aw	Oxisol
MA	São Raim. das Mangabeiras (SRM)	-7.53	-46.03	259	Aw	Oxisol
MG	Uberaba (UBE)	-19.73	-47.95	737	Cwa	Oxisol
MG	Buritis (BUR)	-15.52	-46.40	894	Aw	Oxisol
MS	Ponta Porã (POP)	-22.55	-55.71	650	Cfa	Oxisol
MS	Rio Brilhante (RIB)	-21.77	-54.52	324	Am	Oxisol
MS	S. Gabriel do Oeste (SGO)	-19.42	-54.55	646	Am	Oxisol
MS	Coxim (COX)	-18.51	-54.73	251	Aw	Oxisol
MT	Rondonópolis (RON)	-16.45	-54.56	284	Aw	Ultisol
MT	Primavera do Leste (PRL)	-15.83	-54.38	450	Aw	Oxisol
MT	Nova Xavantina (NOX)	-14.70	-52.35	316	Aw	Oxisol
MT	Campo Novo do Parecis (CNP)	-13.78	-57.83	525	Aw	Oxisol
MT	Sorriso (SOR)	-12.55	-55.72	379	Aw	Oxisol
MT	Querência (QUE)	-12.62	-52.22	361	Aw	Oxisol
PA	Altamira (ALT)	-3.21	-52.21	74.0	Am	Oxisol
PA	Bom Jesus do Tocantins (BJT)	-5.36	-49.13	95	Aw	Oxisol
PI	Uruçuí (URU)	-7.44	-44.34	399	Aw	Oxisol
PR	Campo Mourão (CAM)	-24.04	-52.40	616	Cfa	Oxisol
PR	Londrina (LON)	-23.30	-51.15	610	Cfa	Ultisol
RO	Vilhena (VIL)	-12.73	-60.15	615	Am	Oxisol
RO	Rio Crespo (RIC)	-9.75	-62.75	157	Am	Oxisol
SP	Taquarituba (TAQ)	-23.19	-49.38	561	Cfa	Oxisol
SP	Ibirarema (IBI)	-22.74	-50.38	484	Cfa	Ultisol
SP	Barretos (BAR)	-20.55	-48.54	534	Aw	Oxisol
TO	Figueirópolis (FIG)	-12.10	-49.10	291	Aw	Ultisol

Table 2. Silt, clay, sand, pH, carbon and nitrogen contents (%), of soils in the 28 Brazilian locations where soybean and maize off season yields were simulated.

State	Location	Silt (%)	Clay (%)	Sand (%)	pH	Carbon (%)	Nitrogen (%)
BA	Cocos (COC)	10	41	49	5.9	0.20	0.02
GO	Chapadão do Céu (CHA)	9	37	54	5.4	0.70	0.08
GO	Rio Verde (RIV)	17	26	57	5.3	4.80	0.44
GO	Formosa (FOR)	24	45	31	5.3	1.21	0.12
MA	São R. das Mangabeiras (SRM)	13	32	55	5.5	0.43	0.06
MG	Uberaba (UBE)	5	27	68	5.5	0.35	0.03
MG	Buritis (BUR)	5	22	73	5.7	0.26	0.02
MS	Ponta Porã (POP)	15	59	26	5.0	1.47	0.11
MS	Rio Brilhante (RIB)	8	52	40	5.0	1.97	0.14
MS	S. Gabriel do Oeste (SGO)	37	24	39	5.2	1.60	0.09
MS	Coxim (COX)	7	27	66	5.2	1.18	0.11
MT	Rondonópolis (RON)	46	27	27	5.30	0.59	0.06
MT	Primavera do Leste (PRL)	12	32	56	5.6	1.50	0.09
MT	Nova Xavantina (NOX)	18	32	50	6.4	0.19	0.03
MT	Campo N. do Parecis (CNP)	7	30	63	5.6	0.80	0.06
MT	Sorriso (SOR)	10	56	34	5.2	3.20	0.30
MT	Querência (QUE)	8	49	43	5.5	2.10	0.20
PA	Altamira (ALT)	12	27	61	5.3	1.55	0.13
PI	Uruçuí (URU)	26	24	50	5.1	0.99	0.08
PR	Campo Mourão (CAM)	17	76	7	5.4	2.83	0.25
PR	Londrina (LON)	9	49	42	5.32	0.50	0.05
RO	Vilhena (VIL)	8	39	53	5.6	2.90	0.10
RO	Rio Crespo (RIC)	34	37	29	6.2	1.40	0.10
SP	Taquarituba (TAQ)	10	55	35	4.9	0.66	0.06
SP	Ibirarema (IBI)	17	64	19	6.0	2.74	0.27
SP	Barretos (BAR)	18	61	21	5.5	2.39	0.16
TO	Figueirópolis (FIG)	18	49	33	5.3	0.75	0.04
TO	Bom J. do Tocantins (BJT)	15	39	46	5.3	0.26	0.02

Table 3. Crop models´ performance for simulating soybean yield at the calibration and validation phases. Adapted from Battisti et al. (2017).

Models	RMSE (kg ha^{-1})	d	R^2
		Calibration	
FAO	650	0.91	0.79
DSSAT	548	0.93	0.79
APSIM	550	0.90	0.69
		Validation	
FAO	752	0.77	0.21
DSSAT	511	0.89	0.54
APSIM	732	0.79	0.43

RMSE = Root mean error square; d = Wilmott agreement index; R^2 = coefficient of determination.

Table 4. Crop models´ performance for simulating maize off season yield at the calibration and validation phases. Adapted from Duarte (2018) (*) and Bender (2017) (**).

Models	RMSE (kg ha^{-1})	d	R^2
		Calibration	
FAO*	1459	0.72	0.28
DSSAT**	576	0.86	0.69
APSIM**	1205	0.76	0.31
		Validation	
FAO*	2008	0.71	0.28
DSSAT**	337	0.93	0.77
APSIM**	1554	0.81	0.49

RMSE = Root mean error square; d = Wilmott agreement index; R^2 = coefficient of determination.

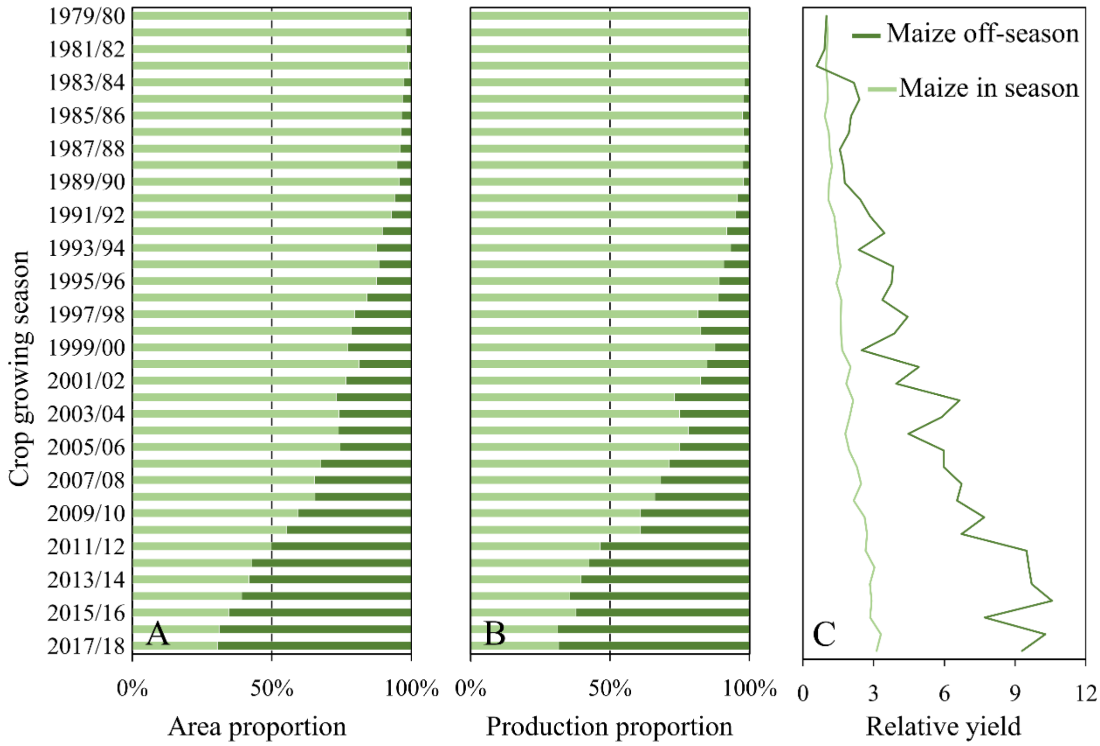

Figure 1. Historical series (1979-2018) of contribution, in proportion (%), of maize off season and maize in season for total maize cultivated area (A) and production (B) in Brazil; Historical changes in the relative yield in maize off season and summer maize (relative yield scaled to 1 in the first crop growing season - 1979/80) (C). Adapted from Conab (2019).

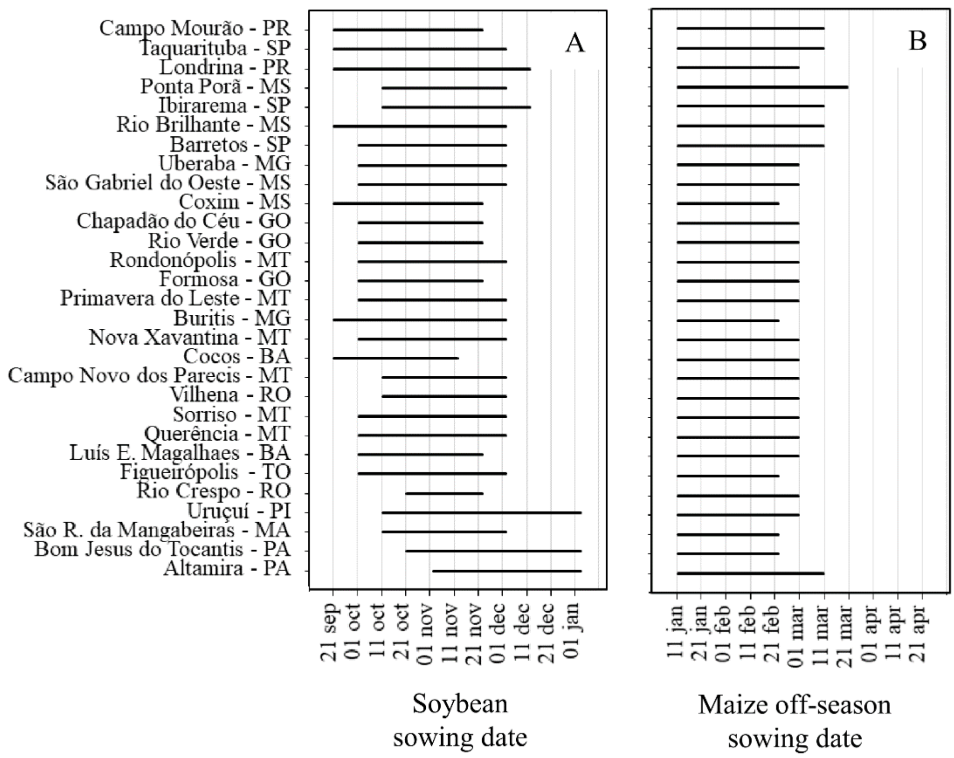

Figure 2. Best sowing windows for soybean (A) and for maize off-season (B), in different Brazilian locations. The criteria used to determine the best sowing dates are presented by Nóia Júnior and Sentelhas (2019).

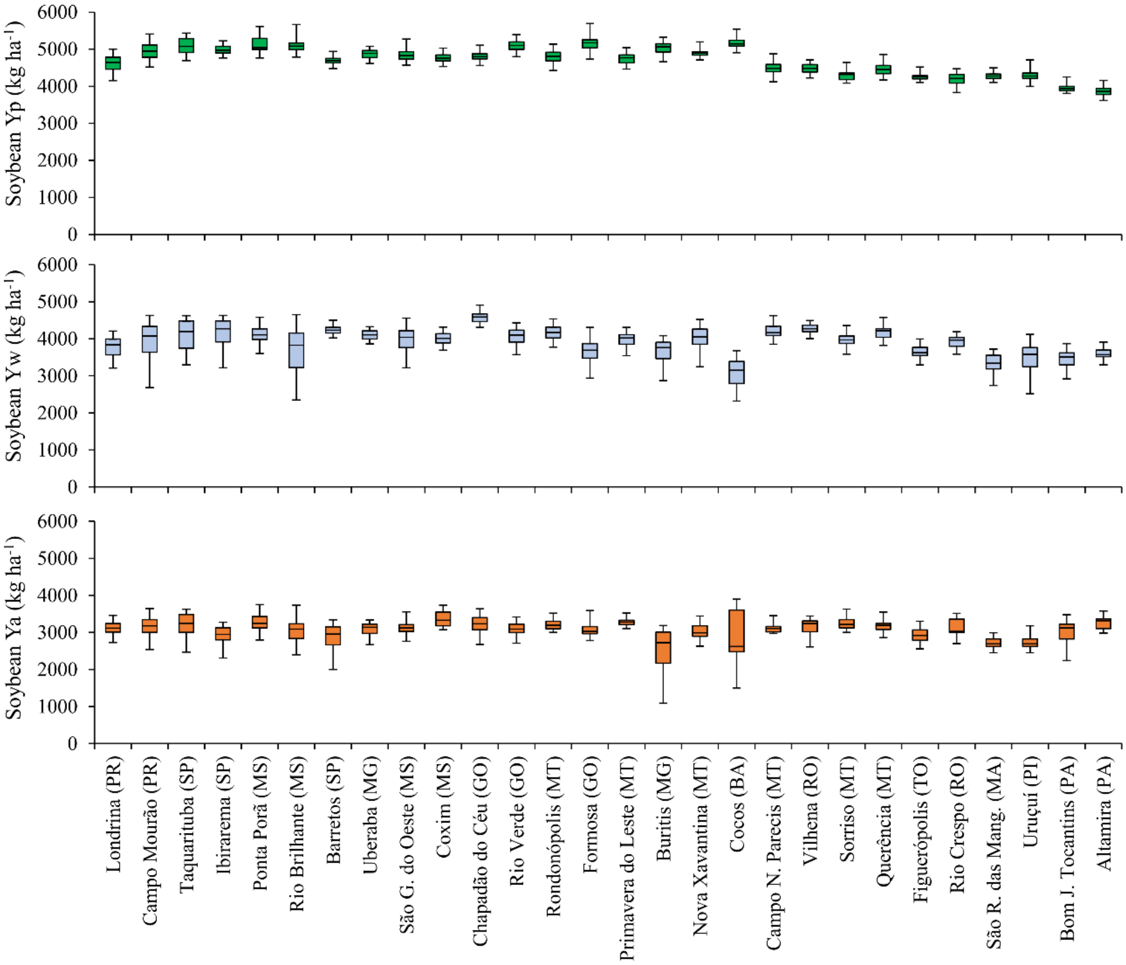

Figure 3. Inter-annual variability of soybean potential (Yp), water-limited (Yw) and actual (Ya) yields for different Brazilian locations. The error bars present the variation of all dataset.

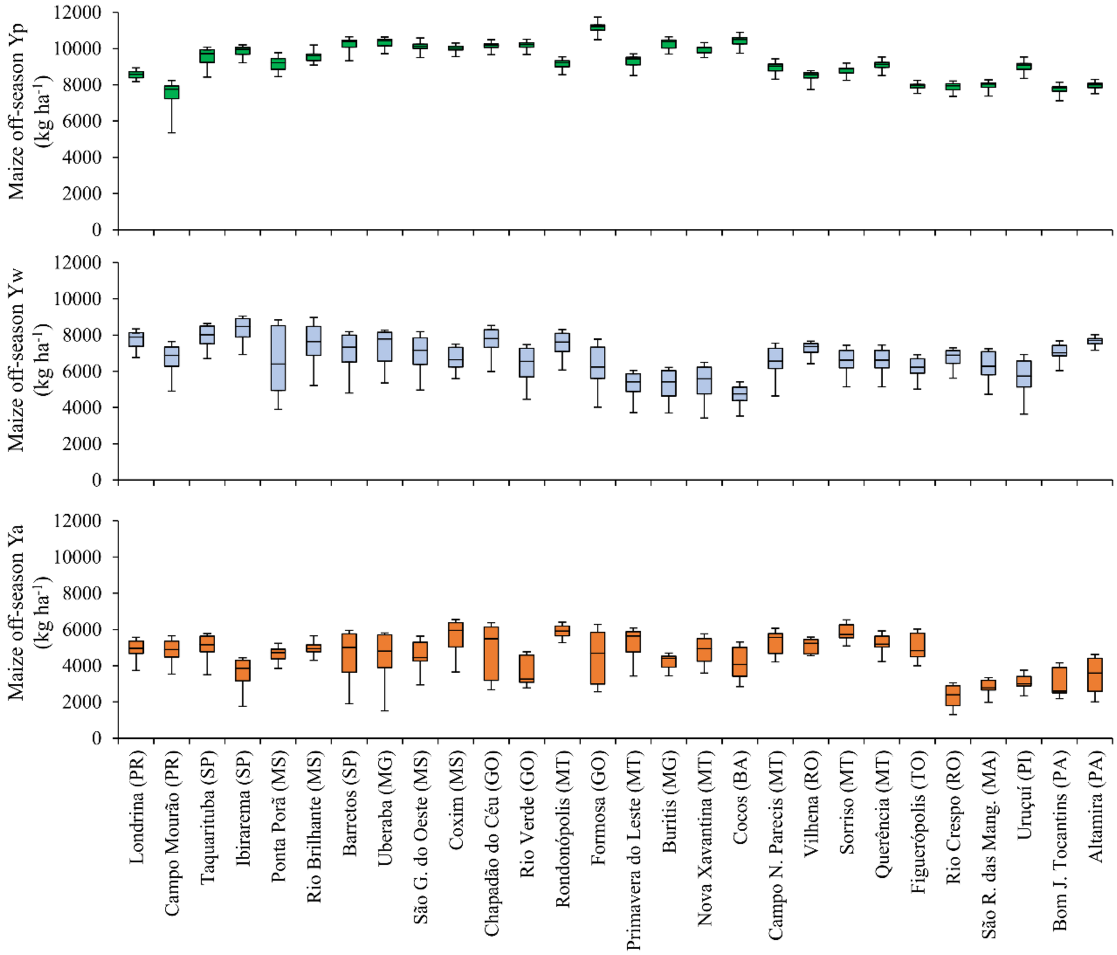

Figure 4. Inter-annual variability of maize off-season potential (Yp), water-limited (Yw) and actual (Ya) yields for different Brazilian locations. The error bars present the variation of all dataset.

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