

LÍVIA MARIA BRUMATTI DE SOUZA

**ASSESSMENT OF FUTURE CLIMATE RISK IN DOUBLE CROPPING
AGRICULTURAL SYSTEMS FOR BRAZIL**

Dissertation submitted to the Applied
Meteorology Graduate Program of the
Universidade Federal de Viçosa in partial
fulfillment of the requirements for the degree of
Master Scientiae.

VIÇOSA
MINAS GERAIS – BRASIL
2019

**Ficha catalográfica preparada pela Biblioteca Central da Universidade
Federal de Viçosa - Câmpus Viçosa**

T

S729a
2019 Souza, Lívia Maria Brumatti de, 1992-
Assessment of future climate risk in double cropping
agricultural systems for Brazil / Lívia Maria Brumatti de Souza.
– Viçosa, MG, 2019.
xiv, 47 f. : il. (algumas color.) ; 29 cm.

Texto em inglês.

Inclui apêndice.

Orientador: Gabrielle Ferreira Pires.

Dissertação (mestrado) - Universidade Federal de Viçosa.

Referências bibliográficas: f. 38-41.

1. Milho - Cultivo. 2. Soja - Cultivo. 3. Cultivo duplo.
4. Mudanças climáticas. 5. Desmatamento. I. Universidade
Federal de Viçosa. Departamento de Engenharia Agrícola.
Programa de Pós-Graduação em Meteorologia Agrícola.
II. Título.

CDD 22. ed.

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APPROVED: February 18, 2019.



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To my mother Lilia Ruth Brumatti de Souza

To my father Air de Souza Dias

ACKNOWLEDGMENTS

To God for all the blessings poured into my life and during this walk.

To my parents and my brother for all the support, advice and understanding during this walk and during my life.

To my advisor, Professor Gabrielle, for all the teachings and patience since the beginning of my scientific career. For believing that I could accomplish this work.

To my co-advisor, Professor Marcos, for all the teachings since ENG 321 classes and scientific initiation. For all the opportunities offered to me and for starting my scientific career.

To Aninha, for all the help with maps of 2016 productivity and planted area, and for the friendship.

To Gabriel, for all the advices and help during the analysis.

To Luiz, for all the patience and support during the end of this trajectory.

To my lab friends: Lais, José Ricardo, Bianca and Lara, for all the good times lived during this 2 years and for all the shared knowledge.

To Graça, for all the support in academic life.

To all professors for each knowledge taught.

To all my friends: Lara, Yan, Fernando, Ana Maria and Vitor, that have always been there for me.

To all the friends of applied meteorology program.

To Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for the financial support.

To UFV and Viçosa, for being my home for 7 years.

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LISTS OF ACRONYMS

A_{2016}	Planted area of maize or soybean for 2016
GR	Gross revenue variation from 2011-2020 to 2041-2050
$P_{2011-2016}$	Average of maize and soybean prices for the 2011-2016 period
$S_{100}M_{120}$	Hybrid combination with soybean and maize with a phenological cycle duration of 100 and 120, respectively
$S_{100}M_{100}$	Hybrid combination with soybean and maize both with a phenological cycle duration of 100 days
$S_{90}M_{90}$	Hybrid combination with soybean and maize both with a phenological cycle duration of 90 days
Y	Second crop maize productivity change from 2011-2020 to 2041-2050, in percentage
Y_{firstdec}	Average second crop maize productivity from 2011-2020
Y_{lastdec}	Average second crop maize productivity from 2041-2050
Y_{2016}	Productivity of maize or soybean for 2016

LIST OF SYMBOLS

CMIP5	Coupled Model Intercomparison Project Phase 5
IBGE	INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA
INLAND	Integrated Model of Land Surface Processes
IPCC-AR5	Intergovernmental Panel on Climate Change – Fifth Assessment Report
LUCID	Land-Use and Climate, Identification of Robust Impacts
MATOPIBA	Agricultural region formed by Brazilian states of Maranhão, Tocantins, Piauí and Bahia
MT	Mato Grosso
RCP	Representative Concentration Pathways
RCP 8.5	Climate scenario which assumes that climate change leads to a radiative forcing of about 8.5 W.m^{-2} in 2100
RCP 8.5 + HLU	Climate scenario which assumes that climate change leads to a radiative forcing of about 8.5 W.m^{-2} in 2100 and land use trajectory is from Pires and Costa, (2010) deforestation scenarios
THRG	Terrestrial Hydrology Research Group

ABSTRACT

SOUZA, Livia Maria Brumatti de, M.Sc., Universidade Federal de Viçosa, February, 2019. **Assessment of future climate risk in double cropping systems for Brazil.** Advisor: Gabrielle Ferreira Pires. Co-advisor: Marcos Heil Costa

Brazil is one of the main producers and exporters of maize and soybean of the world, an economic activity that has great importance in the Brazilian economy. An agricultural practice that contributes to a high production of these grains is double cropping, widely adopted in the main producing regions: Mato Grosso and MATOPIBA. In this system, soybean is planted in the beginning of the rainy season to ensure that climatic conditions are still favorable to plant maize, in the same area and same agricultural calendar. However, in the next years it is expected a climate change as a consequence of changes in atmospheric composition and deforestation of Amazonia and Cerrado biomes. This would affect the sustainability of double cropping until the middle of century, due to a decrease in precipitation in the beginning of rainy season, which leads to a reduction of soybean productivity. Delaying soybean planting dates increase its productivity, but also causes a delay in maize planting dates, which may lead to losses in maize productivity. The goals of this work are to evaluate climate change effects on second crop maize and the sustainability of double cropping system until 2050, in the main producing regions. The simulations showed a decrease in maize productivity as soybean is planted later. The soybean planting date threshold that ensures an increase in soybean productivity without losses in maize productivity is October 05. Adaptation measures, such as the reduction of phenological cycle of both crops, were tested from the gross revenue for the system in the future, considering that planting dates do not change until 2050. Total cycle lengths of the system of about 220, 200 and 180 days showed that as total cycle duration reduces, the gross revenue of the system increases, being 180 days combination the one that has higher gross revenue in MT. In a scenario with intense deforestation, the suggested adaptation measure does not attenuate the effects of climate change and leads to lower gross revenue values. In MATOPIBA, the reduction in the total phenological cycle of the system does not reduce the climate change effects in any scenario. The analysis of gross revenue showed that even the combination of cultivars with shorter cycle length could not achieve or exceed the

reference gross revenue. Other adaptation measures should be adopted together with cultivars adaptation in MT. The climate change effects in MATOPIBA might be stronger and adaptation measures need to be more intense than in MT.

RESUMO

SOUZA, Livia Maria Brumatti de, M.Sc., Universidade Federal de Viçosa, fevereiro de 2019. **Avaliação do risco climático futuro em sistemas safra-safrinha para o Brasil**. Orientadora: Gabrielle Ferreira Pires. Coorientador: Marcos Heil Costa.

O Brasil é um dos principais produtores e exportadores de soja e milho do mundo, atividade econômica que desempenha importante papel para a economia nacional. Uma prática agrícola que obtém grandes rendimentos de soja e milho conjuntamente e que contribui para o destaque na produção desses dois grãos é a adoção dos sistemas safra-safrinha, bastante aplicados em duas grandes regiões produtoras: Mato Grosso e MATOPIBA. Nestes sistemas, a soja é plantada no início da estação chuvosa para garantir que as condições climáticas sejam ainda favoráveis para plantar o milho, sobre a mesma área e no mesmo calendário agrícola. Entretanto, é previsto que as mudanças climáticas causadas pela mudança na composição atmosférica e o desmatamento de biomas naturais como Amazônia e Cerrado, podem ameaçar a sustentabilidade desses sistemas até o meio do século, devido à redução da precipitação durante o início da estação chuvosa, o que provoca perdas de produtividade na soja. O atraso do plantio da soja garante um aumento de sua produtividade, porém acarreta no atraso das datas de plantio do milho, o que coloca em risco a segunda safra. O objetivo deste trabalho foi avaliar os impactos das mudanças climáticas no milho de segunda safra e avaliar, conjuntamente com a soja, a sustentabilidade desses sistemas em cenários futuros. Nossas simulações mostraram uma redução na produtividade do milho à medida que se atrasa seu plantio devido ao atraso no plantio da soja. Uma data limite para o plantio da soja que ocasione um aumento da sua produtividade e que não cause perdas de produtividade no milho é 05 de Outubro. Medidas de adaptação como a redução do tamanho do ciclo fenológico para ambas as culturas foram testadas a partir do impacto na receita bruta do sistema safra-safrinha, considerando que as datas de plantio continuem as mesmas até 2050. Durações de ciclos totais do sistema safra-safrinha de 220, 200 e 180 dias mostraram que à medida que se reduz a duração total do ciclo, maior a receita bruta, sendo a combinação com um total de 180 dias a que mostrou maiores valores, para a região do Mato Grosso. Em cenário com desmatamento intenso, a medida de adaptação sugerida não atenua os efeitos das mudanças climáticas e leva a menores valores de

receita bruta. No MATOPIBA, a redução no ciclo fenológico total do sistema não reduz os efeitos das mudanças climáticas em nenhum cenário. Nossa análise de receita bruta mostrou que mesmo usando a combinação de cultivares com menor duração de ciclo não foi possível atingir ou ultrapassar a receita bruta de referência. Outras medidas de adaptação devem ser adotadas conjuntamente com a adaptação de cultivar para o Mato Grosso. Para o MATOPIBA, os efeitos da mudança climática podem ser intensos até o meio do século, portanto a adoção dessas medidas de adaptação deve ser mais intensa do que no MT.

1. INTRODUCTION

Brazil is the third largest producer and exporter of maize in the world (FAO, 2017). The cultivation of maize, in Brazil, occurs in two harvests: a first crop planted during the beginning or middle of the rainy season and a second crop that starts to be planted in the end of rainy season, after soybean, other important crop for Brazilian economy (the country is the second biggest soybean producer in the world (FAO, 2017)). During the last decade, total maize Brazilian production increased nearly 35% (CONAB, 2018). In the same period, the second crop maize production increased from 30% to 70% of total maize production from 2007 to 2017 (CONAB, 2018) (Fig. 1). One of the drivers of this increase in maize production was the intensification of agriculture through the widespread adoption of soy-maize double cropping systems.

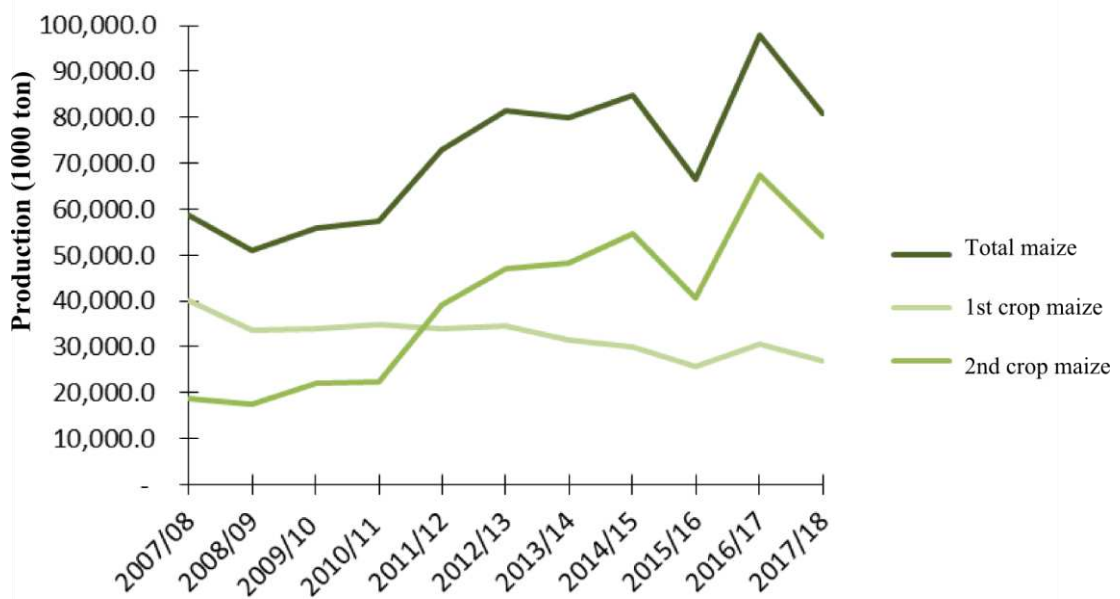


Figure 1 – Maize production for each crop in the last ten years.

Source: CONAB, 2018

Soy-maize double cropping is the most common type of double cropping system in Brazil, however soybean followed by cotton is found in some places (USDA, 2016). This type of agricultural system is characterized by planting a short-cycle of soybean sowed right after sanitary break followed by maize, on the same

area, in the same agricultural calendar (PIRES et al., 2016; ABRAHÃO and COSTA, 2018; NOIA JUNIOR and SENTELHAS, 2019).

The second crop maize, known as milho safrinha, is sown between months of January to June, depending on the state, after soybean is harvested (CONAB, 2016). In this time of the year precipitation, mean temperatures and photoperiod reduce, mainly in the southern region of the country (BORÉM et al., 2015). The reduction of these climatic variables over the months can influence the second crop maize yield according to the choice of the planting date. The later the second crop is planted, the smaller is its productivity due to, mainly, water stress in the end of growing season (HEINEMANN et al., 2008; GARCIA et al., 2018; NÓIA JUNIOR and SENTELHAS, 2019). In fact, flowering and grain filling are the stages of maize development that are more sensitive to water stress impacts in yield (LLANO and VARGAS, 2016; HEINEMANN et al., 2008). Moreover, in Brazil, the variability of maize yield can be explained, mainly, by the precipitation (RAY et al., 2015; LLANO and VARGAS, 2016; SAKURAI et al., 2011; NÓIA JUNIOR and SENTELHAS, 2019) as the production systems are predominantly rainfed.

In the future, it is predicted an increase of temperature, changes in the patterns of precipitation, mainly during the transition months of dry to wet season, and a reduction of the rainy season duration due to climate change caused by changes in atmospheric composition (FU et al., 2013; BOISIER et al., 2015) and deforestation of Cerrado and Amazonia (COSTA and PIRES, 2010; PIRES and COSTA, 2013). This can be a threatening situation to double cropping in the future, since these systems are mainly rainfed and adopted in places with high annual rainfall, long rainy season and with low variability of the onset of the rainy season (ARVOR et al., 2014).

The reduction of rainy season length might decrease the area of double cropping in Brazil by about 10 % until 2050 (ABRAHÃO and COSTA, 2018). The climate change could affect not only double cropping area, but also soybean and maize productivity.

The impacts of climate change on the first of the two crop, soybean, were studied by PIRES et al., (2016). From a modeling study with a pessimistic climate change scenario, these authors found that planting soybean right after sanitary break in Mato Grosso and in a region formed by Brazilian states of Maranhão, Tocantins, Piauí and Bahia, known as MATOPIBA, until 2050 might cause losses in soybean

productivity due to a reduction of precipitation in the transition months of dry to rainy season. In addition, in a scenario with additional deforestation of the Amazon and Cerrado biomes, the losses increased. A possible solution suggested by the authors was to shift soybean planting date to early October, when soybean productivity could slightly increase while it is still possible to plant a second crop.

However, as mentioned before, the climatic conditions during the growing season of maize off-season are increasingly less favorable, and the delay in soybean planting dates causes losses in maize productivity, even without considering climate change (NÓIA JUNIOR and SENTELHAS, 2019). Indeed, in a climate change scenario such conditions are even worse.

A year-to-year climate variability analysis of Mato Grosso state, presents to second crop maize a progressive decrease in productivity for an increase of 1 °C in the local mean temperature with a progressive reduction until 30 % in mean precipitation (COHN et al., 2016). In this study, the sensitivity of second crop area and yield to climate is spread in the entire growing calendar (August to July) due to the delay in planting dates of soybean or limitation of the available soil moisture for the second crop.

In these previous studies, the impacts of climate change were not assessed in both crops together, with respect to their planting dates, to evaluate the viability of double cropping agricultural systems in the future. Therefore, there is a need to evaluate the impact of climate change in productivity of second crop maize according to planting dates of soybean for these regions and to investigate the viability of the double cropping in the future, as well as possible alternatives for adaptation. In other words, a full assessment of the future viability of double cropping should also include modeling the second crop maize productivity under future climatic conditions.

Therefore, to maintain these systems highly productive, it is necessary to understand the dynamics of double cropping systems in the future in the face of climate change as a way of predicting losses and assisting strategies to reduce losses.

2. OBJECTIVES

2.1. General objective

Evaluate the effects of climate change caused by changes in atmospheric composition and deforestation on second crop maize productivity and in the sustainability of soy-maize double cropping system for Brazil in different climate scenarios.

2.2. Specific objectives

- a) Evaluate the changes in second crop maize productivity after climate change caused by changes in atmospheric composition and low levels of deforestation;
- b) Evaluate the changes in second crop maize productivity after climate change caused by changes in atmospheric composition and high levels of deforestation;
- c) Evaluate the sustainability of soy-maize double cropping system in different future climate change scenarios.

3. METHODS

3.1. Study area

I evaluated the effect of climate change in productivity of second crop maize for the main soybean productive regions in Brazil. I considered that the regions that currently grow soybean either already have or are potential areas to implement double cropping systems in the future.

I isolated the pixels that have at least 5% of soybean planted area in 2016. The planted area of 2016 was obtained by converting the tabular data of soybean area from Instituto Brasileiro de Geografia e Estatística (IBGE) to a gridded map. For this, I calculate the ratio between the soybean planted area and the total cropland of Dias et al., (2016) for each micro region. In the absence of 2016, I used the last year (2012) of Dias et al., (2016) data to calculate the ratio. Next, I obtained the soybean map for 2016 by multiplying the micro region ratio and the amount of crop area for each grid cell (map data of 2012).

I focused the results in two regions, Mato Grosso state (MT) and MATOPIBA (Fig. 2). Mato Grosso state had the highest production of soybean and second crop maize in Brazil in the year of 2017 (IBGE, 2018). In addition, MATOPIBA region, even though is not among the greatest producers in the country, has received large investments in the last years, and it is a potential region to expand agriculture.

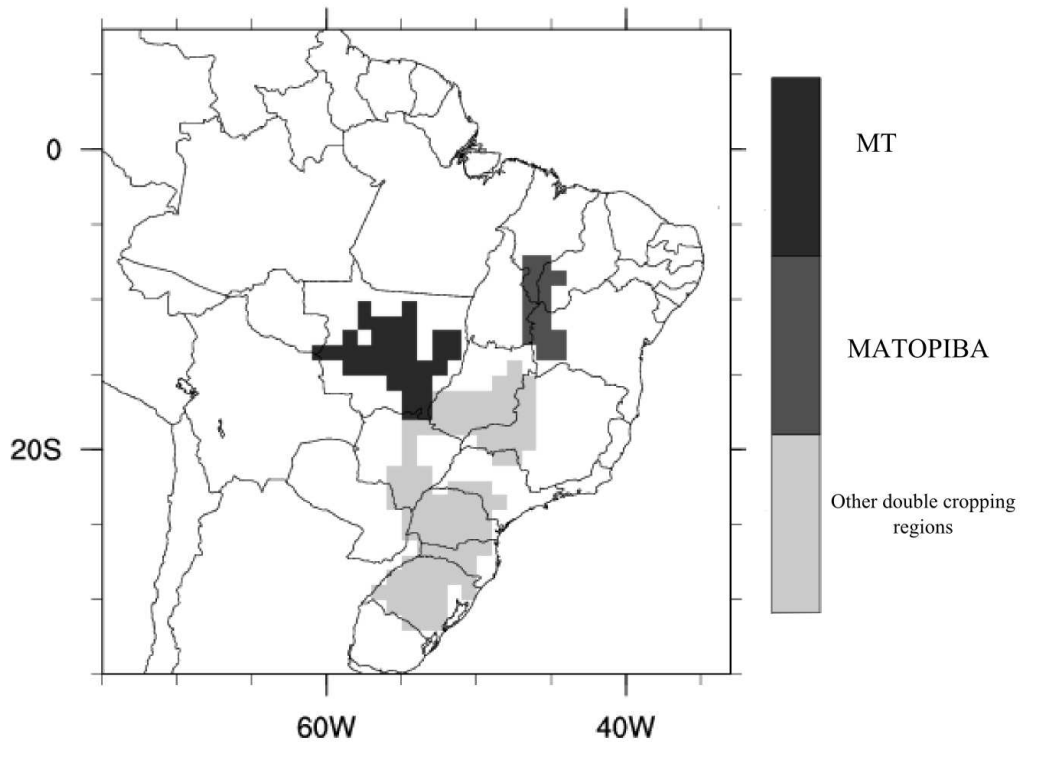


Figure 2 – Study area with at least 5 % of pixel area with soybean in 2016.

3.2. Gridded crop model description

In this work I used the Integrated Model of Land Surface Processes (INLAND), to simulate the productivity of maize throughout the analysis period.

INLAND is a model developed by Brazilian researchers to better represent the Brazilian biomes and the processes that occur in the Brazilian territory, such as, fire, flood and agricultural crops. INLAND is a mechanistic model that considers the balance of water, energy, carbon and momentum of the soil-vegetation-atmosphere system, canopy physiology and the terrestrial carbon balance. It was based on Agro-IBIS model (KUCHARIK and TWINE, 2007), and the version used in this work was the 2.0, that contains 16 plant functional types (PFT), which 12 represent natural vegetation and 4 represent agricultural crops (maize, soybean, sugarcane and wheat).

In maize simulations, I used a daily time step and a spatial resolution of $1^{\circ} \times 1^{\circ}$ (~ 110 km x 110 km). I run a spin-up period of four years for the model to approach an equilibrium state. The model was forced by meteorological data described in section 3.3. The cultivars were chosen according to growing degree days

(GDD) for maturity and the basal temperature, so that it could reach the current number of days of maize phenological cycle described in section 3.4.

This model was used in other works simulating the effect of climate change in soybean productivity for Brazil (PIRES et al., 2016) or evaluating the influence of interannual climate variability, fire and phosphorus limitation on Amazon–Cerrado transitional vegetation structure and dynamics (DIONIZIO et al., 2018).

3.3. Climate scenarios and input data

Two climatic scenarios were used in this work. One that considers the change in atmospheric composition with low levels of deforestation in Cerrado and Amazonia biomes, and other, that considers the change in atmosphere composition with high levels of deforestation in Cerrado and Amazonia biomes. In the scenario with low levels of deforestation, the deforestation levels are according to CMIP5, however they are underestimated for 2050, reaching values of 20 % and 60 % to Amazonia and Cerrado biomes, respectively, and in the reality these deforestation levels are close to the current ones (PIRES et al., 2016).

For the scenario that considers the change in atmosphere composition with low levels of deforestation, I used the emission scenario of CMIP5 (Coupled Model Intercomparison Project Phase 5) presented in the IPCC-AR5 (Intergovernmental Panel on Climate Change – Fifth Assessment Report) known as Representative Concentration Pathways (RCPs). The RCPs vary according to the value of radiative forcing until the year 2100. Here I used RCP 8.5, which considers the value of radiative forcing of 8.5 W.m^{-2} in 2100. This emission scenario is the most pessimistic one, but it is closer to the current emissions (FUSS et al., 2014). During the analysis period (2011-2050), the atmospheric CO_2 concentration ranges from 387 to 541 ppmv.

To reduce the individual bias related to climate models, I used climate data input from four models: HadGEM2-ES, MIROC-ESM, NorESM2-M e MRI-CGCM3. These models represent better the seasonal patterns of precipitation and the beginning and end of rainy season in the main soybean productive regions, hence in potential second crop maize productive regions. This was demonstrated by Pires et

al., (2016), comparing with the seasonal patterns of precipitation from database set of Terrestrial Hydrology Research Group (THRG) (SHEFFIELD et al., 2006).

For the scenario that considers the change in atmosphere composition with high levels of deforestation, I used the scenario RCP 8.5 + HLU created by Pires et al., (2016). This scenario is based in two datasets: first the simulations of CMIP5 that had the effect of land use change fixed are presented in LUCID (Land-Use and Climate, Identification of Robust Impacts) (BROVKIN et al., 2013) project, L2A85 experiment. In this experiment, the atmosphere composition is the same as in RCP 8.5, however the land use is fixed in 2005. Second, the effect of deforestation was simulated by adding the climate anomaly of deforestation scenarios from Pires and Costa (2013). In this scenarios, the deforestation levels in Amazonia and Cerrado biomes reached 40% and 70%, respectively, until the middle of century.

For both scenarios, the climatic variables used as daily input data in simulations, are: precipitation, incoming solar radiation, minimum, mean and maximum temperatures, specific humidity and wind speed.

3.4. Soybean and maize planting dates and cultivars

The planting dates of second crop maize were determined from the planting dates and length of phenological cycle of short-cycle soybean. Pires et al., (2016) considered that the length of phenological cycle of short-cycle soybean is 100 days, and the planting dates used are: September 15, September 25, October 05, October 10, October 25, November 05, November 15, November 25, December 05 and December 15.

Based on the dates of the first crop, and considering that the time between harvesting soybean and planting maize might take up to 20 days in an average-sized farm, I defined the planting dates of second crop maize as: January 13, January 23, February 02, February 12, February 22, March 04, March 14, March 24, April 03, April 13, April 23, May 03, May 13, May 23, June 02, June 12 and June 22. They total 17 planting dates to account for all the sowing season in each different state in Brazil according to CONAB (2016). In this experiment design, I cover a wide range of planting dates and cultivars that might occur in the field.

To achieve the second crop maize planting dates described above I considered that the operation of harvesting soybean and sowing maize occurs at the same time,

such as in the field. I assume that the last day of this operation is the planting date of maize used in simulations with the purpose to evaluate the worst-case situation: the maize sowed later.

The planting window of soybean in MATOPIBA region and Mato Grosso (MT) state vary, respectively, from September to February and from September to December. Maize planting window in these same regions vary, respectively, from February to June and from January to March, according to Table 1.

Table 1 – Planting calendar of soybean and maize in MT and MATOPIBA region.

Brazilian states	Soybean planting period	Maize planting period
MT	September to December	January to March
MA	September to February	February to April
TO	September to December	February to May
PI	October to January	March to June
BA	September to December	April to June

Source: CONAB, (2016).

I considered the length of the phenological cycle of second crop maize nearly 120 days. In maize simulation, I used the maize cultivar that reaches 1900 GDD, considering base temperature of 10 °C. To evaluate the adaptation of the double cropping system to climate change through the adoption of short-cycle maize cultivars, I simulated two more hybrids that reach 1600 GDD and 1500 GDD (both with base temperature of 10 °C), which is equivalent to 100 days and 90 days of duration of phenological cycle, respectively, for the study region. Soybean cultivar of about 90 days (1500 GDD) and 100 days (1600 GDD) used in this work was obtained from Pires et al., (2016).

3.5. Quantification of climate change effects on maize (safrinha) productivity

The quantification of the effects of climate change in short-cycle soybean in MATOPIBA and MT was conducted by Pires et al., (2016) from 2011 to 2050 period. I used a similar method in the quantification of maize productivity. The method is described below.

The effects of climate change on maize productivity were evaluated in a 40-year period, from 2011 to 2050. These effects were quantified from the average productivity of the first (2011-2020) and last decade (2041-2050) of the analysis period. The variation of productivity (Y) was calculated from the difference of last decade yield ($Y_{lastdec}$) to the first decade yield ($Y_{firstdec}$), and then, this difference was divided by the average maize productivity of the first decade (Eq. 1).

$$Y (\%) = \frac{Y_{lastdec} - Y_{firstdec}}{Y_{firstdec}} \times 100 \quad (\text{Eq. 1})$$

Considering that no adaptation occurs in the planting dates on the transition from the beginning to the end of the analysis period, I used Eq. 1 to quantify the effects of climate change for the same planting dates on the first and last decades. To account for a possible adaptation to climate change through a delay in planting dates, I also evaluated the climate change effects in maize productivity changing the planting date for the last decade with a delay of 10 and 20 days in relation to the planting date from first decade. Each calculation is executed for each pixel in the study area (Fig. 2).

3.6. Evaluation of the sustainability of double cropping systems

The viability of double-cropping systems in the future under climate change scenarios was evaluated combining the simulations of maize from each climatic scenario described in section 3.3 with the short-cycle soybean simulations of Pires et al., (2016), that were both conducted for the same scenarios, time-period, climate and crop models.

I called the combination of soybean that reaches 100 days and maize that reaches 120 days of length of phenological cycle, totaling 220 days for the entire double cropping for each calendar (Table 2), as $S_{100}M_{120}$. I assumed that the total cycle of this hybrid combination approaches better from the total cycle used in double cropping system in the study area. I used two more combinations of soybean and maize cycle length, with the purpose to discuss the future adaptation of double cropping systems to a shorter rainy season. I called $S_{100}M_{100}$ the hybrid combination of 100 days of phenological cycle for each crop (soybean and maize) with a total of 200 days of phenological cycle for the system (Table 3). In $S_{100}M_{100}$ I assumed that the adaptation occurs only in maize hybrid, with the purpose of reducing the

phenological cycle, and hence, the productivity of the crop with lower market price to ensure the system profitability. In the last combination, that I called S₉₀M₉₀, I considered the possibility that an intensive adaptation of hybrids occurs in the future. In this combination, the phenological cycle of soybean and maize is about 90 days long and the system has about 180 days of total cycle (Table 4).

Finally, I evaluated the viability of double cropping system in the future from the gross revenue. I decided to evaluate the gross revenue of the system, since the most part of the producers that choose to adopt soy-maize double cropping system export both crops (USDA, 2016) and adopt the system to compensate when one crop has lower prices (ARVOR et al., 2012). Moreover, soybean prices in the last years are almost the double of maize prices (FAOSTAT, 2018), so the analysis considering the prices of both crops allows the assessment of the impact of climate change in the system with more practical view. It might facilitate the evaluation of adaptation measures from the knowledge of which crop influences more in the total final price of the double cropping system.

I calculated the gross revenue variation (GR, USD) as a multiplication of the 2016 productivity (Y_{2016} , ton.ha⁻¹), the 2016 planted area (A_{2016} , ha), the productivity relation of last to first decade ($\frac{Y_{lastdec}}{Y_{firstdec}}$, %) and the average 2011-2016 soy and maize prices (414.58 USD/ton and 198.75 USD/ton, respectively) ($P_{2011-2016}$) (FAOSTAT, 2018) (Eq. 2).

$$GR = Y_{2016} \times A_{2016} \times \frac{Y_{lastdec}}{Y_{firstdec}} \times P_{2011-2016} \quad (\text{Eq. 2})$$

The planted area of 2016 was obtained by converting the tabular data of soybean and second crop maize planted area from Instituto Brasileiro de Geografia e Estatística (IBGE) to a gridded map, like described in item 3.1. The productivity of 2016 for soybean and second crop maize was obtained by the ratio between production and planted area for each crop in tabular form and for each micro region from IBGE.

In this analyze, the planted area in MT and MATOPIBA remains the same for both periods and are 6.77×10^6 ha and 2.22×10^6 ha for soybean and 3.35×10^6 ha and 9.25×10^4 ha for second crop maize, respectively. These values

were filtered to study area represented in Fig. 2. Thus, I consider that the deforested areas of biomes are converted into pasture instead of new soybean or maize planted areas.

Table 2 – Soybean and maize planting dates and estimated harvest dates for $S_{100} M_{120}$

Soybean (100 days) planting date *	Soybean (100 days) harvest date	Time to harvest and plant (days)	Maize (120 days) planting date	Maize (120 days) harvest date
September 25	January 03	20	January 23	May 21
October 05	January 13	20	February 02	May 31
October 15	January 23	20	February 12	June 10
October 25	February 02	20	February 22	June 20
November 05	February 12	20	March 04	June 30
November 15	February 22	20	March 14	July 10
November 25	March 04	20	March 24	July 20
December 05	March 14	20	April 03	July 30
December 15	March 24	20	April 13	August 10

* Planting dates from Pires et al., (2016).

Table 3 – Soybean and maize planting dates and estimated harvest dates for $S_{100} M_{100}$

Soybean (100 days) planting date *	Soybean (100 days) harvest date	Time to harvest and plant (days)	Maize (100 days) planting date	Maize (100 days) harvest date
September 25	January 03	20	January 23	May 02
October 05	January 13	20	February 02	May 12
October 15	January 23	20	February 12	May 22
October 25	February 02	20	February 22	June 01
November 05	February 12	20	March 04	June 11
November 15	February 22	20	March 14	June 21
November 25	March 04	20	March 24	July 02
December 05	March 14	20	April 03	July 12
December 15	March 24	20	April 13	July 22

* Planting dates from Pires et al., (2016).

Table 4 – Soybean and maize planting dates and estimated harvest dates for *S₉₀ M₉₀*

Soybean (90 days) planting date *	Soybean (90 days) harvest date	Time to harvest and plant (days)	Maize (90 days) planting date	Maize (90 days) harvest date
September 25	December 24	20	January 13	April 13
October 05	January 03	20	January 23	April 23
October 15	January 13	20	February 02	May 2
October 25	January 23	20	February 12	May 12
November 05	February 02	20	February 22	May 22
November 15	February 12	20	March 04	June 01
November 25	February 22	20	March 14	June 11
December 05	March 04	20	March 24	June 21
December 15	March 14	20	April 03	July 01

* Planting dates from Pires et al., (2016).

3.7. Significance tests

I used the Student's t-test, with 5% level of significance and n=10 years, to evaluate the hypothesis that second crop maize productivity in the last decade (2041-2050) is different from the productivity of the first decade (2011-2020) due to future climate change. This statistical analysis was applied to each group of simulations determined by climates scenarios.

Pires et al., (2016), using the same significance test under the same conditions described above, found that changes in soybean productivity from the 2041-2050 to 2011-2020 period was statistically significant in MT and MATOPIBA.

4. RESULTS

4.1. Effects of climate change on second crop maize productivity

The simulations of maize with 120 days of phenological cycle indicate that, in both climate scenarios, the changes in maize productivity from 2011-2020 to 2041-2050 varies spatially and with the planting date (Fig. 3).

The months of January, February and March are those recommended to plant second crop maize in MT and in MATOPIBA according to climatic risk agricultural zoning obtained in Agritempo platform (<http://www.agritempo.gov.br>). These months present a different behavior in changes in maize productivity than in the months after March.

For planting dates taking place in January, losses in productivity do not occur if we keep the planting date in 2041-2050 the same as it is in 2011-2020. However, delaying planting dates reduces the gain in maize productivity. From February to June, maize productivity losses are predicted if the planting date is kept constant throughout the analysis period.

In February, yield losses of 5% start to appear in MATOPIBA in the middle of the month, more precisely in western Bahia state in RCP 8.5 (Fig. 3 b). For RCP 8.5 + HLU, the losses in this region start to appear only in the end of March (APPENDIX A, Fig. A.2). In MT, losses of 5% in productivity in February 22 in RCP 8.5 scenario may occur (APPENDIX A, Fig. A.1). These losses occur earlier in the RCP 8.5 + HLU for MT, more precisely in February 12 (Fig. 3 h).

Planting in the middle of March causes losses in maize productivity, mainly in south of MT and MATOPIBA, for RCP 8.5 scenario, with losses greater than 10 % (Fig. 3 c). In MATOPIBA, the losses were significant and are worrisome to Bahia and Piauí, states that begin to sow second crop during or after March. In RCP 8.5 + HLU scenario, the region most affected is MT, with a significant decrease in productivity in almost all the state (Fig. 3 i).

Sowing after the middle of March may be unviable. The losses in productivity increase more as planting dates are delayed, generating a fall in productivity in MT and MATOPIBA greater than 10 % in RCP 8.5 scenario (Fig. 3 d-f), with more significant pixels than other months. For RCP 8.5 + HLU scenario, the effect was smaller than in RCP 8.5 scenario in MATOPIBA region. The losses in MATOPIBA

occur mainly in April, month where sowing has already begun in almost all region, and increase in planting dates after the middle of the month, for both scenarios (Fig. 3 d-f,j-l).

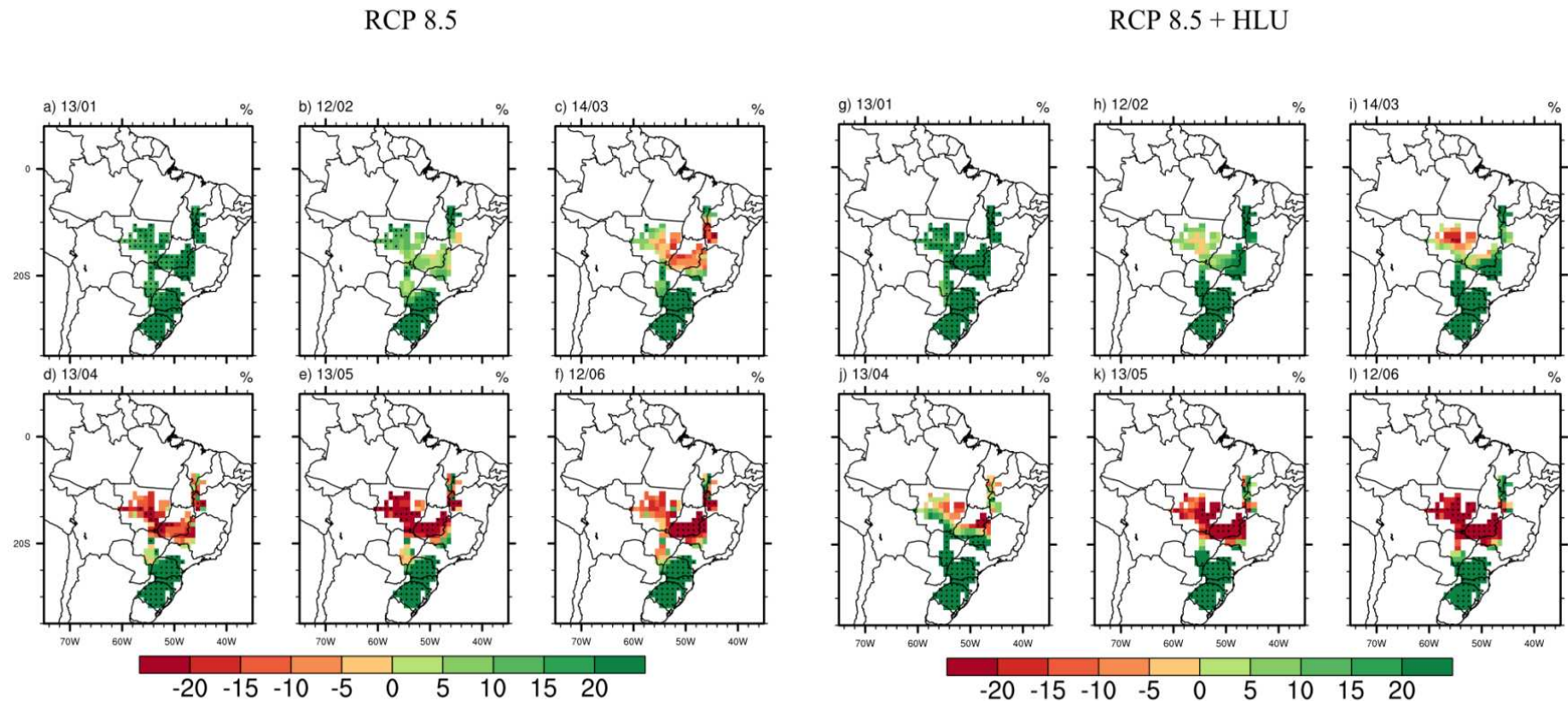


Figure 3 – Percentage change in second-crop maize yield from 2011-2020 to 2041-2050 for the middle of month. In a) to f) atmospheric composition and land use trajectories is according to RCP 8.5. In g) to k) atmospheric composition is according to RCP 8.5 and land use trajectories are according to Pires and Costa (2013) deforestation scenarios. The pixels with a dot are those that have statistically significant changes in productivity according to Student's t-test ($\alpha = 5\%$).

Delaying the planting dates in 10 days, with the aim to adapt to a later onset of the rainy season to ensure greater productivity of soybean proposed by Pires et al., (2016) results in a decrease in maize productivity for almost all planting dates in both scenarios.

The delay in January (Fig. 4 a-b) does not lead to expressive losses in productivity like in other months. In this case, productivity falls up to 10 % in some pixels of MT but is compensated by significant increase in productivity up to 10 % in northern of MT, in both climate scenarios (Fig. 4 a-b; Fig. 5 a-b).

For later months, the losses in productivity are higher. The more delayed are the planting dates, more losses occur in all regions, except for the southern region of the country. Significant losses in productivity reach up to 30 % when the planting date is March 4 instead of February 22 in the last decade in MT, in both scenarios (Fig. 4 e; Fig. 5 e). From this planting date until the beginning of May, the losses increase.

For MATOPIBA region, where maize starts to be planted in February (Table 1), the delay of up to 10 days in planting dates reach losses in productivity greater than 10 % and 30 %, for RCP 8.5 + HLU and RCP 8.5 respectively (Fig. 4 d; Fig. 5 d).

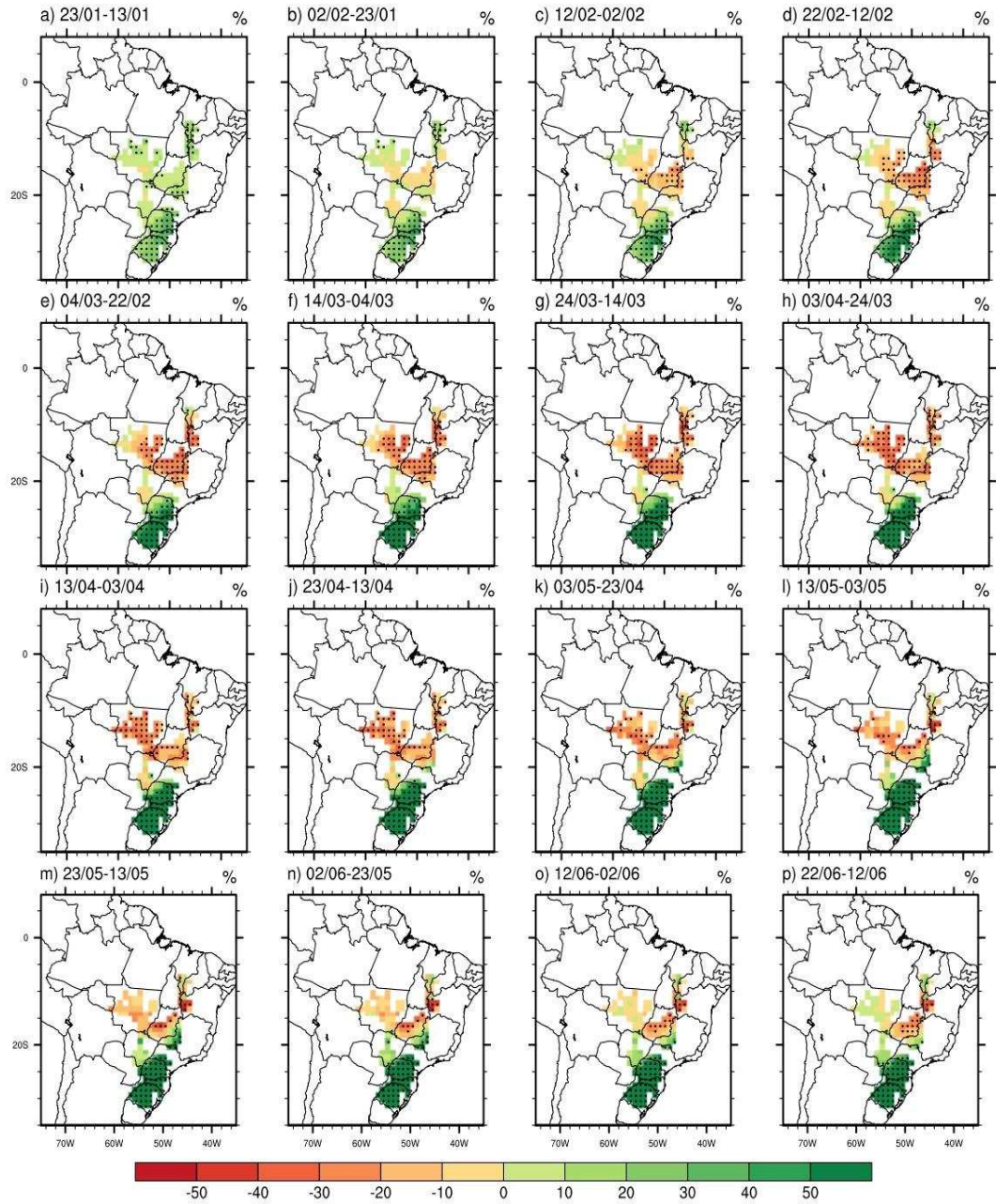


Figure 4 – Percentage change in second-crop maize yield from 2011-2020 to 2041-2050, considering a delay in planting date of 10 days in the middle of century for RCP 8.5 scenario. The pixels with a dot are those that have statistically significant changes in productivity according to Student's t-test ($\alpha = 5\%$).

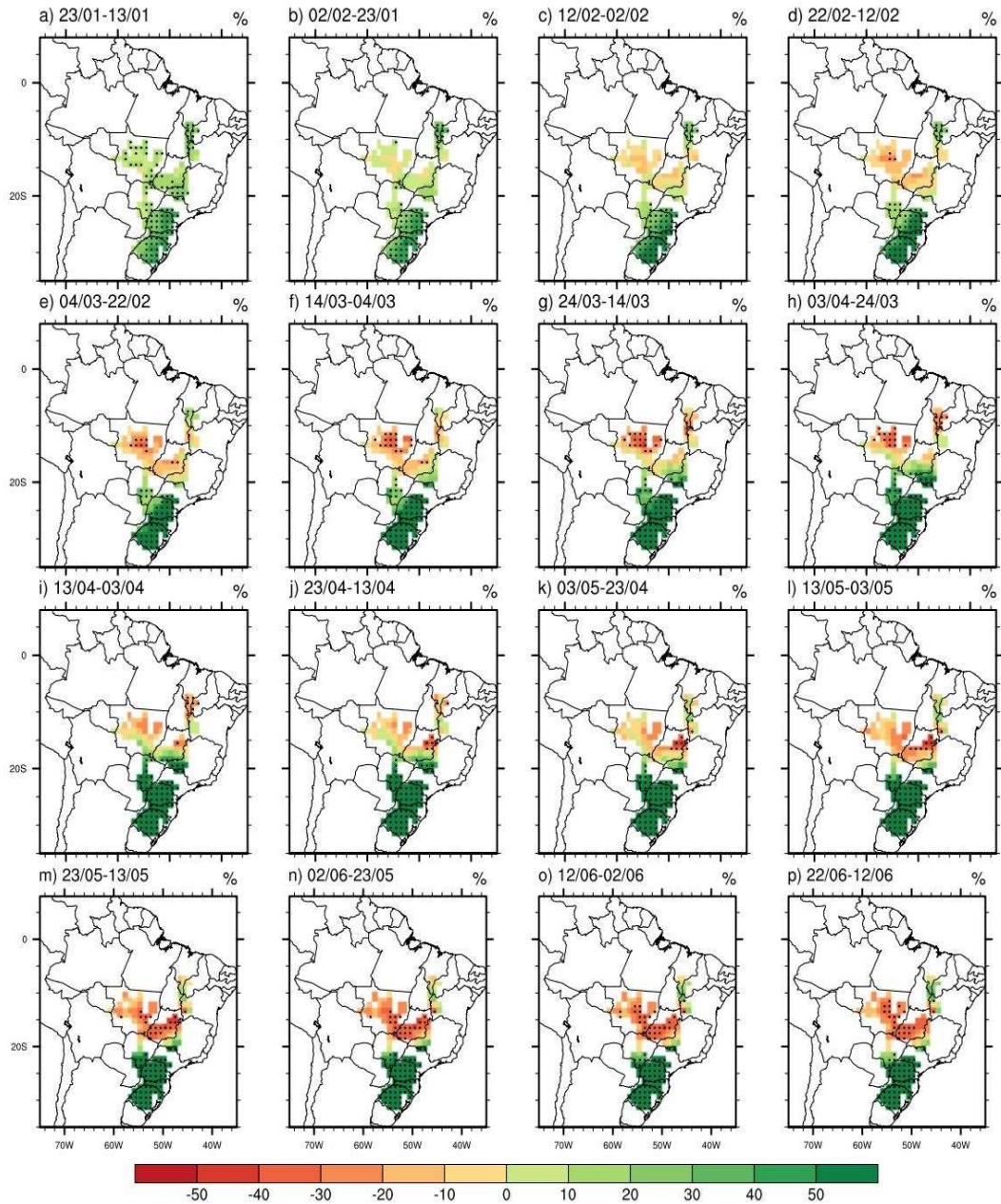


Figure 5 – Percentage change in second-crop maize yield from 2011-2020 to 2041-2050, considering a delay in planting date of 10 days in the middle of century for RCP 8.5 + HLU scenario. The pixels with a dot are those that have statistically significant changes in productivity according to Student's t-test ($\alpha = 5\%$).

When the delay in planting dates reaches 20 days, the effect is stronger and the losses in maize yield are greater than when the planting dates are delayed in 10 days, even in January and February months, for both scenarios.

In both scenarios, delaying the planting dates in 20 days from February is unviable for both regions, due to high losses in productivity (Fig. 6 and Fig. 7).

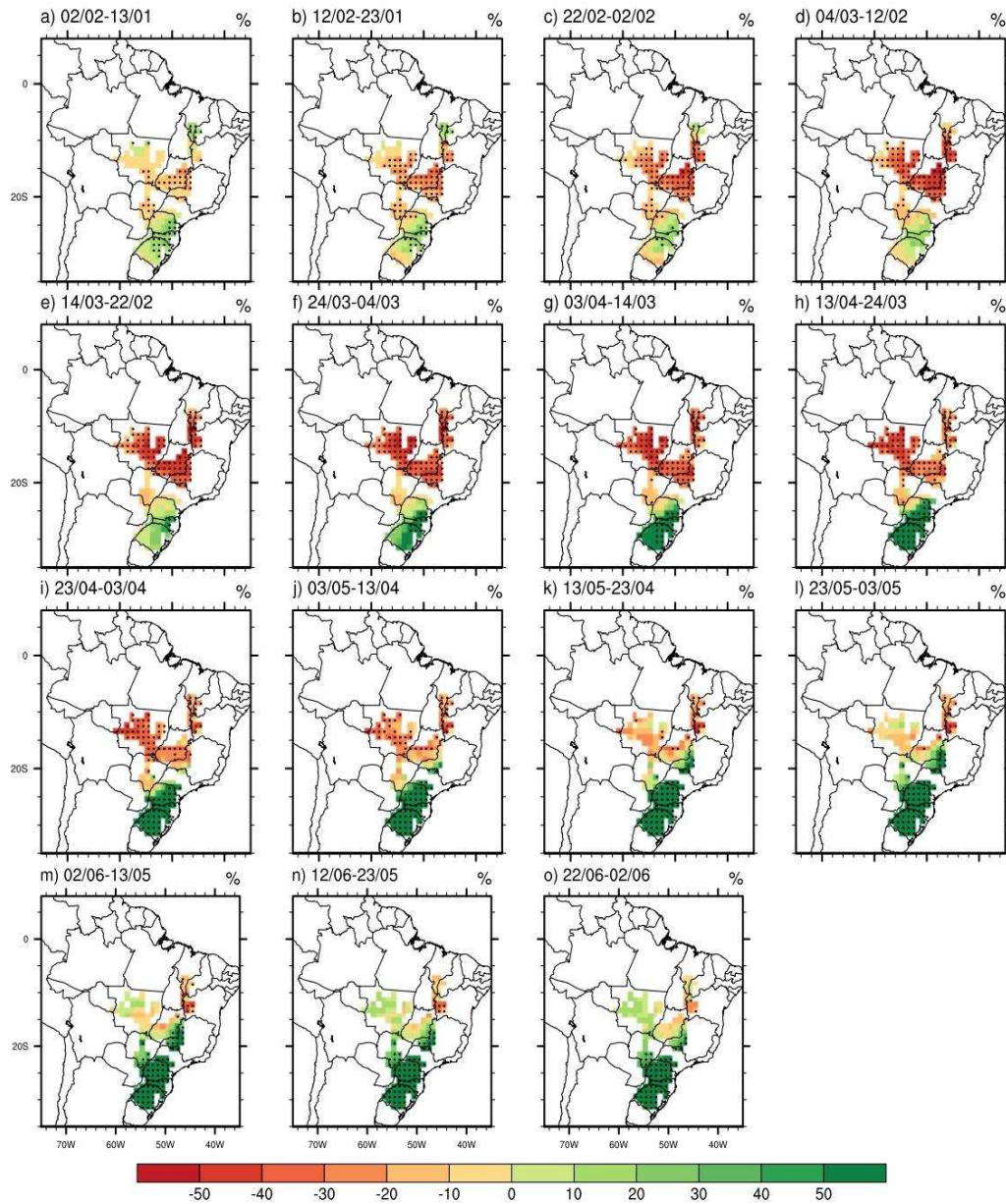


Figure 6 - Percentage change in second-crop maize yield from 2011-2020 to 2041-2050, considering a delay in planting date of 20 days in the middle of century for RCP 8.5 scenario. The pixels with a dot are those that have statistically significant changes in productivity according to Student's t-test ($\alpha = 5\%$).

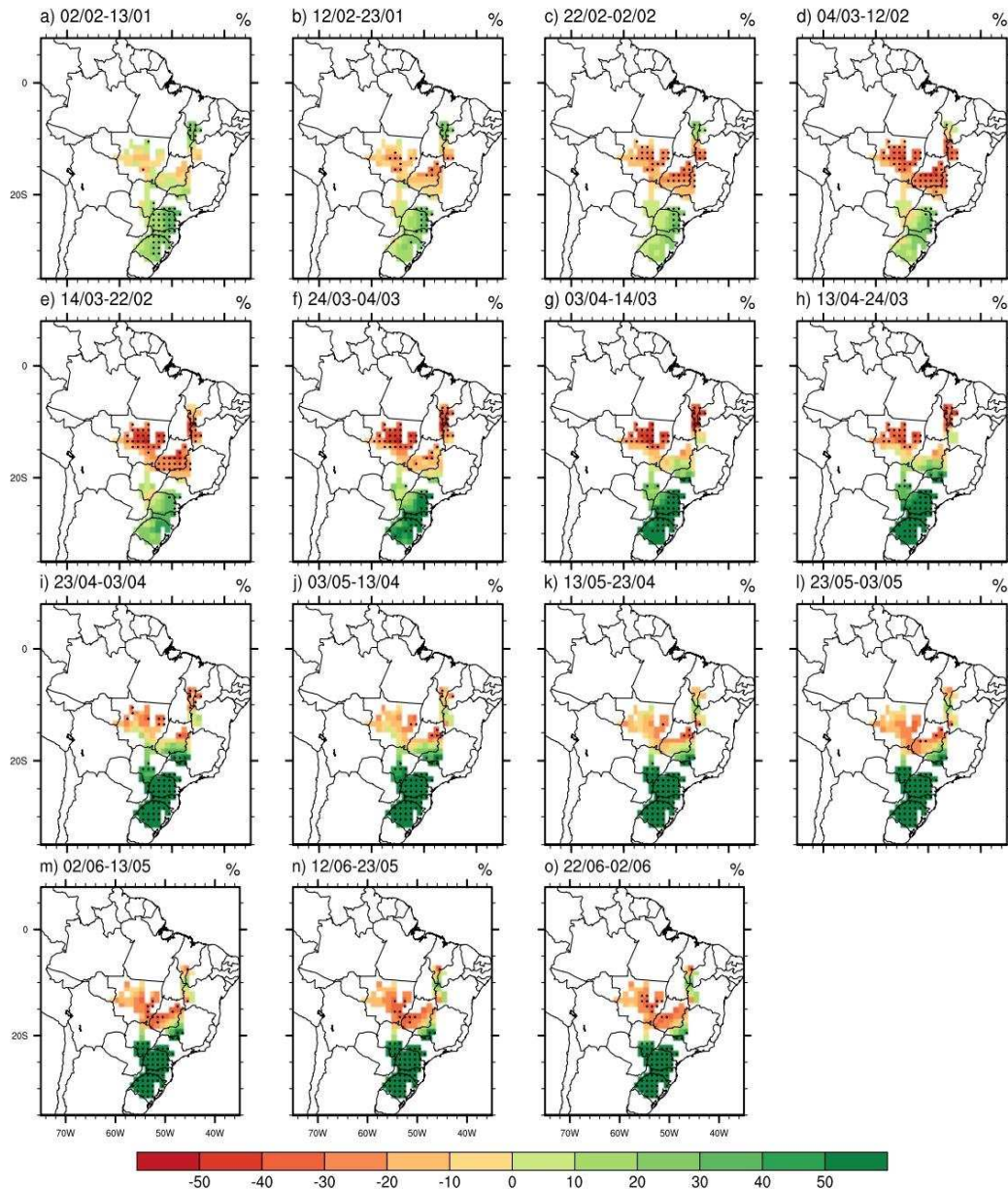


Figure 7 - Percentage change in second-crop maize yield from 2011-2020 to 2041-2050, considering a delay in planting date of 20 days in the middle of century for RCP 8.5 + HLU scenario. The pixels with a dot are those that have statistically significant changes in productivity according to Student's t-test ($\alpha = 5\%$).

4.2. Effects of climate change on double-cropping systems

To evaluate the sustainability of soy-maize double cropping system in the future, I combined the planting dates of soybean from Pires et al., (2016) with maize, according to the methodology described in section 3.6.

I assessed the gross revenue of double cropping system for the future, based on the gross revenue of 2016. For each region, the gross revenue was evaluated according to the planting and harvesting windows. In this case, soybean planting operation can only begin after the sanitary break, a period regulated in law, that determines the time period when live soybean plants are not allowed in the field, with the aim to control Asian soybean rust. In MT, this period begins in June 15 and ends in September 15 (INDEA, 2015). On the other hand, MATOPIBA sanitary break period is between July 1 and October 15, within the study area (ADAPEC, 2016; AGED-MA, 2013; ADAB, 2017; ADAPI, 2018). After the end of this period, the farmers can start to plant soybean.

Considering the sanitary break, I evaluated the gross revenue of the system from September 25 and from October 25 for MT and MATOPIBA, respectively. In general, the more the soybean planting dates are delayed, the greater is its gross revenue. In contrast, the maize gross revenue is smaller as planting dates are delayed, due to a decrease in productivity caused by climate change and decrease in precipitation, photoperiod and temperature due to beginning of dry season, for both climatic scenarios (Fig. 10 a-b; Fig. 11 a-b). This decrease and increase in yield for maize and soybean, respectively are demonstrated in Fig. 8 for RCP 8.5 scenario and in Fig. 9 for RCP 8.5 + HLU. However, on the planting dates from November there is an increase in gross revenue caused by an increase in precipitation and temperature. However, these conditions may also lead to higher likelihood of infection of Asian rust in soybean, which causes a decrease in productivity. The model used in soybean simulations does not consider the effects of this disease in productivity and might be overestimating the gross revenue of soybean from November on.

The climate change effect for the analysis period is more harmful in soybean gross revenue than in maize, for both scenarios (Fig. 10; Fig. 11) due to more intense climate change effect in the transition of dry to rainy season, when soybean is

planted. The variation of gross revenue among planting dates is greater due to higher impacts in soybean yield.

The hybrid combination $S_{100}M_{120}$ with a total phenological cycle of 220 days indicates that there is a threshold planting date for losses in maize productivity. In MT it is possible to plant until February 12 for RCP 8.5 and until February 02 for RCP 8.5 + HLU scenario in the middle of century. In MATOPIBA the threshold planting date is February 02 under RCP 8.5 scenario. The soybean planting dates that turn this possible to this hybrid combination are: October 15 and October 05 to MT in RCP 8.5 and RCP 8.5 + HLU, respectively, and October 05 to MATOPIBA in RCP 8.5 scenario. As the planting dates are delayed after this threshold, the losses increase for this hybrid. This hybrid combination is the one that presents smaller gross revenue among all hybrids combination tested in this work, mainly in MT.

I tested other hybrid combination with total phenological cycle smaller than 220 days, with the aim to evaluate the adaptation in the future. The hybrid combination $S_{100}M_{100}$, with a total phenological cycle of about 200 days, presents a slightly higher gross revenue than $S_{100}M_{120}$ in the planting dates until November, however the gross revenue of $S_{90}M_{90}$, that has 180 days of phenological cycle, was higher than other hybrid combinations tested in this work for MT in RCP 8.5 scenario (Fig. 10). The $S_{90}M_{90}$ combination had the higher gross revenue among all three hybrids combinations tested (Fig. 10). However, its gross revenue was not equal or higher than in 2016.

A maize hybrid with 100 days of cycle is more resilient to climate change than a maize hybrid with 120 days of phenological cycle: in MT in RCP 8.5 scenario, $S_{100}M_{100}$ presents a slightly higher gross revenue than $S_{100}M_{120}$. This indicates that a reduction of the duration of the cycle avoids losses in maize in the end of phenological cycle. In RCP 8.5 + HLU, the gross revenue is smaller than gross revenue of RCP 8.5 scenario, for all planting dates in both regions. The gross revenue in MT almost does not vary among the three hybrids combination and the gross revenue was lower than in 2016 (Fig. 11).

The same happens in MATOPIBA in the RCP 8.5 + HLU scenario, where no hybrid combinations presents higher gross revenue among all combinations tested. Moreover, in the best case the gross revenue in MATOPIBA is half of production the value of 2016 (Fig. 11 a). This behavior repeats in RCP 8.5 scenario (Fig. 10 a),

which means that early maturity cultivars do not compensate the effect of climate change in this region, in any scenario.

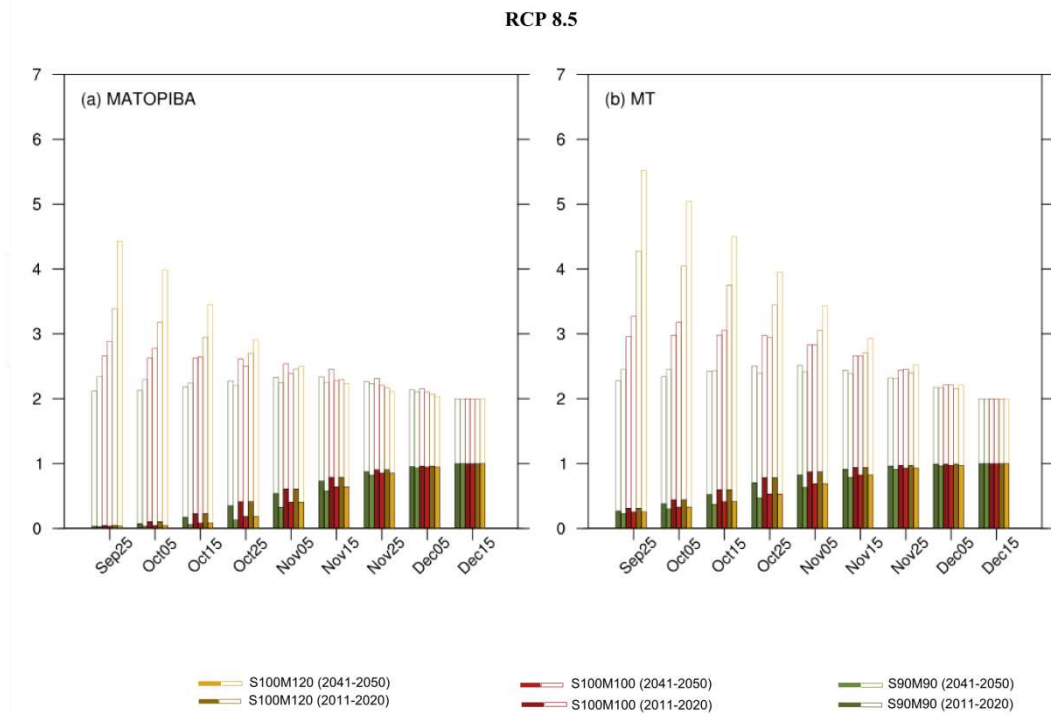


Figure 8 - Yield ratio for each planting date according to yield of December 15 $\left(\frac{Y}{Y_{15/12}}\right)$ for each decade and cultivar combination for soy-maize double cropping according to RCP 8.5 scenario.

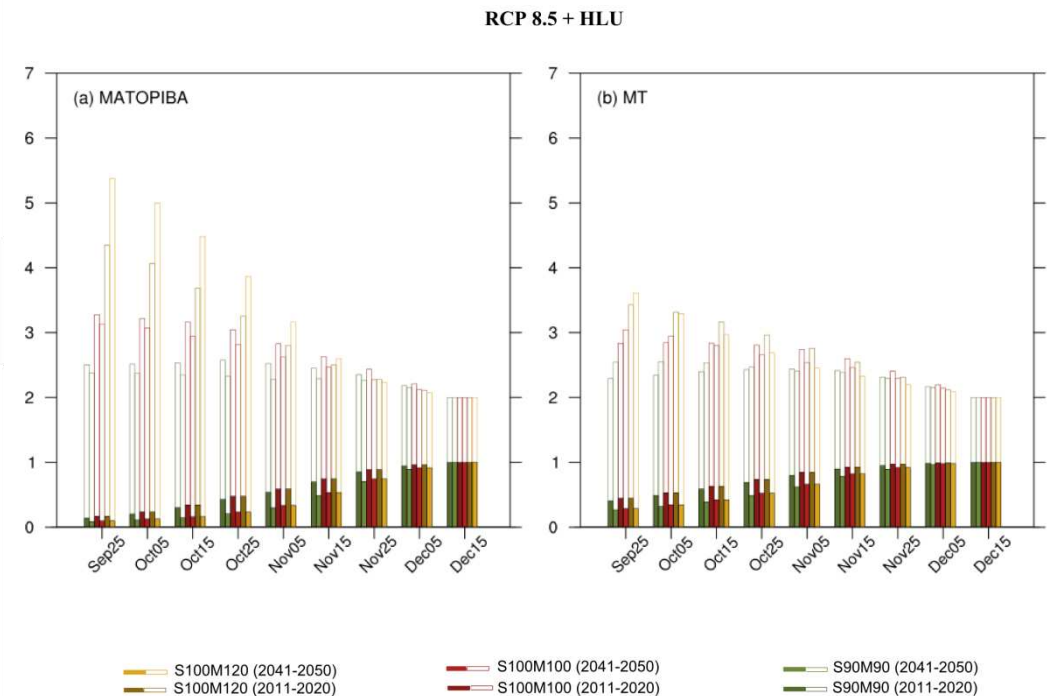


Figure 9 - Yield ratio for each planting date according to yield of December 15 $\left(\frac{Y}{Y_{15/12}}\right)$ for each decade and cultivar combination for soy-maize double cropping according to RCP 8.5 + HLU scenario.

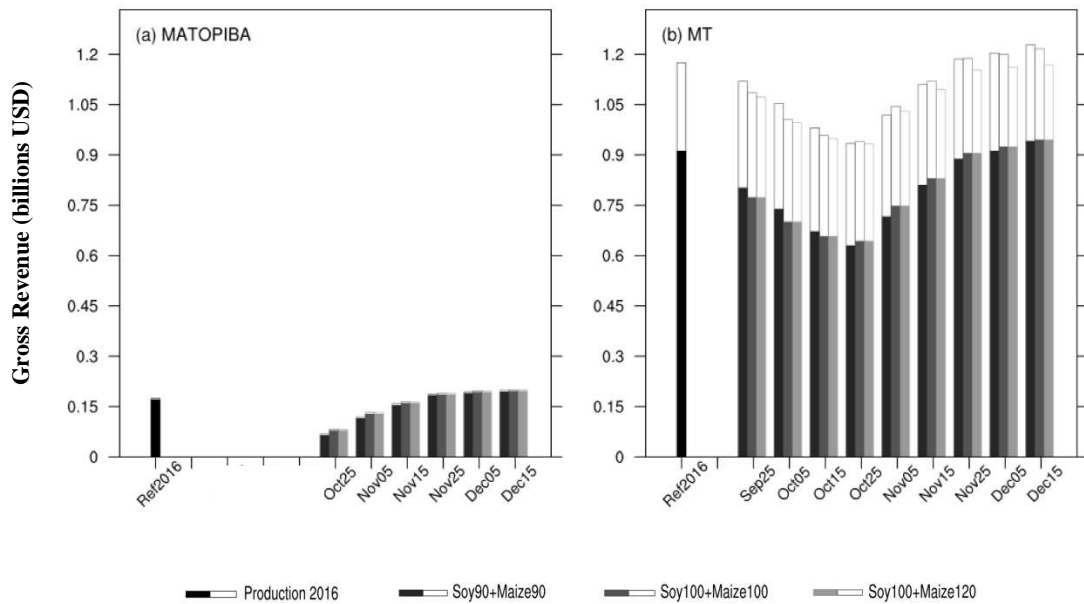


Figure 10 – Gross revenue variation (2011-2020 to 2041-2050) of soybean and second-crop maize for each planting date in MATOPIBA region (a) and MT (b), for RCP 8.5 scenario. In MATOPIBA region, the planting dates of Sep 25, Oct 05 and Oct 15 are within the period of sanitary break for the region.

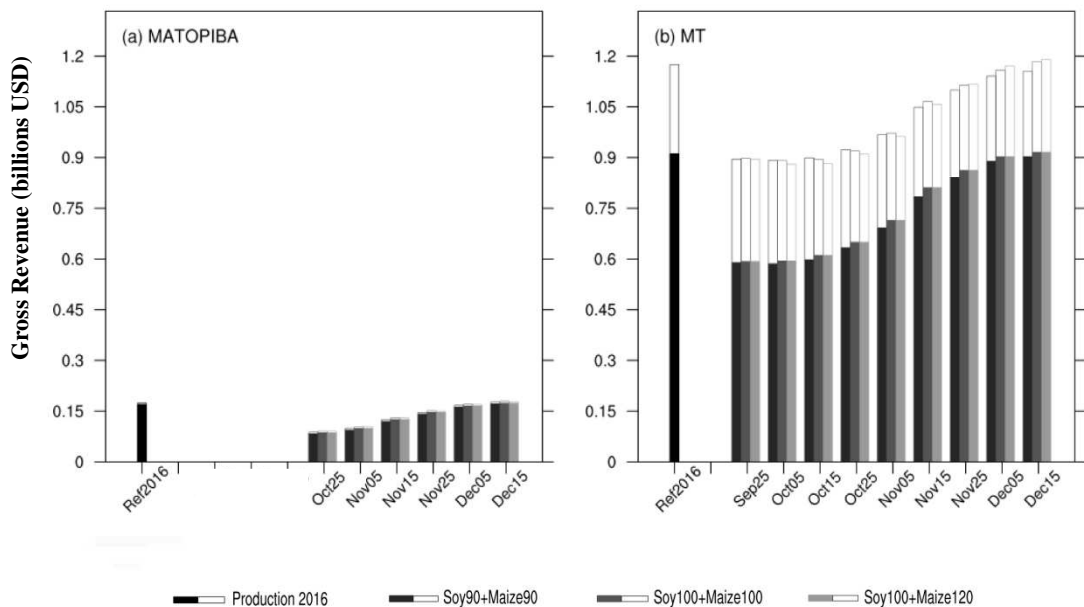


Figure 11 – Gross revenue variation (2011-2020 to 2041-2050) of soybean and second-crop maize for each planting date in MATOPIBA region (a) and MT (b) for RCP 8.5 + HLU scenario. In MATOPIBA region, the planting dates of Sep 25, Oct 05 and Oct 15 are within the period of sanitary break for the region.

In summary, the assessment of climate change effects in second crop maize and in the sustainability of soy-maize double cropping system indicate that until 2050:

- With no delay in the planting dates of soybean there is no losses in maize productivity;
- With a delay in soybean planting dates, losses in maize productivity increase with the delay in 10 and 20 days in planting date;
- Gross revenue of soybean increase while maize gross revenue decrease as planting occurs later;
- Gross revenue of the system in a scenario with low levels of deforestation is higher than gross revenue of the system in a scenario with high levels of deforestation;
- Gross revenue of the system is higher for $S_{90}M_{90}$ than $S_{100}M_{100}$ and $S_{100}M_{120}$ hybrid combination, in MT for RCP 8.5 scenario.
- Cultivars adaptation of maize and soybean may not compensate the effects of climate change in RCP 8.5 + HLU.

5. DISCUSSION

The results suggest that, in addition to the first crop soybean yield, climate change might affect the second crop maize productivity until the middle of century in MT and MATOPIBA, the main production regions of these grains in Brazil. The second crop maize grows in a time of the year when precipitation, photoperiod and temperature decrease, due to the autumn-winter transition. These are important climatic variables to agriculture and are related to productivity. The later planting of second crop maize may cause losses in productivity due to water stress in the end of growing season (HEINEMANN et al., 2008; GARCIA et al., 2018). The losses simulated when the second crop maize is planted in February, March and following months is corroborated by studies (HEINEMANN et al., 2008; GARCIA et al., 2018; NÓIA JUNIOR and SENTELHAS, 2019) that do not consider the effects of climate change.

The climate change impacts on the second crop maize productivity are mainly indirect, due to the delay in planting dates caused by a delay in soybean planting dates to avoid sowing during the low precipitation period in the beginning of the future wet season. However, the economic losses can increase in scenarios that consider a climate change. Estimated precipitation changes in MT and MATOPIBA, for RCP 8.5 and RCP 8.5 + HLU scenarios in the half of this century indicate that precipitation could decrease in almost all months of the second crop maize growing season (Fig. 12).

This reduction in the amount and intensity of precipitation throughout the second crop growing season may be a challenge to double cropping systems in the future. Soybean might suffer losses in productivity when planted right after the sanitary break due to a delay in the onset of rainy season in MT and MATOPIBA, but a delay on the planting dates restores the high yield (PIRES et al., 2016). However, the more the planting dates are delayed, the greater is the decrease in maize productivity, regardless of climate scenario and model used. As previously indicated in the literature, it can be explained by an increased water stress during the growing season of maize, mainly in the end of maize phenological cycle. In addition to precipitation, the model used in simulations considers other climatic variables like temperature and solar radiation that can influence this reduction. However, studies

have shown the precipitation is the main climatic variable that affect maize yield (RAY et al., 2015; LLANO and VARGAS, 2016; SAKURAI et al., 2011; NÓIA JUNIOR and SENTELHAS, 2019) in rainfed systems. For MT, precipitation falls from March to July (in RCP 8.5) and from January to July (RCP 8.5 + HLU) (Fig. 12 b). This precipitation decrease plays an important role to explain the higher losses in productivity when the planting date is delayed.

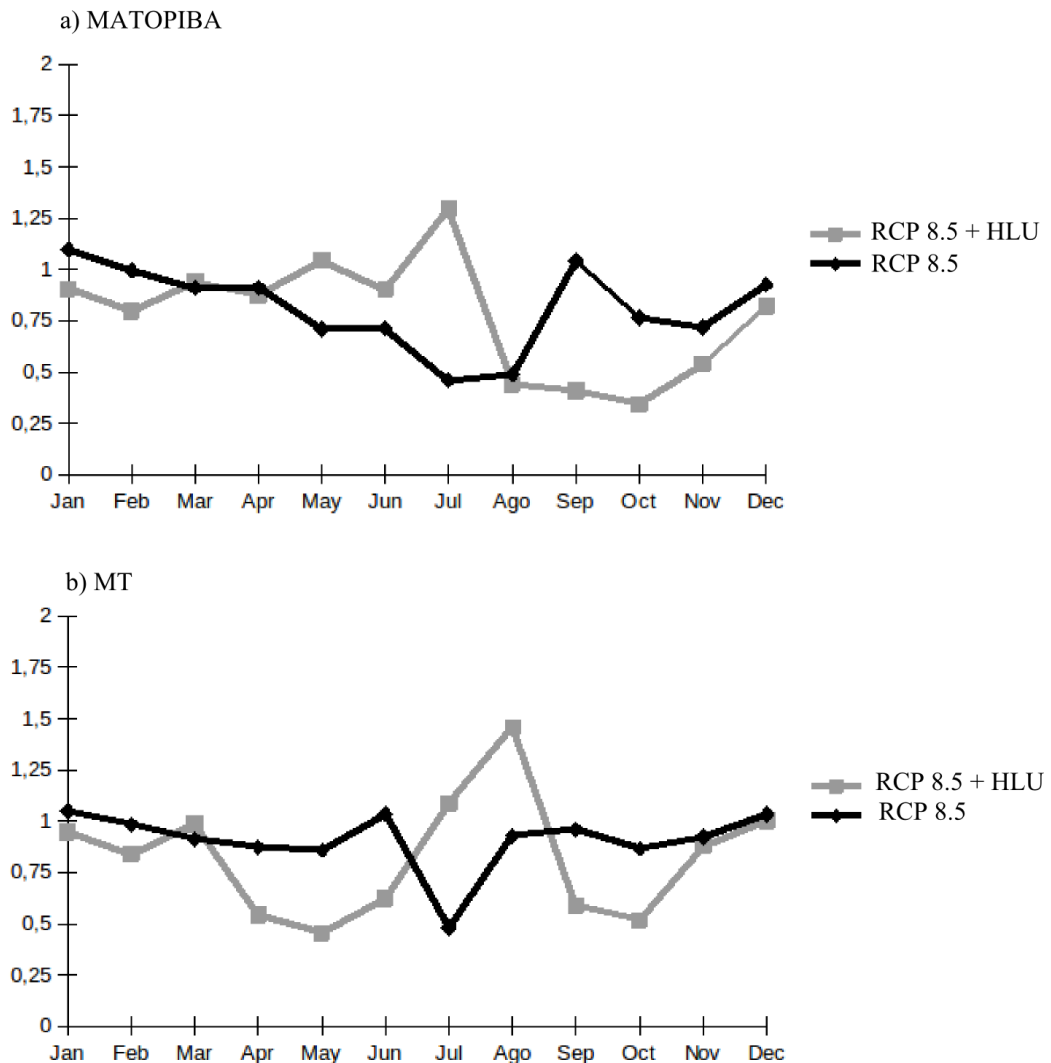


Figure 12 – Precipitation change between 2041-2050 and 2011-2020 $\left(\frac{Prec_{2041-2050}}{Prec_{2011-2020}}\right)$ for each study region: a) MATOPIBA and b) MT for both scenarios. In RCP 8.5+ HLU, deforestation levels of Amazonia and Cerrado biomes are: 20 % and 60 % in first decade and 40 % and 70 % in last decade, respectively. In RCP 8.5, deforestation levels of Amazonia and Cerrado biomes are 20 % and 60 % in the first decade, deforestation levels of both biomes in the last decade remains almost the same, like demonstrated by Pires et al., (2016).

This effect in productivity was expected because some studies have been indicating an increase of the dry season length over the Amazon rainforest, mainly in the southern Amazonia (MARENGO et al. 2001; DEBORTOLI et al., 2015). In addition, until the middle of century, this increase could be greater because of climate change caused by the changes in atmospheric composition (FU et al., 2013; BOISIER et al., 2015) and the deforestation (COSTA and PIRES, 2010; SUMILA et al., 2017).

In the case of MATOPIBA, precipitation in RCP 8.5 falls progressively from March to July, repeating the patterns shown in MT, except for June. This is the time of the year that maize is planted in these regions, which can explain the progressive losses in productivity for second crop maize over the months.

In RCP 8.5 + HLU scenario losses in precipitation are also predicted in almost all months, but in May in MATOPIBA, there is a gain in precipitation, and this can reduce the losses in planting dates of January, February and mid-March due to an increase of precipitation during the stages of flowering and grain filling (LLANO and VARGAS, 2016).

The effect of intense deforestation demonstrates that the reduction in precipitation in the last decade was higher than in first decade, and was more intense than the scenario with low levels of deforestation in MT and in initial months (January, February, March and April) for MATOPIBA. For high levels of deforestation in Amazonia and Cerrado biomes, the length of dry season increases, affecting the precipitation in the beginning and, mainly, in the end of dry season (COSTA and PIRES, 2010). However, the methodology used to generate RCP 8.5 + HLU scenario from LUCID data and Pires and Costa (2013) deforestation scenarios has limitations in places where precipitation is low, which indicates a potential underestimation of maize yield losses in MATOPIBA in this scenario.

Currently, the dry season in MT starts in May (ARVOR et al., 2014), and in April (KLINK and MACHADO, 2005) for MATOPIBA. The analysis of precipitation (Fig. 12) suggests that it decreases as early as February in the future during the second crop growing season implies in losses in maize productivity.

This is a critical situation to the double cropping farmers, as it can become increasingly risky to maintain these systems in the future. Abrahão and Costa (2018)

estimated that shorter rainy season might reduce the suitable area for double cropping in 10% until the middle of century. Pires et al., (2016) showed that planting right after the end of sanitary break caused losses in short-cycle soybean productivity of about 40% and 11% until the middle of century in the MATOPIBA and MT in RCP 8.5. In addition, in scenarios with high levels of deforestation the effect of climate change is more intense and the losses increase. A strategy without technology changes suggested by these authors was to shift the planting dates from September 25 to October 05 in these regions to increase the productivity, but taking the risk that possible losses can occur in the second crop.

In fact, the simulations of the second crop maize for $S_{100}M_{120}$ showed that losses in productivity may occur as planting dates are delayed. The beginning of losses in maize productivity, presented in section 4.1, determines the threshold planting dates possible to plant a second crop in soy-maize double cropping system. For soybean planted in October 05, considering the time necessary to harvest it, the maize needs to start to be planted by the beginning of February. For this planting date the simulations showed that productivity losses are not expected in any of these regions for any scenarios simulated. However, such productivity losses start to take place from the middle of February on. These planting dates correspond to a short-cycle soybean planted from October 15 and October 25.

The simulations showed that, for future farmers to continue to adopt double cropping, they might not have many options to adapt without technology. Therefore, there is a need to invest more in research in the next years. Shifting planting dates of short-cycle soybean slightly increases yield, however this is only recommended until October 05, when second crop maize productivity does not suffer losses.

An alternative is to adapt cultivars of soybean and maize, reducing their phenological cycle with the aim to avoid water stress caused by the shortening of the rainy season in the future. With this purpose I evaluated three cultivars combinations of soybean and maize, including the hybrid combination that approaches better to current cultivars combination ($S_{100}M_{120}$). The hybrids combinations chosen to simulate the adaptation have 200 and 180 days of total phenological cycle of the system.

Evaluating the double cropping system gross revenue in the future based in 2016 gross revenue for each region, the results indicate that these systems might be less profitable than they are today for both scenarios, even with hybrid adaptation.

The gross revenue achieve the reference gross revenue of 2016 only from November ends in both scenarios, but the effect of Asian rust in soybean is not considered in the model used to simulate productivity. Asian rust is caused by a fungus that it is favored by high temperature and humidity, climatic conditions common for the months of November, December, January and February in the study region. The infestation by Asian rust causes losses in soybean productivity, such as the infestation that occurred in the 2001/2002 in Brazilian states of Goiás, Mato Grosso and Mato Grosso do Sul, with losses varying from 30 % to 75 % (YORINORI et al., 2005).

Comparing the three cultivars combinations tested, the worst cultivar combination was the one that best approaches the current total cycle of the system about of 220 days ($S_{100}M_{120}$), achieving the lower gross revenue of the system in MT. Also, the gross revenue increases as the total phenological cycle of the system decreases. This indicates the need to turn the phenological cycle of the cultivars shorter in the future to achieve higher gross revenue for MT in RCP 8.5. On the other hand, in the scenario with high levels of deforestation (RCP 8.5 + HLU), besides that gross revenue was smaller when compared with scenario with low levels of deforestation, the adaptation of hybrids of soybean and maize is not sufficient to attenuate the effect of climate change, since the gross revenue does not vary among combinations tested in this work and was lower than reference of 2016. For MATOPIBA, in both scenarios, the gross revenue reaches nearly half of the gross revenue of 2016 to October 25 planting date.

Analyzing the limitations of photoperiod and rainy season until 2050 using HADGEM2-ES from RCP 8.5 for MT and MATOPIBA, Abrahão and Costa (2018) found that an adoption of short cycle cultivars with 90 days of cycle for soybean and maize, totaling 180 days of double cropping phenological cycle, leads to a smaller reduction of area suitable for double cropping than a combination of soybean and maize hybrids that reaches 220 days of phenological cycle, demonstrating that adapting cultivars could be a way to reduce the effect of rainy season reduction in MT. However, in MATOPIBA even with the adoption of shorter cultivars, the reduction of the suitable area remains higher.

The results of this work agree with Abrahão and Costa (2018) for both regions in adaptation measures. The adoption of shorter cultivars in MT could be a possible solution to maintain the sustainability of soy-maize double cropping in the

future if the additional deforestation tested by this work does not occur. MATOPIBA might suffer greater losses in gross revenue of the system and suitable area of double cropping until 2050.

In a high level of deforestation scenario, it might not be possible to adopt double cropping even in MT only with the adaptation of cultivars. For soybean planted early, the losses in productivity are higher in high levels of deforestation (PIRES et al., 2016; OLIVEIRA et al., 2013). And the losses of maize productivity begin to appear earlier than in RCP 8.5 scenario, more precisely for planting dates after February 12 in MT for S₁₀₀M₁₂₀. Then, in other maize hybrids the losses could appear earlier too when compared with RCP 8.5 scenario. For this scenario, in the future, the farmers will have more losses in both crops for MT, reducing the profitability of the system.

Until 2028, it is estimated that soybean will be the Brazilian crop that will further expand the area, adding 10 millions of hectares (MAPA, 2018). The expansion of soy-maize double cropping system is motivated by the expansion of soybean. If this expansion occurs from the advance of the agriculture frontier in biomes, the losses in productivity will be greater. The MATOPIBA is the region where expansion is likely to occur, due to great investments received in the last years and because is a region with lower lands cost's and inserted in the Cerrado biome, that has lower protection laws than the Amazon biome. Between the years of 2000 to 2014, Cerrado was the biome with more area of new croplands, increasing 81 % until 2014, and the majority of new areas resulted by the conversion of natural vegetation to cropland (ZALLES et al., 2018). In the Amazon biome, deforestation rates are slowly increasing after 2012 due to reduction of measures of conservation, such as: revision of Brazilian Forest Code, that allows amnesty for landowners that practiced illegal deforestation in the past years, which can suggests that the law can be changed and this could motivate deforestation; the reduction of environmental-licensing requirements; suspension the ratification of indigenous lands and the reduction of protected areas (SOARES-FILHO and RAJÃO, 2018).

This work complements recent previous studies (PIRES et al., 2016; ABRAHÃO and COSTA, 2018) and indicates that double cropping might be unsustainable in the future: due to a later onset of the rainy season, either the first or the second crop are predicted to show decreased productivity, depending on the sowing date adopted by the farmer. As currently, export prices of soybean is twice as

high as maize price, farmers might consider prioritizing the first crop. In addition, maize cultivated at the beginning of the rainy season (first crop maize) has been showing decreased production in recent years due to area competition with soybeans (CONAB, 2016). A reduced first and second crop production could lead to a decreased supply of maize in the market and directly affect other activities that depend on it, such as poultry and swine feeding. The implications to the agricultural market and food security are still challenging to assess. For example, the most part of poor population feed with chicken which is the cheapest animal protein, the increase on the maize prices could increase the price of chicken and limit the access of population to meat.

6. CONCLUSIONS

The results of this work suggest that the double cropping system (soybean followed by maize) might be threatened until 2050 in MT and MATOPIBA due to climate change. The productivity of maize second crop starts to fall in February, and the losses increase in the next months of growing season in these places for $S_{100}M_{120}$. The beginning of losses in maize productivity allowed the identification of a threshold planting date that turns maize second crop possible in the future. This will be viable to soybean planted in October 05, when soybean productivity slightly increases and does not occur losses in second crop maize productivity planted in February 02.

The effects of climate change in short-cycle soybean productivity was evaluated by Pires et al., (2016), and regions like MT and MATOPIBA may suffer losses in productivity of about 11 % and 40 %, respectively in RCP 8.5 scenario. The combination of soybean simulations by Pires et al., (2016) with second crop maize allowed the evaluation of the viability of double cropping in the future under climate change scenarios. In general, in case no adaptation takes place, double cropping system in the future will not be as profitable as currently, demonstrating the need for farmers to adapt to climate change.

To minimize climate change effects in double cropping system in the future, adaptation measures need to be implemented. The adoption of early maturity cultivars, with 180 days total cycle for the two crops, in MT may offset the effects of climate change and turn the system almost as profitable as it is currently. This demonstrates the need to invest in more research related to genetic improvement of crops to adapt to climate change, since the cultivar combination mentioned before does not yet exist. In MATOPIBA, even the adoption of $S_{90}M_{90}$ might not allow a profitable system.

The system gross revenue reduces for scenarios with high levels of deforestation. The deforestation of Amazonia and Cerrado biomes to increase production by increasing the planted area leads to lower productivity and reduces the production of both crops hence the net profit of the system. This result emphasizes

the need to protect more the Brazilian biomes through the adoption of more conservation measures by the government.

The gross revenue of the system increases when cultivars with a combined cycle of 180 days are adopted comparing with combinations of cultivars with longer total cycle. However, even with the adaptation through the use of different cultivars, the gross revenue in MT is slightly lower than the reference, indicating that, for future double cropping systems to reach or overcome the 2016 reference, additional adaptation practices need to be simultaneously adopted. For MATOPIBA, this adaptation needs to be more intense, since the short-cycle cultivars do not compensate the effect of climate change.

One alternative to keep double cropping viable in the future is the adoption of irrigation. Irrigate crops in the main critical time of water stress of double cropping system, the transition of dry to rainy season, when soybean has higher productivity losses (PIRES et al., 2016), can increase the productivity of soybean and turns the system more profitable, since the results of this study showed that soybean is more affected than maize. Battisti et al., (2018) found that irrigation might increase soybean yield and reduce the yield variability in the future climate change scenario. However, this practice has high costs and requires large amounts of water, being dependent on water and economic resources.

Other alternative may be to reduce the time necessary to harvest soybean and to plant maize in average farms. Currently, these operations may take up to 3-4 weeks. The development and adoption of efficient machinery that allows this in fewer days, without fails and with homogeneous planting, leads to early planting dates of maize and an increase of productivity. These and other measures need to be evaluated and adopted to maintain the double cropping system sustainable until the middle of century.

Finally, coupled biophysical and economic studies should be conducted to assess the impact of this climate predicted effects in double-cropping systems and in other productive chains that depend on both soybean and, more critically, maize.

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APPENDIX A

A1 – Percentage change in second crop maize productivity for other planting dates simulated

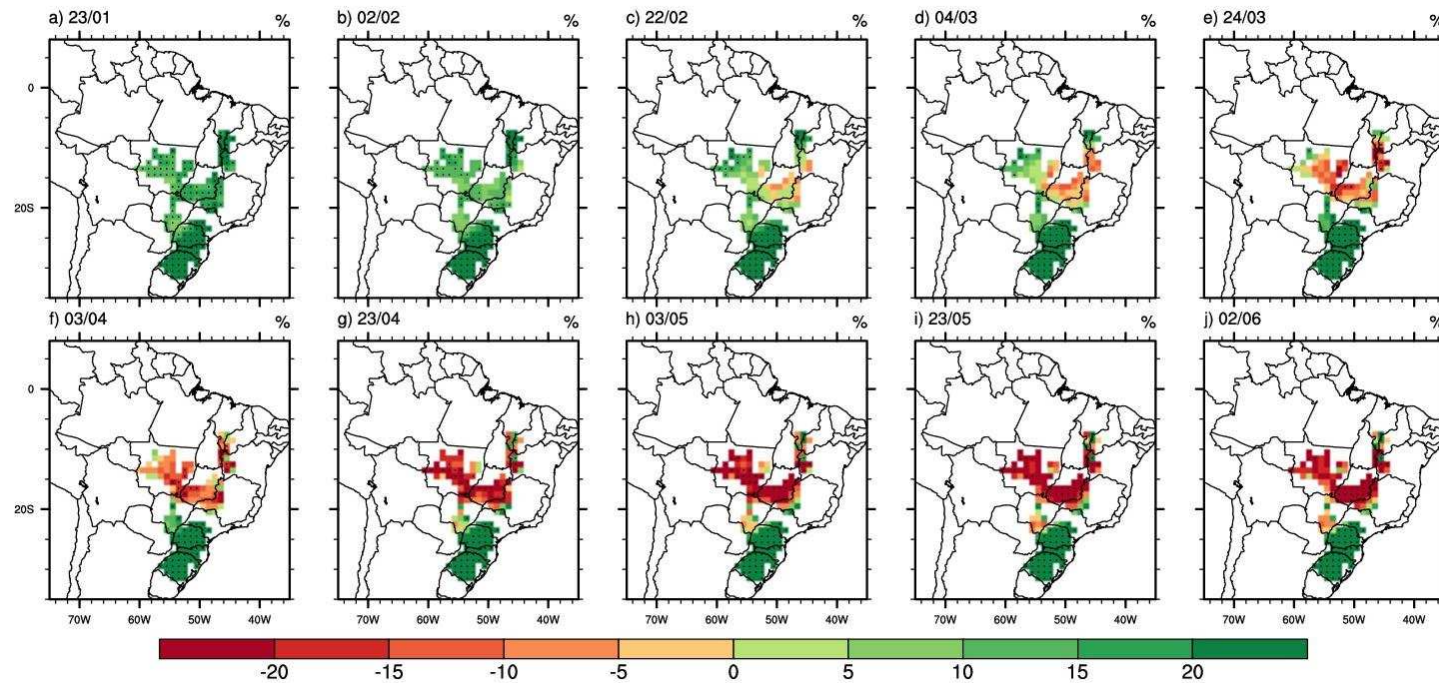


Figure A.1 - Percentage change in second-crop maize yield from 2011-2020 to 2041-2050. In a) to j) atmospheric composition and land use trajectories is according to RCP 8.5. The pixels with a dot are those that have statistically significant changes in productivity according to Student's t-test ($\alpha = 5\%$).

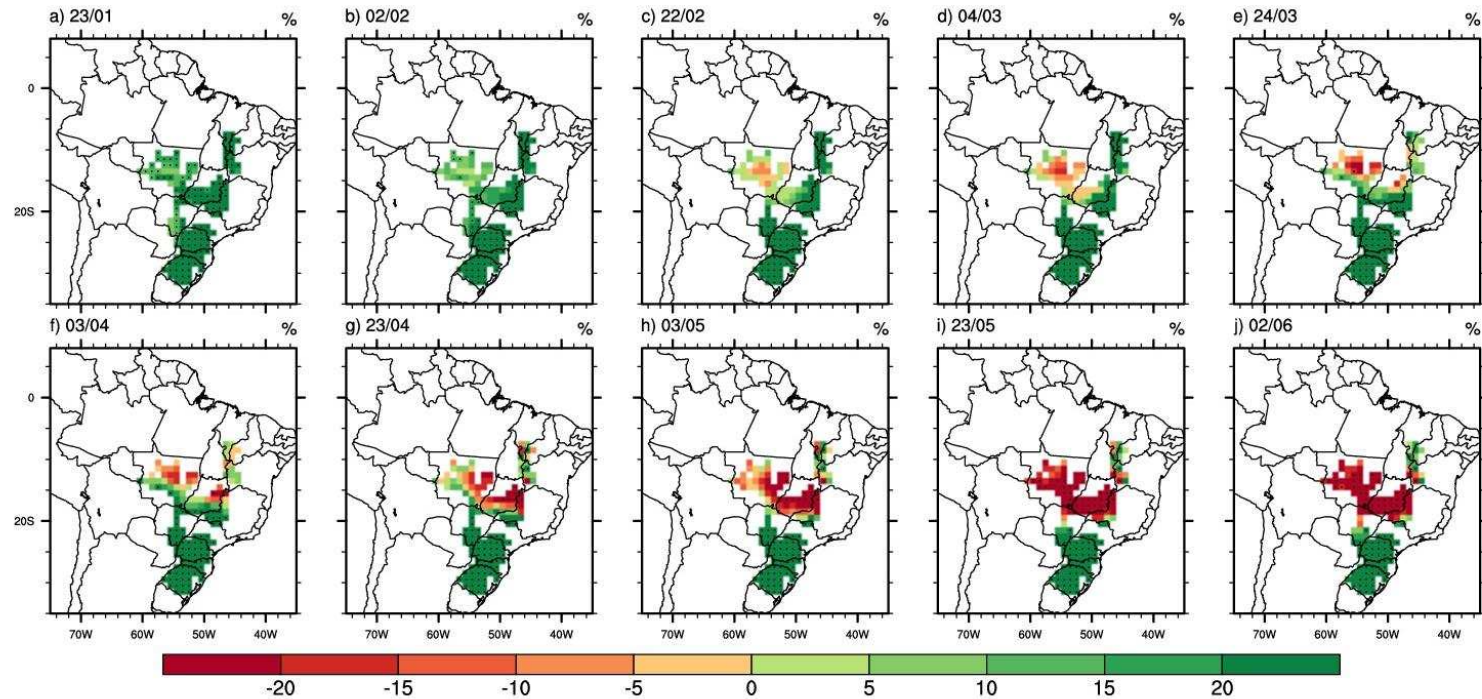


Figure A.2 - Percentage change in second-crop maize yield from 2011-2020 to 2041-2050. In a) to j) atmospheric composition is according to RCP 8.5 and land use trajectories are according to Pires and Costa (2013) deforestation scenarios. The pixels with a dot are those that have statistically significant changes in productivity according to Student's t-test ($\alpha = 5\%$).

A.2 – Average percentage change on yield of second crop maize for each region and each climatic scenario

Table A. 1 – Percentage change on second crop maize productivity for all planting dates simulated to MATOPIBA in RCP 8.5 scenario.

MATOPIBA			
Planting date on first decade	No adaptation (%)	Delay 10 days on last decade (%)	Delay 20 days on last decade (%)
13 jan	25.1676*	16.4136*	4.3133
23 jan	23.1123*	10.3157*	-5.6903
02 feb	19.8121*	2.4282	-17.2297*
12 feb	16.0016*	-6.2613	-23.9348*
22 feb	11.5908	-14.2103*	-34.7152*
04 mar	5.9221	-19.3947*	-36.2427*
14 mar	-1.1348	-21.7994*	-32.5015*
24 mar	-6.6127	-19.3931*	-25.7984*
03 apr	-8.0737*	-15.3784*	-22.1038*
13 apr	-6.298	-13.745*	-22.2571*
23 apr	-4.3806	-13.8168*	-23.1928*
03 may	-5.3397	-15.6379*	-23.1501*
13 may	-9.3717*	-17.4419*	-21.4865*
23 may	-12.3524	-16.6464*	-17.789*
02 jun	-14.5878	-15.7586	-12.1479
12 jun	-17.4221	-13.8827	-
22 jun	-16.82	-	-

* Statistically significant changes on maize yield according to Student's t-test ($\alpha = 5\%$).

Table A. 2 – Percentage change on second crop maize productivity for all planting dates simulated to MT in RCP 8.5 scenario.

MT			
Planting date on first decade	No adaptation (%)	Delay 10 days on last decade (%)	Delay 20 days on last decade (%)
13 jan	16.7852*	7.5399	-3.7107
23 jan	14.4734*	2.4974	-11.224*
02 feb	12.7369*	-2.3553	-18.1121*
12 feb	11.5926*	-6.415	-25.2215*
22 feb	10.8219	-11.4485	-31.8874*
04 mar	8.0883	-16.86*	-36.9806*
14 mar	2.8527	-22.0386*	-39.3183*
24 mar	-3.5727	-24.9453*	-39.5776*
03 apr	-7.8915	-25.8485*	-35.5451*
13 apr	-13.8183	-25.088*	-26.8177*
23 apr	-19.9057*	-21.755*	-16.9774
03 may	-23.734*	-19.0772	-7.1321
13 may	-25.3086*	-14.2833	0.846
23 may	-23.5779	-10.0891	7.5236
02 jun	-19.3552	-3.5577	11.1748
12 jun	-11.8972	1.5614	-
22 jun	-4.22	-	-

* Statistically significant changes on maize yield according to Student's t-test ($\alpha = 5$ %).

Table A. 3 – Percentage change on second crop maize productivity for all planting dates simulated to MATOPIBA in RCP 8.5 + HLU scenario.

MATOPIBA			
Planting date on first decade	No adaptation (%)	Delay 10 days on last decade (%)	Delay 20 days on last decade (%)
13 jan	27.3571*	21.5516*	12.2025*
23 jan	28.5800*	18.6903*	5.1757
02 feb	29.5995*	14.8428*	-3.4274
12 feb	31.6881*	10.7380	-13.7013*
22 feb	33.1541*	3.7677	-24.2104*
04 mar	30.1031*	-4.9756	-31.8214*
14 mar	20.0349*	-13.8767	-32.7008*
24 mar	8.5736	-15.1576*	-26.7691*
03 apr	2.7280	-11.3314	-16.5513*
13 apr	1.8867	-4.1114	-8.3940
23 apr	5.6254	0.9079	-4.2723
03 may	5.6415	0.2183	-4.8136
13 may	2.3303	-2.8076	-4.5208
23 may	0.0595	-1.7042	0.1338
02 jun	0.4751	2.3538	3.2995
12 jun	4.7602	5.7281	-
22 jun	8.7923	-	-

* Statistically significant changes on maize yield according to Student's t-test ($\alpha = 5\%$).

Table A. 4 – Percentage change on second crop maize productivity for all planting dates simulated to MT in RCP 8.5 + HLU scenario.

MT			
Planting date on first decade	No adaptation (%)	Delay 10 days on last decade (%)	Delay 20 days on last decade (%)
13 jan	19.6504*	10.8806*	-1.5839
23 jan	15.9645*	2.9286	-11.1653
02 feb	10.2089	-4.8819	-19.3055*
12 feb	4.5031	-11.3436	-26.5262*
22 feb	0.8674	-16.4064	-29.8611*
04 mar	-2.7159	-18.3743*	-30.4361*
14 mar	-3.3353	-17.6194*	-28.5175*
24 mar	-0.7366	-13.8681*	-22.4641*
03 apr	2.8483	-7.4161	-15.7352
13 apr	4.0639	-5.2867	-12.0755
23 apr	-1.4274	-8.4928	-13.4432
03 may	-10.9368	-15.7550	-17.9311
13 may	-19.9311	-21.9993	-20.8051
23 may	-26.4536*	-25.3276*	-22.5030
02 jun	-28.3987*	-25.6904*	-22.5377*
12 jun	-27.7312*	-24.6651*	-
22 jun	-25.3254*	-	-

* Statistically significant changes on maize yield according to Student's t-test ($\alpha = 5\%$).