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Challenges to the Adaptation of Double Cropping Agricultural Systems in Brazil under Changes in Climate and Land Cover

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Abstract: The wide adoption of highly productive soy–maize double cropping has allowed Brazil to become one of the main producers and exporters of these commodities. However, land cover and climate change could affect the viability of double cropping due to a shortening of the rainy season, and both crops could be affected. The goals of this study were to evaluate if adaptation measures such as adoption of shorter-cycle cultivars and delaying sowing dates are effective to maintain soybean and maize yield in the main producing regions in Brazil. We used a crop model and four climate models to simulate double cropping in two climate scenarios that differ in Amazonia and Cerrado deforestation levels. We tested if 10 soybean and 17 maize sowing dates and three cultivar combination could reduce the impacts of a shorter rainy season in double cropping yield and gross revenue. Results showed a decrease in maize yield due to a delay of soybean sowing dates and rainfall reduction during the growing season. Adaptation through delaying sowing dates and the adoption of short cycle cultivars was not effective to maintain system revenue in all the study regions in a scenario with high deforestation levels.

Keywords: maize; soybean; deforestation; climate change; double cropping; adaptation

1. Introduction

Brazil is the third largest producer and second largest exporter of maize in the world [1]. In Brazil maize grows either in the beginning or in the middle of the rainy season, the latter as a second crop that is sowed after soybean is harvested (known as maize off-season). During the last decade, total Brazilian maize production increased nearly 96% [2], while maize off-season production increased from 34% to 73% of total maize production [2]. This remarkable increase in maize production was mainly driven by the intensification of agriculture through the widespread adoption of soy–maize double cropping systems.

Soy–maize double cropping in Brazil is predominantly rainfed and cultivated in places where the rainy season is 6–7 months long [3–5]. In this system, soybean is sowed in the beginning of the rainy season while maize is sowed in the same area after the soybean is harvested. Maize off-season grows in a time of the year when rainfall, mean temperature and photoperiod are reducing in almost all producing regions in the country [6], which could affect crop yield depending on the choice of the sowing date. Therefore, the later the second crop is planted, the lower is its yield, mainly due to water stress by the end of the growing season [7–9]. Therefore, Brazilian commodity agriculture is particularly vulnerable to climate change, especially changes in precipitation and temperature [4,10–12].

While the local rainy season is barely long enough to accommodate the cycle of these two crops, recent studies have shown a shorter rainy season in Brazil [10,13–15] due to both changes in atmospheric composition and widespread Amazonia and Cerrado deforestation (currently these biomes cover about of 80% and 50% of original area [16], respectively), conditions that might intensify in the future [11,17]. This is a threatening situation to farmers that choose to adopt double cropping because it can lead to yield losses in both crops.

The potential future impacts of climate change on soybean were studied by Pires et al. [4], who found that sowing soybean right 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), a practice commonly adopted by farmers in highly productive regions, might cause yield losses due to rainfall reduction in the transition from dry to rainy season. In addition, in a scenario with increased Amazon and Cerrado deforestation, rainfall reduction and yield losses dramatically increased. While the authors suggested shifting the soybean sowing date from the end of September to October, when the crop yield could slightly increase, the impacts of the delay in maize off-season sowing dates were not addressed. Potential future reductions on maize off-season yield in Mato Grosso state (the largest producing region in Brazil) were predicted by Andrea et al. [18] and Spera et al. [19]. In addition to the effects on the individual crops, some studies evaluated the potential impacts of climate change and technological development in the soy–maize double cropping system in Mato Grosso state [20,21]. These studies estimate that soybean yield might slightly increase or nearly does not change while maize off-season yield might reduce in the same period.

While previous studies present important conclusions about the effects of future climate change on soy–maize double cropping, especially in Mato Grosso, some questions remain. In particular, as the rainy season becomes shorter and water stress causes yield losses in the field, farmers are expected to adapt through the adoption of shorter-cycle cultivars or delaying crop sowing dates. Could either of these adaptation strategies be effective to prevent great production loss and maintain a highly productive soy–maize double cropping, even if deforestation continues to increase and causes further rainfall reduction in Brazil? In addition, are these strategies sufficient to offset negative climate effects in all producing regions in the country? This is particularly important for at least two reasons: First, both soybean and maize production in Brazil is expected to increase 33% and 20%, respectively, in the next years [22] to meet the increased global demand for food. Second, deforestation in Amazonia is significantly increasing again in recent years after a dramatic reduction in 2005–2014 [23], while Cerrado deforestation is historically high.

Therefore, the aim of this study was to model the effects of a shorter rainy season and a warmer climate (caused by both a change in the atmospheric composition and land use) on double-cropping yield and assess how adaptation through the delaying of crop sowing dates and the adoption of shorter-cycle cultivars impact on the viability of soy–maize double cropping systems until the middle of the century.

2. Experiments

2.1. Study Area

We evaluated the effects of climate change caused by both a change in the atmospheric composition and deforestation in maize off-season yield and the viability of double cropping in the main soybean producing regions in Brazil. We assume that potential areas to implement double-cropping in the near future are those that currently grow soybean.

The soy planted area of 2016, considered as our reference, was calculated from the conversion of tabular data from Instituto Brasileiro de Geografia e Estatística (IBGE) to a gridded map. The soybean and total cropland area ratio in each micro-region were based on Dias et al. [24]. Where 2016 data was missing, we used the 2012 data from Dias et al. [24], the most recent available. The soybean planted area map is the result of the micro-region ratio and the amount of total cropland area for each pixel. The study region is defined by pixels that have at least 5% of its area planted with soybeans.

Even though results are shown for all the planted area in Brazil, we focused our analysis in two regions: Mato Grosso state (MT) and the region formed by the Brazilian states of Maranhão, Tocantins, Piauí, and Bahia, known as MATOPIBA (Figure 1). These regions are particularly important: MT has the highest soybean and maize off-season production in Brazil [25] and MATOPIBA is a new and active agriculture frontier that has received large investments recently, and is a potential region to expand intensive agriculture.

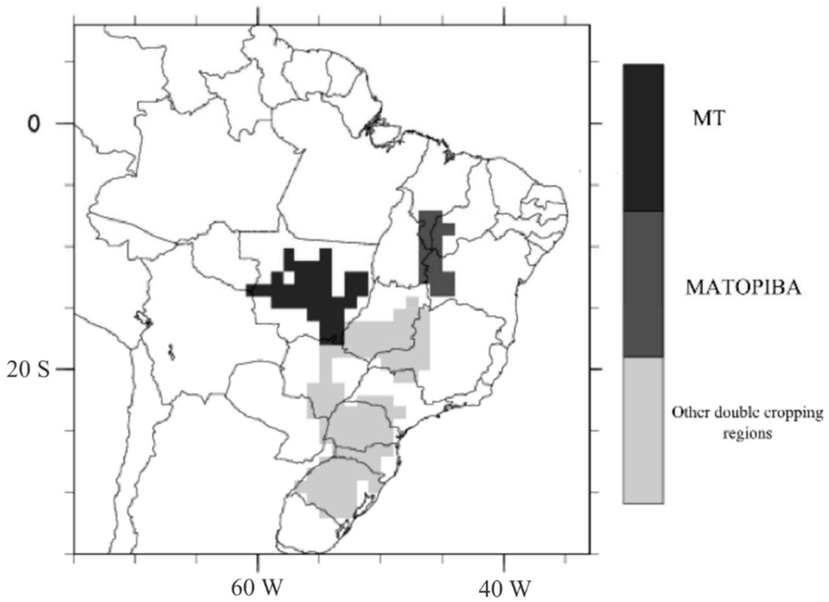

Figure 1. Study area with at least 5% of pixel area planted with soybeans in 2016.

2.2. Climate Scenarios and Input Data

Two climate scenarios were evaluated: The first considered the change in atmospheric composition with low deforestation levels, and the second considered the change in atmospheric composition with high Amazon and Cerrado deforestation levels.

The first scenario was the highest emission scenario of the Coupled Model Intercomparison Project Phase 5 (IPCC/CMIP5): RCP (Representative Concentration Pathway) 8.5 [26]. Despite being a pessimistic scenario, the deforestation levels are likely underestimated for 2050, reaching values of 20% and 60% in Amazonia and Cerrado biomes, respectively, amounts that are close to the current ones [4].

To assess how increased land use change effects on local climate until the middle of the century could affect double cropping, we evaluated a second scenario that derived from two datasets. The first dataset comprised the simulations of IPCC RCP 8.5 but with land use fixed (not changing) from 2005 on, presented in L2A85 experiment of Land-Use and Climate, Identification of Robust Impacts (LUCID) project [27]. This dataset discounts the biogeophysical effects of increased deforestation on local climate during the study period, only responding to greenhouse gas emissions. To account for the biogeophysical effects of increased deforestation on local climate, climate anomalies of climate scenarios derived from deforestation scenarios from Pires and Costa [28] were added to L2A85 meteorological data. In a pessimistic approach as in RCP 8.5, we assumed that deforestation levels in Pan-Amazonia and Cerrado biomes would reach 40% and 70%, respectively, until the middle of century. This scenario, depicted in Pires et al. [4] and called hereafter as RCP 8.5 + HLU (RCP 8.5 with High levels of Land Use change), assumes that natural vegetation is replaced by pasturelands. While RCP 8.5 + HLU meteorological data encompass both the biogeophysical effects of a change in atmospheric composition and land use change, the CO_2 trajectories remain the same as in RCP 8.5.

To reduce the individual bias related to climate models, we used climate data input from four models: HadGEM2-ES, MIROC-ESM, NorESM2-M, and MRI-CGCM3. These models better represented the seasonal patterns of rainfall and the beginning and end of rainy season in the main soybean producing regions, hence in potential double cropping producing regions [4].

The meteorological variables used as daily input data in simulations were rainfall, incoming solar radiation, minimum, mean, and maximum temperatures, specific humidity, and wind speed. CO_2 atmospheric concentration was also prescribed to the crop model and directly affected photosynthesis equations.

2.3. Double Cropping Simulation and Crops Sowing Dates and Cultivars

In our simulations, soy–maize double cropping was represented by prescribing the sowing dates and cycle length as they normally occur in the field. Thus, the maize off-season simulated sowing dates occurred after soybean simulated harvest dates. Soy sowing dates were 15 September, 25 September, 5 October, 10 October, 25 October, 5 November, 15 November, 25 November, 5 December, and 15 December, with an average of 100 days of phenological cycle length, as in Pires et al. [4]. In addition, because the interval between harvesting soy and planting maize might take up to 20 days in an average-sized farm, we set the sowing dates of maize off-season as: 13 January, 23 January, 2 February, 12 February, 22 February, 4 March, 14 March, 24 March, 3 April, 13 April, 23 April, 3 May, 13 May, 23 May, 2 June, 12 June, and 22 June. All of these 17 sowing dates encompassed the entire sowing season for each Brazilian state according to CONAB (Companhia Nacional de Abastecimento) [29].

The soybean sowing window in MATOPIBA and MT varied, from September to February and from September to December [29], respectively. The maize sowing window in these same regions varied from February to June and from January to March [29], respectively.

The current maize off-season phenological cycle length was considered as an average of 120 days in 2011–2020 (Table S5), with a simulated cultivar of 1900 growing degree days (GDD) and base temperature of 10 °C. To evaluate the adaptation of double cropping in the future through the adoption of shorter cycle maize cultivars, we simulated two more cultivars with 1600 GDD and 1500 GDD, and around 100 and 90 days cycle length in 2011–2020 (Tables S6 and S7), respectively. The soybean cultivar with an average cycle length of 90 days was also assessed (1500 GDD and base temperature of 10 °C) as an adaptation option [4]. The cycle length of both crops for all cultivars reduced until the end of the analysis period due to an increase in temperature caused by climate change and deforestation.

2.4. Crop Model Description

We simulated crop growth with the Integrated Model of Land Surface Processes (INLAND) [4,30–32]. The model, based in Agro-IBIS [33], is a fifth-generation model that considers the balance of water, energy, carbon, and momentum of the soil–vegetation–atmosphere system. INLAND includes explicit representation of physiological (photosynthesis, stomatal conductance, evapotranspiration) and phenological (allocation of dry matter, senescence) processes. Physiological processes are simulated with an hourly time-step and phenological processes with a daily time-step. This model was tested and used in several previous studies: Simulating the effect of climate change in soybean productivity for Brazil [4]; evaluating the effects of fire, climate, and nutrient limitation on vegetation of the Amazon–Cerrado border region [30]; simulating the feedbacks between vegetation and land surface water cycle coupled to a hydrological model [32]; and simulating the surface fluxes of plateau and valley environments in the Amazon [31].

We ran our simulations with a spatial resolution of $1 \times 1°$ (~110×110 km) forced by meteorological data described in Section 2.2 and the same experiment design as the soybean simulations of Pires et al. [4]. This spatial resolution was sufficient to capture large- to meso-scale processes affecting crop production.

2.5. Quantification of Climate Change Effects on Maize Off-Season

We estimated the effects of different climate scenarios on maize off-season yield from 2011 to 2050 according to Equation (1).

$$Y\ (\%) = \frac{Y_{2041-2050} - Y_{2011-2020}}{Y_{2011-2020}} \times 100 \tag{1}$$

where $Y_{2011-2010}$ is the average simulated crop yield during 2011 to 2020 and $Y_{2041-2050}$ is the average simulated crop yield during 2041 to 2050. Statistically significant results were determined by Student's *t*-test (α = 5%, n = 10 years).

A no-adaptation scenario was assessed considering that maize off-season sowing dates remain the same throughout the analysis period. Possible adaptation to a later onset of the rainy season was assessed by delaying the sowing dates in 10 and 20 days in 2041–2050.

2.6. Evaluation of the Viability of Double Cropping System in the Future

The future viability of soy–maize double-cropping systems was assessed through the combination of our simulations of maize off-season yield with the short-cycle soybean yield simulations from Pires et al. [4]. Both sets of crop simulations were run for the same conditions, scenarios, time-period, climate, and crop models.

We tested three cultivar combinations of soy–maize double cropping to evaluate adaptation alternatives: (a) The longer cycle combination $S_{100}M_{120}$, with soybean that reaches ~100 days and maize that reaches ~120 days of cycle length, totaling ~220 days for the entire crop calendar; (b) a cultivar combination with the same cycle length for maize and soybean ($S_{100}M_{100}$), both with ~100 days, totaling ~200 days; and (c) the shorter cycle combination, with cultivars of soybean and maize with ~90 days of cycle length ($S_{90}M_{90}$), totaling ~180 days for the crop calendar. Even though these numbers were an average for 2011–2020, cycle length was expected to decrease until 2050 in response to a warmer climate.

For each cultivar combination described above, we evaluated the viability of soy–maize double cropping from the gross revenue, since the majority of the farmers that choose to adopt soy–maize double cropping export both crops, which allows compensation when one crop has lower prices [34]. Moreover, soybean prices in the last years were almost the double of maize prices [35]; thus, the analysis considering crops prices was more practical and realistic to assess the economic impacts in double cropping.

We calculated the gross revenue variation of each crop (gross revenue (GR) in US Dollar, USD) based on the 2016 observed yield (Y_{2016}, ton.ha^{-1}), the 2016 planted area (A_{2016}, ha), the simulated yield ratio $\left(\frac{Y_{2041-2050}}{Y_{2011-2020}}\right)$, and the average 2011–2016 soy and maize prices (414.58 USD/ton and 198.75 USD/ton, respectively) ($P_{2011-2016}$) [35] (Equation (2)).

$$GR = Y_{2016} \times A_{2016} \times \frac{Y_{2041-2050}}{Y_{2011-2020}} \times P_{2011-2016} \tag{2}$$

The 2016 planted area was fixed throughout the analysis period because we assumed that newly deforested areas were converted to pasturelands instead of new soybean or maize areas (totaling 6.77×10^6 ha and 2.22×10^6 ha for soy in MT and MATOPIBA, and 3.35×10^6 ha and 9.25×10^4 ha for maize off-season, respectively, in the same regions). The soybean and maize off-season 2016 yield is the ratio between the production and planted area for each crop in tabular form and for each micro region from IBGE.

The commodities' prices also did not vary throughout the period. As INLAND did not simulate the effects of plant diseases on yield, we evaluated the gross revenue only until November 15, when climate conditions are less favorable to infection by Asian soybean rust in the region (Figure S5).

3. Results

3.1. Effects of Climate Change on Maize Off-Season Yield

The simulations of the maize off-season with an average of 120 days of cycle length indicate that, in both climate scenarios, the changes in yield varied both spatially and with the sowing date (Figure 2).

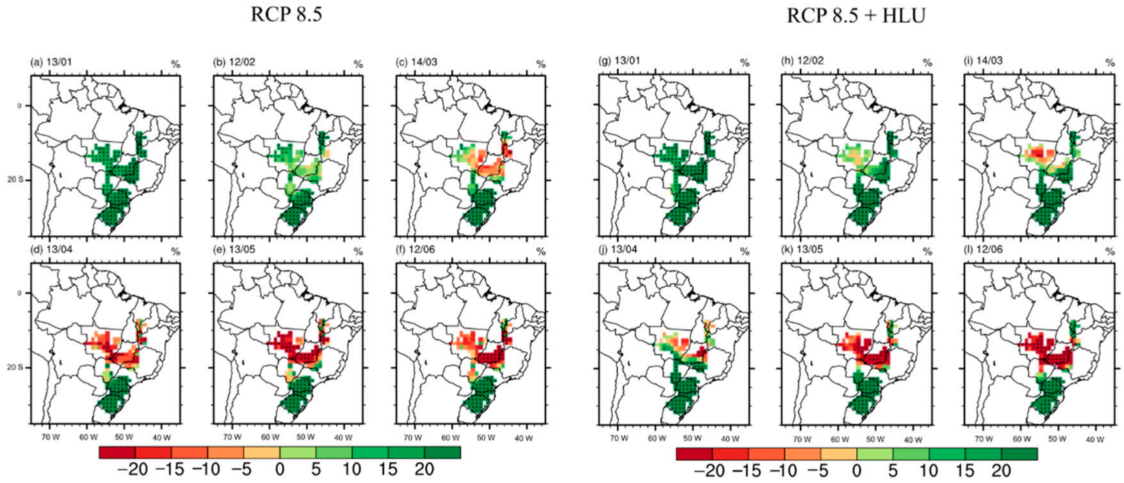

Figure 2. Percentage change in maize off-season yield from 2011–2020 to 2041–2050 for the middle of each month. In (**a**–**f**) results from RCP 8.5. In (**g**–**l**) results from RCP 8.5 + HLU. Dots represent pixels with statistically significant changes in yield according to Student's *t*-test (α = 5%). The average productivity changes for each region, sowing date, and scenario are listed in Tables S1–S4.

The no-adaptation scenario indicated that maize off-season yield did not decline for January sowing dates. However, sowing after February led to yield losses that increased as the crop was sowed later for both climate scenarios (Figure 2 and Figure S7). In addition, for each sowing date, yield losses were greater in RCP 8.5 + HLU than in RCP 8.5 (Figure 2 and Figure S6).

The timing of yield losses indicated that there was a threshold sowing date until when there was no expressive yield reduction in soy–maize double cropping until the middle of the century. In MT these dates were 12 February (RCP 8.5) and 2 February (RCP 8.5 + HLU), while in MATOPIBA dates were 2 February (RCP 8.5) and 24 March (RCP 8.5 + HLU). The associated soybean sowing dates of this cultivar combination were 15 October (RCP 8.5) and 5 October (RCP 8.5 + HLU) in MT and 5 October (RCP8.5) and 25 November (RCP 8.5 + HLU) in MATOPIBA.

Sowing by the middle of March decreased maize yield by 10% in southern MT and MATOPIBA (Figure 2c). Again, high deforestation levels led to greater yield losses. Simulations also show that sowing after the middle of March may cause yield losses greater than 20% and may be unviable.

Delaying sowing operation with the aim to adapt to a later onset of the rainy season to ensure greater productivity of soybean as proposed by Pires et al. [4] resulted in a decrease in maize yield for almost all sowing dates in both scenarios. The more delayed the sowing dates, the greater the losses were simulated in all regions, except for the southern region of the country (Figures S1–S4).

The maize off-season yield losses simulated in MATOPIBA and MT regions were related to water stress during the growing season (Figure 3). Decreased soil moisture during the crop development led to stomatal closure and limited photosynthesis [36] (stomatal conductance and photosynthesis were linked in the model). Even though scenarios with high atmospheric CO_2 concentration were usually expected to have a no-change or slight increase on C4 crop yield [37], our results showed that this physiological effect of CO_2 was not sufficient to avoid the maize off-season yield losses caused by the water stress in MT and MATOPIBA. Other producing regions, such as the southern part of the country, did not show precipitation reduction (Figure S8) and presented increased maize yield.

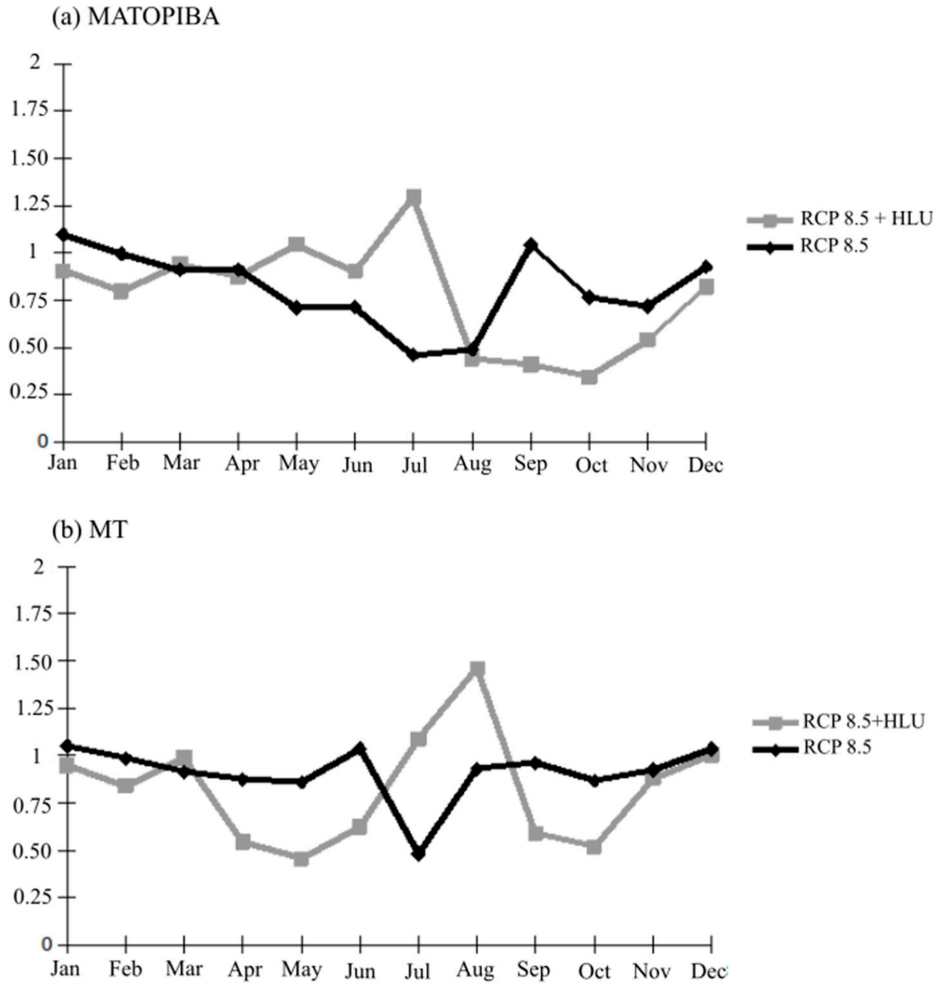

Figure 3. Precipitation change between 2041–2050 and 2011–2020 $\left(\frac{Prec_{2041-2050}}{Prec_{2011-2020}}\right)$ for each study region: (**a**) The region formed by the Brazilian states of Maranhão, Tocantins, Piauí, and Bahia (MATOPIBA) and (**b**) Mato Grosso state (MT) for both scenarios. In 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, and deforestation levels of both biomes in the last decade remain almost the same, as demonstrated by Pires et al. [4].

3.2. Effects of Climate Change on the Viability of Double Cropping in the Future

The gross revenue (GR) was evaluated according to the sowing and harvesting windows of each region. In Brazil, soybean sowing operation can only begin after the end of the sanitary break. In MT, the sanitary break currently lasts from 15 June to 15 September [38], while in MATOPIBA it lasts from is 1 July to 15 October within the study area [39–42]. Considering these restrictions, we evaluated the gross revenue from 25 September and from 25 October for MT and MATOPIBA, respectively.

In general, later soybean sowing dates led to greater gross revenue, indicating a more favorable climate as the rainy season develops in the region. In contrast, maize off-season gross revenue was smaller for later sowing dates due to a decrease in yield (Figures 4 and 5) caused by a reduction in precipitation, photoperiod, and temperature by the end of the rainy season and beginning of the dry season, for both climate scenarios (Figure 6a,b and Figure 7a,b). These changes in maize and soybean yield are illustrated in Figure 4 (RCP 8.5) and Figure 5 (RCP 8.5 + HLU).

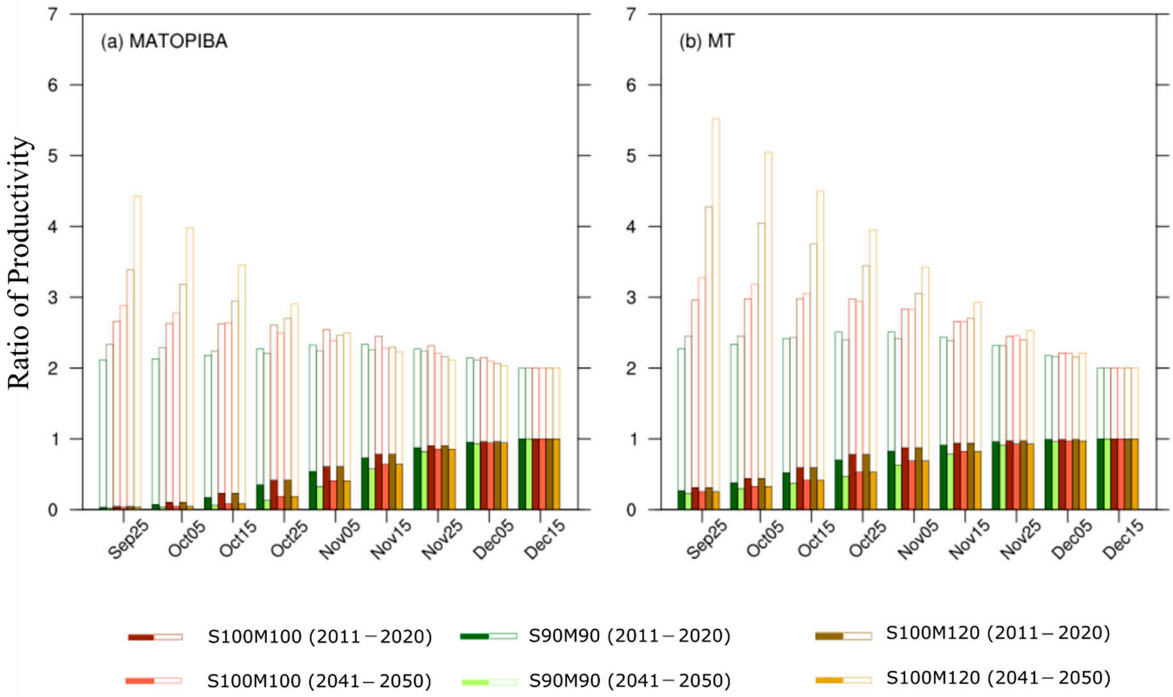

Figure 4. Yield ratio for each sowing date according to yield of 15 December $\left(\frac{Y}{Y_{15/12}}\right)$ for each decade and cultivar combination for soy–maize double cropping according to RCP 8.5 scenario in (**a**) MATOPIBA and (**b**) MT region. The filled and blanked bars represent soybean and maize yield ratio, respectively, for each cultivar combination and period.

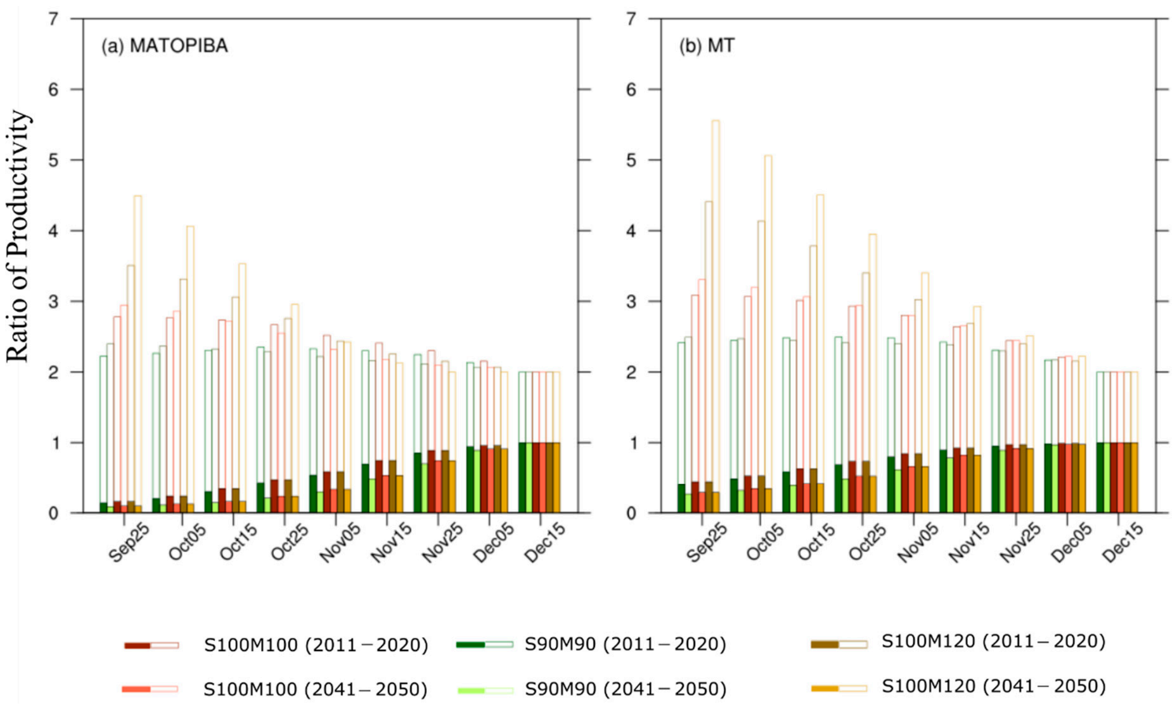

Figure 5. Yield ratio for each sowing date according to yield of 15 December $\left(\frac{Y}{Y_{15/12}}\right)$ for each decade and cultivar combination for soy–maize double cropping according to RCP 8.5 + HLU scenario in (**a**) MATOPIBA and (**b**) MT region. The filled and blanked bars represent soybean and maize yield ratio, respectively, for each cultivar combination and period.

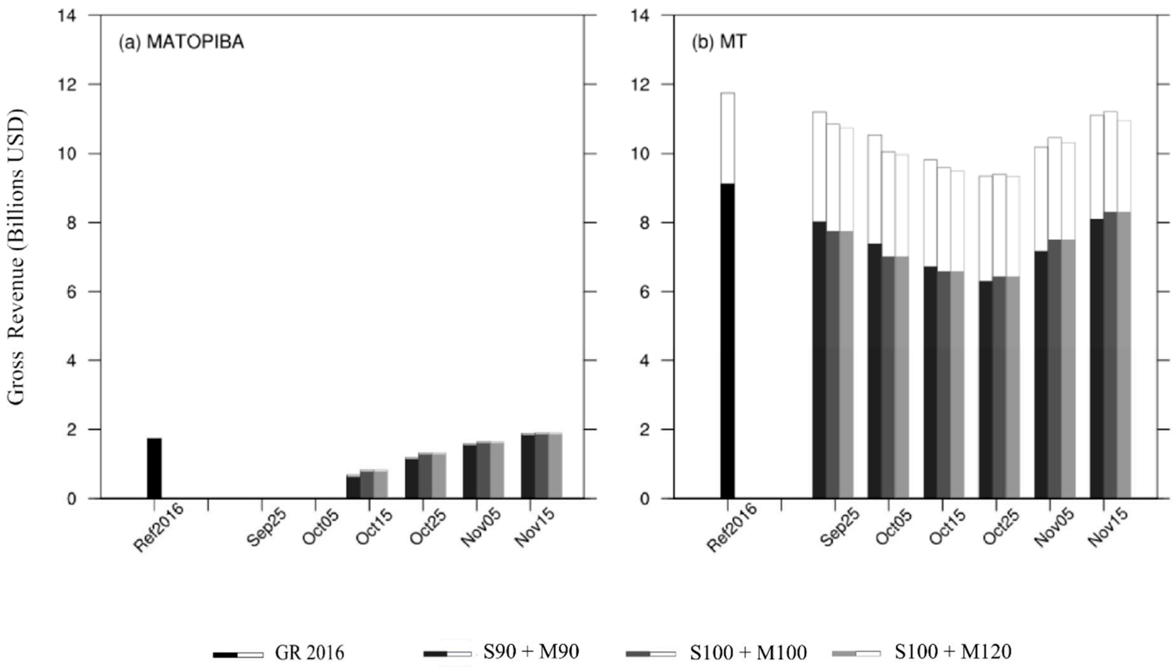

Figure 6. Gross revenue variation (2011–2020 to 2041–2050) of soybean and maize off-season for each sowing date in MATOPIBA (**a**) and MT (**b**), for RCP 8.5. In MATOPIBA, the sowing dates of 25 September, 5 October, and 15 October are within the period of sanitary break for the region. The filled and blanked bars represent soybean and maize gross revenue, respectively, for each cultivar.

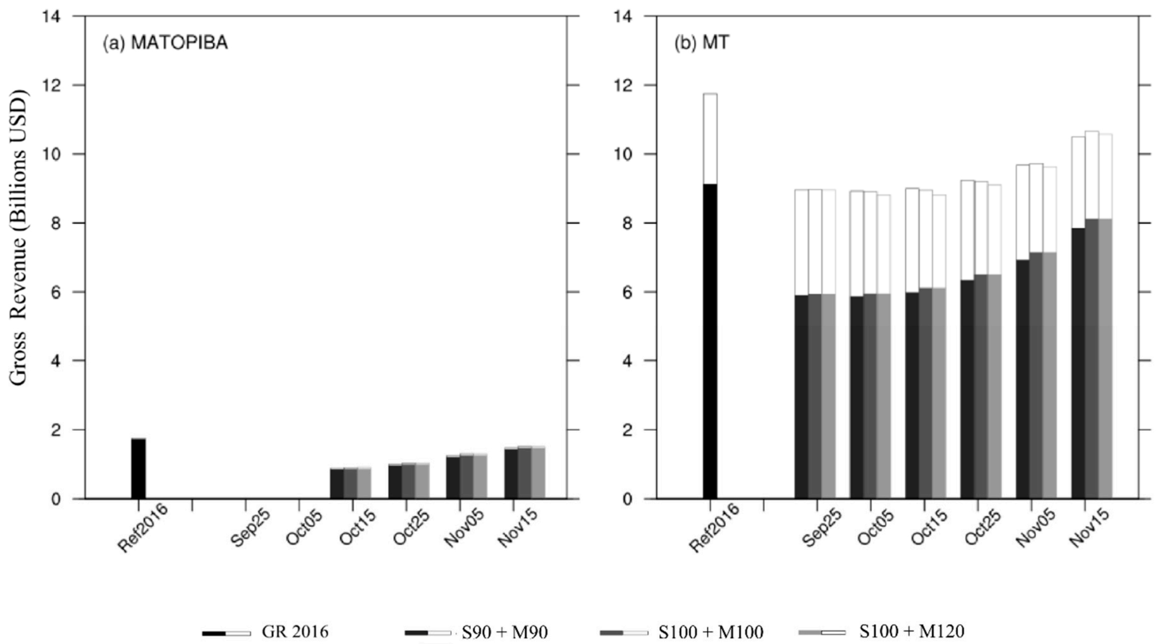

Figure 7. Gross revenue variation (2011–2020 to 2041–2050) of soybean and maize off-season for each sowing date in MATOPIBA (**a**) and MT (**b**), for RCP 8.5 + HLU scenario. In MATOPIBA, the sowing dates of 25 September, 5 October, and 15 October are within the period of sanitary break for the region. The filled and blanked bars represent soybean and maize gross revenue, respectively, for each cultivar.

For both scenarios, the impacts were greater in soybean than in maize gross revenue (Figures 6 and 7) due to a more intense climate change effect in the dry-to-wet season transition, when soybean was sowed, and when vegetation evapotranspiration provided most of the moisture to the atmosphere [43].

Climate change, in both scenarios, led to a decrease of all cultivar combinations' gross revenue as compared to 2016 (here considered our reference). Double cropping gross revenue could decline around 1 billion USD in MATOPIBA in RCP8.5 and RCP8.5 + HLU from 2011 to 2050 compared with the reference. Greater losses could occur in MT in the same period, reaching 2.8 (2.3) billion USD in RCP8.5 + HLU (RCP8.5). The lowest gross revenue occurred in $S_{100}M_{120}$, the cultivars closest to the currently cultivated in the region (Figures 6 and 7) in both scenarios and almost all sowing dates, and hence the greatest impacts of climate change on yield (Figures 4 and 5). The cultivar combination $S_{100}M_{100}$ showed a slightly higher gross revenue than $S_{100}M_{120}$ in the sowing dates until November, indicating that a maize cultivar with 100 days of cycle length could avoid intense climate effects by the end of the cycle and may be more resilient to climate change than the one with 120 days. The $S_{90}M_{90}$ gross revenue was higher than other cultivar combinations tested in this study for MT in RCP 8.5 (Figure 6). However, its gross revenue was not equal or higher than the reference of 2016.

Finally, RCP 8.5 + HLU led to smaller gross revenue than RCP 8.5 for all sowing dates in both regions and for all cultivar combinations (Figure 7). In this scenario, the gross revenue in MT remained nearly the same among the three-cultivar combination, but lower than the reference (Figure 7). The same occurred in MATOPIBA, where no cultivar combination showed a higher gross revenue than the reference among all combinations tested. In fact, in the best case the gross revenue in MATOPIBA was the half that of the reference (Figure 7a), even for RCP 8.5 (Figure 6a). This result indicated that neither sowing dates' adaptation or early maturity cultivars might compensate for the effect of land cover and climate change in this region.

4. Discussion

The results indicate that, in addition to soybean, maize off-season yield could be affected by climate and land cover change until 2050 in MT and MATOPIBA, the main Brazilian producing regions. The negative effects of climate change on maize yield do not extend to the southern part of the country and are concentrated on Central Brazil, close to the deforested area and where an increase in dry season duration is predicted [10,13,15,43]. The maize off-season yield losses simulated are close to those simulated by Andrea et al. [21] for the RCP 8.5 scenario until the middle of the century. The maize off-season yield losses might reflect not only the effects of future climate change, but also indirect effects, due to a delay in sowing dates caused by a delay in soybean sowing operation in a later wet season onset. The later sowing of maize due to a later sowing and harvesting of soybean may cause yield losses due to water stress in the end of the maize growing season [9,44].

As soy–maize double cropping is predominantly rainfed in MT and MATOPIBA, it is very sensitive to the rainy season duration. The shortening of the rainy season has been observed over the Amazon, mainly in the southern part, and central Brazil [10,13,15,17,45], in places with high agricultural presence. Rainfall reduction is more prominent on the rainy season onset [10,17], but might also occur in the rainy season offset [13,15,43]. In fact, in places with intense deforestation in the Southern Amazon, dry spells higher than 15 days have been occurring at the onset (September, October) and the offset (March, April) of the rainy season [10]. Modeling estimates indicate that the shortening of the rainy season caused by both climate change and deforestation might intensify in the future and increasingly affect double cropping [4,21].

While an adaptation of soybean sowing dates might be sufficient to prevent yield losses, it could implicate in later sowing and lower yield of maize. As our results suggest, delaying the soybean planting operation by 10 days might not be sufficient to guarantee the maintenance of high double cropping with the average cycle length of current cultivars ($S_{100}M_{120}$), indicating that farmers might not have many options to adapt without biomes conservation and technology. Investigating policy and technology alternatives to this scenario might be important research topics for the next years.

An alternative is to reduce crops' cycle length so that double cropping could adapt to a shorter rainy season. Hampf et al. [20] estimated that advances in crop management and genetics could attenuate the impacts of climate change in soybean and maize yield, increasing its productivity in about

40% and 68% until 2040. In addition, Abrahão and Costa [5] concluded that cultivars with 90 days of cycle length for soybean and maize (totaling 180 days) leads to a smaller reduction of suitable area for double cropping than a combination of soybean and maize cultivars that reach 220 days of phenological cycle in MT and MATOPIBA, even though in the latter the area reduction remains high. The results of this study agree with Abrahão and Costa [5] for both regions. The adoption of shorter-cycle cultivars in MT could be a possible solution to maintain highly productive soy–maize double cropping if additional deforestation does not take place, while MATOPIBA might still be affected.

In a high level of deforestation scenario, our results indicate that cultivars' cycle reduction alone might not be sufficient to prevent yield losses in all the study region. Indeed, recent literature have been increasingly strengthening the connection between crops production and deforestation in Brazil [11,46–48], demonstrating that biomes' conservation is essential to a highly productive agriculture. However, Amazon deforestation has been significantly increasing again in recent years after a dramatic reduction in 2005–2014 [23,49], and new cropland areas increased 81% in Cerrado in 2000–2014, the majority of it resulting by the conversion from natural vegetation [50]. Along with an increase in pasturelands, it is estimated that soybean will further expand its area by 10 million hectares until 2028 [51], probably driving double cropping expansion.

The absence of adaptation, technology adoption, and biomes' conservation might implicate that either the first or the second crop show decreased productivity, depending on the sowing date adopted by farmers. In addition, the production of maize cultivated at the beginning of the rainy season has been declining due to area competition with soybeans [29]. A reduced first and second crop production could lead to a decreased supply of soy and maize in the market and directly affect other activities that depend on it, such as poultry and swine feeding. In addition, reduced soybean and maize production could lead to increased deforestation rates to compensate yield losses, triggering a negative feedback that leads to even lower production [11,46].

5. Conclusions

The results of this study suggest that adaptation through the adoption of shorter-cycle cultivars and a delay in sowing dates might not be sufficient to maintain a highly productive soy–maize double cropping system until 2050 in MT and MATOPIBA in the face of climate change caused by both a change in the atmospheric composition and land cover. Delaying soybean sowing dates due to a later rainy season onset offsets soybean yield losses but decreases maize yield. Importantly, higher yield and economic losses are predicted in the scenario with high deforestation levels, emphasizing the need to intensify conservation measures in the region so that regional agriculture is sustainable. Existing conservation public policies must be strengthened, such as the Forest Code, the Nationally Determined Contribution (NDC) to the UN Framework, and the Low-Carbon Agriculture plan [11]. Additionally, the expansion of the soy moratorium to Cerrado [52,53] could play an important role in reducing the intensive deforestation rates in this biome. The effectiveness of these conservation policies might be determinant for the adaptation of regional agriculture to global climate change.

The adoption of highly productive shorter-cycle cultivars, with 180 days total cycle for the two crops in MT may partially offset these effects and increase the profitability of the system. However, adaptation through a delay in sowing dates and the adoption of shorter-cycle cultivars might not be effective to all of the studied regions if deforestation in Amazonia and Cerrado continues, especially in MATOPIBA, where even the best adaptation scenario leads to only the half of the reference gross revenue, and additional adaptation strategies should be assessed considering local specificities.

Finally, the implications to the agricultural market and food security are still challenging to estimate in the region, and further investigation is needed to assess the impact of the predicted effects in double-cropping systems in other productive chains that depend on both soybean and, more critically, maize.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4433/11/12/1310/s1, Figure S1: –Percentage change in maize off-season yield from 2011-2020 to 2041-2050, considering a delay in sowing date of 10 days for RCP 8.5 scenario. Pixels that have statistically significant changes in productivity according to Student's *t*-test (α = 5%) are represented with a dot; Figure S2: Percentage change in maize off-season yield from 2011–2020 to 2041–2050, considering a delay in sowing date of 10 days for RCP 8.5 + HLU scenario. Pixels that have statistically significant changes in productivity according to Student's *t*-test (α = 5%) are represented with a dot; Figure S3: Percentage change in maize off-season yield from 2011–2020 to 2041–2050, considering a delay in sowing date of 20 days for RCP 8.5 scenario. Pixels that have statistically significant changes in productivity according to Student's *t*-test (α = 5%) are represented with a dot; Figure S4: Percentage change in maize off-season yield from 2011–2020 to 2041–2050, considering a delay in sowing date of 20 days for RCP 8.5 + HLU scenario. Pixels that have statistically significant changes in productivity according to Student's *t*-test (α = 5%) are represented with a dot; Figure S5: Daily mean temperature and precipitation in 2011–2020 represented by HadGEM2-ES. The likelihood of Asian rust infestation in soybean is higher after middle of November (~316 days) due to increase in temperature and precipitation; Figure S6: Percentage change in maize off-season yield from 2011–2020 to 2041–2050. In a) to j) results for RCP 8.5 scenario. Pixels that have statistically significant changes in productivity according to Student's *t*-test (α = 5%) are represented with a dot; Figure S7: Percentage change in maize off-season yield from 2011–2020 to 2041–2050. In (a) to (j) results for RCP 8.5 + HLU scenario. Pixels that have statistically significant changes in productivity according to Student's *t*-test (α = 5%) are represented with a dot; Figure S8: Monthly rainfall change during the growing season of maize off-season for 2011–2020 to 2041–2050 period. In *a* to *d* are represented the rainfall change for February to May in RCP 8.5 scenario. In e to h are represented the rainfall change for February to May in RCP 8.5 + HLU scenario; Table S1: Percentage change of maize off-season yield for all sowing dates simulated to MATOPIBA in RCP 8.5 scenario; Table S2: Percentage change of maize off-season yield for all sowing dates simulated to MT in RCP 8.5 scenario; Table S3: Percentage change of maize off-season yield for all sowing dates simulated to MATOPIBA in RCP 8.5 + HLU scenario; Table S4: Percentage change of maize off-season yield for all sowing dates simulated to MT in RCP 8.5 + HLU scenario; Table S5: Maize cultivar with 1900 GDD; Table S6: Maize cultivar with 1600 GDD; Table S7: Maize cultivar with 1500 GDD.

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