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Review

Impacts of Climate Change Scenarios on the Corn and Soybean Double-Cropping System in Brazil

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Abstract: Brazil is one of the main producing and exporting countries of corn and soybean and a continental country with climatic diversity that allows the cultivation of these crops in various agricultural systems. Double cropping is a widely adopted system throughout the national territory, where it is possible to cultivate soybeans at the beginning of the growing season, followed by corn in succession, in the same growing season. The present study aims to systematize the scientific knowledge about the impacts of future climate change scenarios on yield and on the double-cropping system of soybean + corn in Brazil. Systematic review procedures were adopted. The soybean yield is projected to increase in all regions of Brazil under all climate scenarios. Corn yields under future climate scenarios are projected to decline, with the subtropical climate region being less affected than the northern regions. The double-cropping systems of soybean + corn tend to present increasing climate risks in tropical climate regions. Climate change scenarios point to a delay in the start of the rainy season that will delay the sowing of soybeans, consequently delaying the sowing of corn in succession, resulting in fewer rainy days to complete its cycle.

Keywords: agriculture; global warming; crop model; climate change adaptation; tropical climate; subtropical climate; semi-arid climate; crop yield; phenology

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1. Introduction

The last few decades have been marked by a considerable increase in population worldwide, making the food supply and food security the focus of continuing discussions. Current food production needs to almost double in the next thirty years to ensure global food security [1,2]. The need to produce more food is evident every day; however, food production must occur sustainably. Food production areas should not exert pressure on deforestation since forests provide several environmental services for nature and humankind, such as biodiversity conservation, climate regulation, and carbon sequestration [3,4]. Increasing crop yields in consolidated areas is essential to avoid expanding cultivated areas. In the coming years, intensifying agriculture in consolidated areas could save 0.8 billion hectares from deforestation [5–8].

Corn (*Zea mays*) and soybeans (*Glycine max*) are two primary sources of calories and protein for humans and animals essential for the world's food supply. They provide derivatives for direct and indirect human consumption and serve as a basis for animal feed and as raw materials to produce biofuels [9]. Brazil occupies a prominent position worldwide as a food supplier, ranked among the leading exporters of cereals, oilseeds, fruits, and animal protein. The country is the world's largest soybean producer, with 36.95 million hectares grown and 124.8 million tons produced in the 2019–2020 harvest. Brazil is the third largest corn producer in the world, having grown approximately 18.5 million hectares in the 2019/2020 harvest and produced 102.5 million tons [10].

One of the main reasons for these high production levels of corn and soybean is the possibility of cultivating both crops within the same growing season in an intensive production system called the double-cropping system. In this system, early soy is sown at the beginning of the growing season (September/October), and after its harvest (January/February), corn is sown on the same plot. Currently, corn produced in this system represents 73.2% of the total national production, adding 75 million tons to the national harvest in the last four decades [10]. Therefore, this intensive production system received special mention in the latest report [9], which attributed the rapid growth of Brazilian corn production to the possibility of two harvests in the same growing season, new varieties, and targeted government support.

Contrary to the need to increase food production, some researchers have warned that climate change may reduce global food production in the coming decades. Climate change will positively or negatively affect the yields of crops grown commercially in the many regions of the world where they are produced, depending on the severity and type of these changes [11–17]. Future climate change, associated with land use change and population growth, will put global food security at risk and increase malnutrition, especially in less-developed countries [18]. In particular, in most of South America and Africa, Australia, and Central Asia, 50% or more of the population will be at risk of malnutrition when assuming climate change scenarios and their impacts on food production in the projections [19,20]. There is evidence that climate change has negatively affected the yield of Europe's main crops since 1974, although without risks to food security [21]. On the other hand, future climate change scenarios suggest that the yield of most major crops is expected to increase by +5% to +15%, depending on the crop and the region of Europe [22].

In addition to decreasing food security and increasing risk of malnutrition, crop yield losses due to climate change are affecting several countries' economies, especially in the least-developed countries, which generate a significant part of their income in this sector. Climate change caused by the rise in CO_2 levels since the pre-industrial period currently represents an annual loss of USD 22.3 billion for corn, 6.5 billion for soy, 0.8 billion for rice, and 13.6 billion for wheat worldwide. Yield losses are located mainly in low latitudes [23]. For the same crops, each degree Celsius increase in the global average temperature would reduce the global yields of wheat by 6.0%, rice by 3.2%, corn by 7.4%, and soybean by 3.1% on average [24].

Global climate change has been occurring due to the increase in the concentration of CO_2 in the composition of atmospheric air caused by anthropic action, causing, among others, an increase in global temperature and changes in the amounts of rain and in the pattern of rainy seasons, a trend that will be maintained in the coming decades. Projections indicate that the temperature in Brazil will increase in a generalized way. Some regions of the country will register greater increases in temperature and frequency of heat waves, in addition to drier periods, for example, the Midwest, Northeast, and Southern Amazon regions. In the South, there should be greater volumes of rain, concentrated in short periods of global warming of 1.5 °C. An IPCC Special Report on the impacts of global warming warned of an increase of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [25].

Datasets analyzed over the past four decades revealed statistically significant warming patterns in almost all regions of the country and a reduction in consecutive wet days, an increase in consecutive dry days, and a reduction in total annual precipitation. Climate projections suggest intensified warming patterns under future scenarios with an increase in the concentration of atmospheric CO_2. Average temperature estimates for the middle and end of the century will increase by between 1.4 °C to 1.9 °C and 1.6 °C to 3.2 °C compared to the current level, respectively, varying according to representative concentration pathway scenarios (RCPs) 4.5 and 8.5. Hot days and nights will tend to be more frequent, and the duration of heat waves is expected to increase in all regions throughout the 21st century [26]. The impact of climate change on precipitation varies according to climate model and region.

However, projections show a 7.75% increase in the global average annual rainfall by the end of this century, with an increase in the heavy precipitation index in all regions [27]. In Brazil, precipitation is estimated to increase on consecutive dry days and decrease on consecutive wet days in almost all regions. According to future scenarios, the frequency and intensity of extremely high rainfall days in Brazil are expected to increase [26].

Increased temperature and reduced rainfall have been identified as the leading causes of yield losses in soybean and corn crops. Some studies point to compensatory effects of the increase in atmospheric CO_2 for some commercial crops, especially in C3 plants like soybean, and less or null in C4 plants like corn [15,28–33]. Regions with colder weather may benefit from the increase in temperature or have fewer negative impacts on the yield of these crops, while the warmer regions will experience the greatest losses. Regionalized studies are required for better understanding [34–36].

Considering the importance of Brazilian soybean and corn production in the context of global food security, the intensification of food production per unit area, and the possible impacts that future climate change will have on these crops, it becomes important to understand the interactions that future climate change will have on soybean and corn crops and agricultural production systems practiced in Brazil. The present study aims to systematize the scientific knowledge about the impacts of future climate change on yield, phenology, and the double-cropping system of soybean + corn in Brazil. As far as we know, this is the first study to systematize scientific knowledge about the impacts of climate change on the soybean + corn double-cropping system in Brazil. The findings provide support regarding the expected impacts and possible strategies for adapting the agricultural sector to future climate change. Following this introductory section, the materials and methods are described in the following section. The results and discussions are presented in the third section. Finally, the fourth section presents the conclusions of the study.

2. Materials and Methods

The present study was carried out using the research synthesis method, particularly a quantitative synthesis that sought to find numerical values for variables of interest in scientific articles published in journals indexed to national and international databases as secondary sources of information [37]. A systematic review was carried out on the selected articles according to the procedures described below and the research flowchart shown in Figure 1.

This study adopted the systematic review procedures developed by the Center for Evidence-Based Conservation (CEBC), restricted by inclusion criteria and defined methods for literature searches, data extraction, meta-analysis, and synthesis [38]. To support the smooth running of a systematic review study, first, it is necessary to elaborate on a research question. This research question needs to meet the established goals, seeking to investigate the relationship between two events and delimit the variables about the topic and the criteria for inclusion of the studies. Some suggested components for elaboration are Population, Intervention, Comparison, Outcome, and Study Type, didactically presented by the acronym PICOT, as shown in Table 1. The defined components seek to meet the objective of the study, which is to analyze the impacts that future climate changes will have on productivity, phenology, and the double-cropping system of soybean + corn crops in Brazil, delimiting the criteria for inclusion of studies.

Only studies based on crop modeling were included because they have a biophysical basis and are the recommended method for this type of measurement [39–45]. The crop models needed to be fed with future climate data. The data are forecast based on CO_2 emission scenarios and modeled by global circulation models (GCM). They present mandatory quantitative yield data for at least one of the target crops in different time horizons until the end of the century and to a baseline.

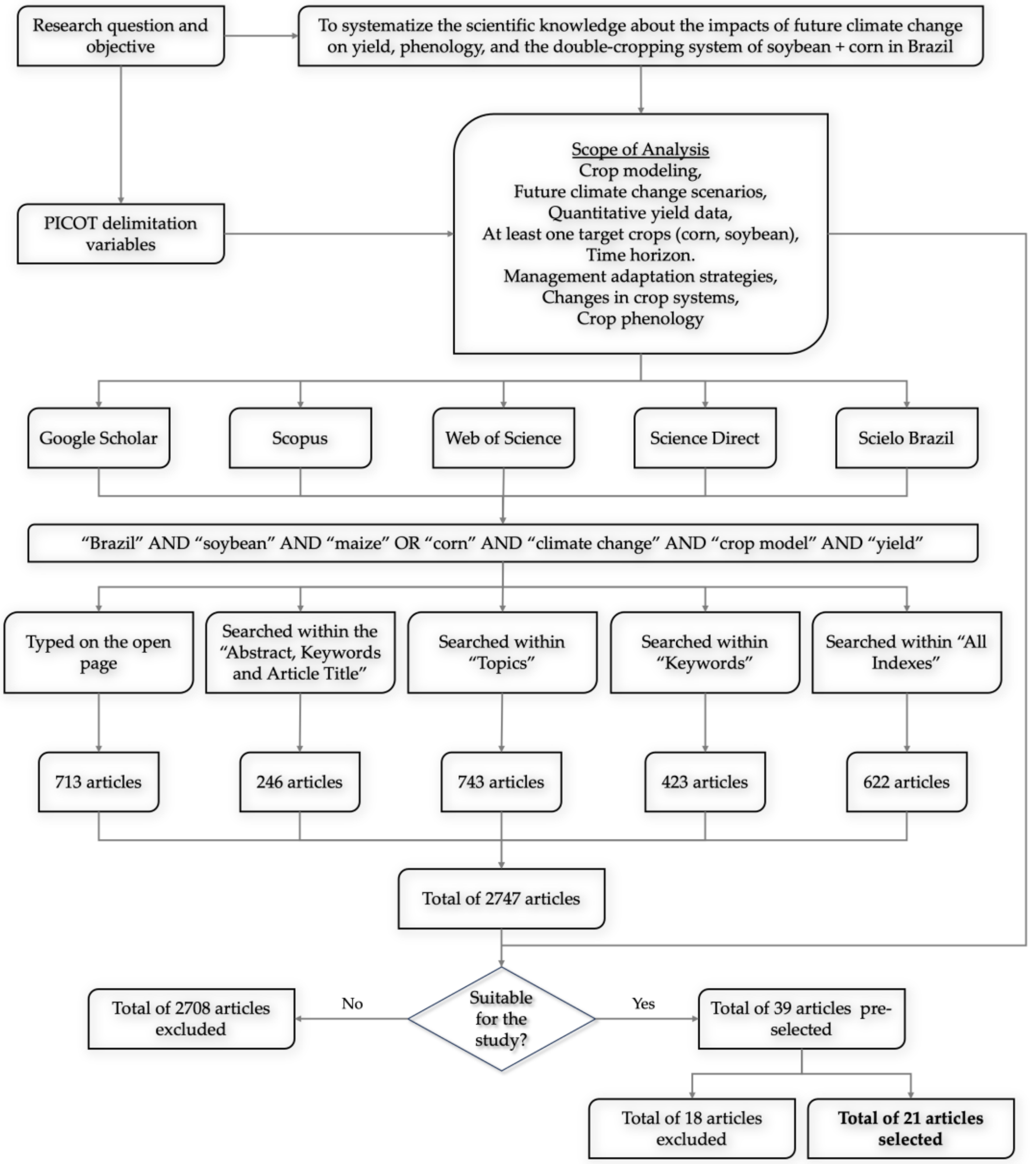

Figure 1. Overview of the methodological steps followed in carrying out this study. Source: Elaborated by the authors.

Table 1. The acronym PICOT and the definitions of the variables.

P.I.C.O.T.	Variable Definition
Population	Soybean and corn crops grown in Brazil.
Intervention	Future climate changes projected up to the end of the 21st century with Global Circulation Models (GCMs), including temperature, precipitation, and CO_2 concentration as variables.
Comparator	Current climate (baseline)
Outcomes	Quantitative results of crop yields. If available, data on the impacts of climate change on crop phenology, crop system, and possible strategies for adapting crop management.
Types of studies	Studies that used crop models to estimate crop yields.

Data referring to management adaptation strategies, changes in crop systems, and differences in crop phenology were gathered, presented, and analyzed qualitatively to support the analysis of the results and discussions. However, these variables were not considered as inclusion or exclusion criteria for the studies in this research.

The search for articles was carried out in five scientific database platforms: Scopus, Web of Science, Science Direct, Scielo Brazil, and Google Scholar. We defined and used an appropriate set of terms to retrieve as many articles aligned with the scope of the study as possible. The search terms vary according to the specific features of the database platform's search engine and its sensitivity in retrieving articles on the topic. We defined specific search terms in order to retrieve articles whose content met the objective of the study. In the databases with higher sensitivity, more restrictive terms were used, while in those with lower sensitivity, broader terms were used. In the first step of article selection, called pre-selection, the title and abstract of the retrieved articles were analyzed, aiming to identify the presence of the variables needed for the article to be included in the study. In the second step of the selection process, the pre-selected articles were read in full to determine if they met all the inclusion requirements, and when they did not, they were discarded. The search was carried out until 12 March 2020.

In the Scopus database, the following string of terms "Brazil" and "soybean" or "corn" or "maize" and "climate change" or "global warming" were searched within the "Abstract, Keywords and Article Title", and 246 articles were retrieved. In the Web of Science, the "topics" used were: "Brazil" and "soybean" and "maize" or "corn" and "climate change" and "crop model" and "yield", and 743 articles were retrieved. In the Scielo Brazil database, the search included the terms "Brazil" and "soybean" or "corn" or "maize" and "climate change" or "global warming" applied to "All Indexes," and 622 articles were retrieved. In the Science Direct platform, the "keywords" field was filled out with the terms "Brazil" and "maize" or "corn" or "soybean" and "climate change" or "global warming" and "yield", and 423 articles were retrieved. Finally, in the Google Scholar platform, the terms "Brazil" and "climate change" and "soybean" or "corn" or "maize" and "crop model" and "yield" were typed on the opening page, and 713 articles were found.

As a result of the search in all databases, 2747 related articles were retrieved. After the pre-selection step, only 39 articles met the selection criteria and were pre-selected for the next step. After a careful reading and discussion, 21 articles were found that covered all the requirements determined for inclusion in this systematic review.

Climate impact assessment studies work with a considerable number of variables and scenarios that differ from each other. Some authors assume many of these variables within their structure, which can be mentioned as main differences: scenarios of CO_2 emissions, global circulation models (GCM), crop models, time horizons, regions, and climates, including or not the direct effects of the increase in CO_2 concentration, crop systems, sowing dates, cultivars, and other different crop-management strategies. Due to the large number of variables in each study and the limited availability of data in each one, creating a quantitative set of data by a systematic analysis becomes a challenging task subject to the risk of comparing non-comparable data and generating information of dubious quality.

A qualitative analysis of the yields reported in the articles was performed to avoid such risks, capturing their specificities and categorizing the information. Crop yield variation was organized according to the variables found in the studies, except for the management adaptations, which are qualitatively discussed later. Data were grouped into two groups that directly impact crop yield. One group referred to the time frame assumed in the studies (up to the middle of the 21st century and until the end of the 21st century), and the other referred to the climatic classification of the regions where the studies were conducted. Studies carried out in the two time frames, or with the two crops, or conducted in different climatic zones, were cited once for each frame in the same figure. The findings are presented in a way that indicates the crop model used by the study, if the direct effects of CO2 were considered, and the study from which the data originated.

The classification described by [46] was used to group crop yield by climate type existing in Brazil. These authors classified Brazilian climates in A, B, and C climatic zones following the Köppen [47] criteria. Zone A or tropical includes the Af (without dry season), Am (monsoon), Aw (with dry winters), and As (with dry summer) climates. Zone B, called the dry or semi-arid zone, refers to the Bsh (low latitude and altitude) climate. Zone C, called the subtropical zone, includes Cfa (with hot summers) and Cfb (with temperate summers), both without dry season; Cwa (with hot summers), Cwb (with temperate summers), and Cwc (with cool summers), with dry winters; and Csa (with dry and hot summer) and Csb (with dry and temperate summer) climates. In the present study, Zone A is tropical, B is semi-arid, and C is subtropical. Studies that conducted their analysis in more than one climatic zone and did not present data separated by region were included in the zone where the largest analysis area was included in their respective research.

3. Results and Discussion

A total of twenty-one articles were selected and included in this systematic review. The main relevant variables of these studies for this research are presented in Table 2.

Table 2. Summary of the main variables analyzed in the studies: authors, crop studied, crop models used in simulations, scenarios of assumed CO_2 emissions, periods of comparison, and if the direct effects of CO_2 on plants were considered or not.

Ref.	Crop	Crop Model	Co_2 Emission Scenarios *	Periods	CO_2 Effects
[48]	Corn	AquaCrop	RCP 4.5	1998/2025/2055	YES
[49]	Corn	DSSAT	RCP 4.5 and 8.5	1995/2025/2055/2085	YES
[50]	Corn	DSSAT	SRES A1	2007/2025	YES
[51]	Corn	SISDRENA	RCP 4.5 and 8.5	1993/2058	NO
[52]	Corn	DSSAT	SRES A1	2012/2040	YES
[53]	Corn	DSSAT	SRES A2, A1 and B1	1997/2077	NO
[54]	Corn	DSSAT	RCP 4.5 and 8.5	2024/2055/2085	NO
[55]	Corn	AquaCrop	RCP 4.5 and 8.5	1993/2023/2055/2085	YES
[56]	Corn	DSSAT	RCP 4.5 and 8.5	2020/2055	YES
[57]	Corn	DSSAT	RCP 4.5 and 8.5	2000/2055/2085	YES
[58]	Soybean	Inland	RCP 8.5	2020/2040	YES
[59]	Soybean	AquaCrop	RCP 4.5 e 8.5	2014/2050/2085	YES
[60]	Soybean	DSSAT	SRES A2 and B2	1975/2028/2056	NO
[61]	Soybean	DSSAT, APSIM e MONICA	SRES A1	1988/2055	YES
[62]	Soybean	DSSAT e SoySim	SRES A1 and RCP 4.5	1995/2020/2070	YES
[63]	Soybean	AquaCrop	RCP 4.5	1998/2025/2055	YES
[64]	Soybean + corn	MONICA	SRES A1	2016/2040	NO
[65]	Soybean + corn	DSSAT	SRES A2 and B2	1975/2085	YES
[66]	Soybean + corn	AZS BioMA	SRES A1 and B1	2000/2020/2050	YES
[67]	Soybean + corn	Inland	RCP 8.5	2005/2050	YES
[68]	Soybean + corn	DSSAT	SRES A2 and B2	1975/2020/2050/2080	YES

Note: * The description of the emission scenarios can be accessed in Appendix A. Source: prepared by authors.

Ten of them evaluated the corn crop exclusively, six evaluated the soybean crop exclusively, and five evaluated both crops simultaneously, totaling fifteen articles evaluating corn and eleven evaluating soybeans. Furthermore, among the articles selected for corn, five carried out their evaluations in two different time frames: up to the middle (2050) and up to the end of the 21st century (2100); and one in the two different climatic zones was presented twice each, totaling twenty-one evaluations for corn. The same situation occurred for soybeans, with four articles carrying out their evaluations in these two time frames, in addition to one article whose study was conducted in two distinct climatic zones and was included twice, totaling sixteen articles evaluating soybeans.

Different scenarios of atmospheric CO_2 concentration were used for simulation, representing moderate (SRES B1, B2, and RCP 4.5) and high emissions (SRES A1, A2, and RCP 8.5); more information on climate scenarios can be found in Appendix A. These scenarios provide information for a wide range of Global Circulation Models (GCM). For all scenarios simulated by these models, all climates, and time frames, the temperature is projected to increase. The precipitation simulation showed some differences. Projections point to a reduction in the annual volume and shortening of the rainy season in tropical and semi-arid climates, while the projections for the subtropical climate showed a neutral to a slight increase in the annual volume of precipitation. Some studies pointed to an increase in extreme climatic events, such as droughts or heavy rain, in a short time period.

Among the studies, five did not consider the direct effects of increasing the concentration of atmospheric CO_2 in crops, three for corn and two for soybeans. Nevertheless, several authors have reported the beneficial effects of the increase in the concentration of atmospheric CO_2 on commercial crops. In general, these benefits are realized in the accumulation of biomass and greater yield. Furthermore, such effects have been observed with greater intensity in plants that use the C3 photosynthesis pathway, such as soybean, compared to those that use C4, such as corn [69–72].

Almost all the studies evaluated management adaptations to improve crop yields under climate change scenarios, except for one. The changes in crop-management practices that appeared most frequently were different sowing dates, cultivar maturation, irrigation, fertilization, plant density, and drainage systems, by order of relevance. Ten studies evaluated the impact that climate change will have on the phenological cycle of crops.

The crop model most used was the Agrotechnology Transfer Decision Support System (DSSAT), which for the two specific crops are CSM-CROPGRO-Soybean and CERES-Maize, used in fourteen studies. The second model most used was AquaCrop, a model developed and recommended by FAO, used in four articles. The other models, MONICA, Inland, AZSBio, Sisdrena, APSIM, and SOYSIM, were used only in one or two cases each. As previously reported, this tool has been proven to be effective for carrying out these studies, presenting itself as a fast, practical, and low-cost tool compared to experiments in controlled environments required to verify how climate changes affect crops. To reinforce the fitness of these models, in the following sections, the results of some experimental studies are presented in comparison to the results simulated by the crop models.

3.1. Expected Impacts of Future Climate Changes on Soybean

For the soybean crop, it is possible to observe that most of the analyzed studies demonstrate that there will be yield gains in future climate change scenarios, as shown in Figure 2. Among the sixteen studies considered, five demonstrated possibilities of yield losses, and only one did not present the possibility of yield increases among its variations. The trend of yield increases captured by the studies did not result in a net negative variation between the projected maximum gains and losses, with a significant variability in this indicator. The maximum increase in yield could be +85%, and the maximum projected loss could be −80%.

The main cause pointed out for the increase in soybean yield is the increase in the concentration of atmospheric CO_2. Several authors have shown the positive effects of extra CO_2 fertilization on C3 plants, such as soybeans [73,74]. Gains of up to a 40% increase in photosynthetic efficiency were reported [70]. The plant height, leaf area, dry mass, water use efficiency (WUE), and yield also increased [75]. For this reason and because the CO_2 accumulation in the atmosphere is increasing, it is recommended to consider it as a variable in modeling assessments. Only two studies did not consider the direct effects of the highest CO_2 concentration, one in each climate type. Both assume in their results that there may be yield losses and gains, a different trend from the increasing trend shown in most studies. The soybean yield ranges from neutral to an increase of up to 60% when only the studies that considered the direct effects of CO_2 are considered and the maximum and minimum values for yield variations are disregarded, assuming all the other study variables are the same.

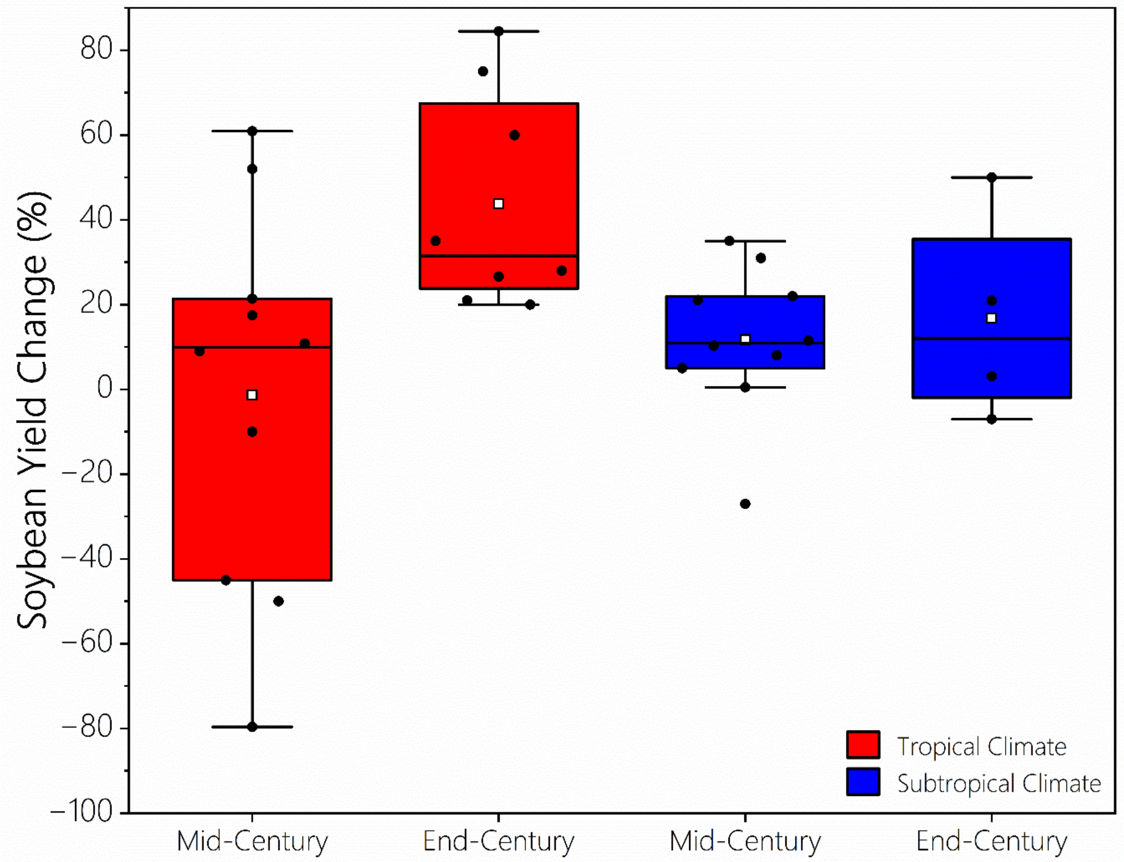

Figure 2. Studies that evaluated the impact of future climate changes on the soybean yield in different Brazilian climatic zones and temporal cuts. Variations according to treatments and variables used in each study. Source: prepared by authors.

Nine studies were conducted in the tropical climate. Six of them assume only increased yield, one only loss, and two consider the possibility of having both losses and gains. However, some considerations are needed regarding this statement, as some of the studies presenting losses have methodological specificities that need to be considered.

Among the three studies suggesting the possibility of future yield losses, the negative result reported by [64] can be attributed to the fact that the direct effects of CO_2 were not considered. The losses found by [58] are attributed to the treatments used since the yield of early soybeans planted at the beginning of the growing season (25/9) and medium-cycle soybean varieties planted at the optimum season are evaluated. Losses are caused by the fact that the study fixes sowing in the first planting season, and the climate models indicate a delay in the start of the rainy season and a reduction in rainfall volume at the beginning of the sowing season. When analyzing only soybean sown at the beginning of the rainy season, which occurs most frequently in the Brazilian tropical region, there are no losses, further reinforcing the tendency to increase yield. Another study [66] differed from the others with the highest losses and was the only one that did not present the possibility of increasing yield in future climate scenarios. The authors explain the losses caused by the shortening of the soybean cycle, especially in the reproductive phase.

When comparing tropical and subtropical climates, it is possible to state that the biggest gains and losses projected are found in the tropical climate. One study [58] was the only one that presented the results in an accessible way, allowing separate analyses for the two climates considered. This study presented results for several regions of Brazil and part of Paraguay and Argentina, grouped here according to the prevailing climate in the respective places. The yield increases will be greater in South Brazil and Argentina than in Central Brazil, Matopiba, Mato Grosso, and Paraguay, both for the treatment of early planting with an early-cycle variety and when planting a medium-cycle cultivar at the ideal time. Although an agreement of increased yield predominates among the studies in a subtropical climate, the results presented in Figure 2 suggest more noticeable gains in the tropical climate, especially beginning in the second half of the 21st century.

As reported, there is an agreement in the findings reported in studies conducted in the subtropical climate compared to those in the tropical climate. There is less variability between the maximum and minimum yield reported, with 50% being the greatest yield increase and 27% being the greatest loss. It must be considered that the study presenting the greatest loss in the subtropical climate was the only one that did not consider the direct effects of the increase in the atmospheric CO_2 concentration. When this is disregarded, there is a clear tendency to increase yield. The variation in yield averages between the evaluated periods is also smaller in the subtropical climate.

Corroborating the yield data presented so far, some studies have reported gains in soybean yield exposed to high concentrations of CO_2 similar to those reported by the authors under Brazilian conditions determined by modeling [76,77] or experiments in a controlled environment [78,79]. Although the increase in temperature caused by the accumulation of atmospheric CO_2 causes yield reduction, the beneficial effects of fertilization with CO_2 exceed offset losses and promote yield gains [80,81].

The analyzed studies show a tendency to increase soybean yield over the years, being more accentuated at the end of the century than in the middle in both climates. This is possible because most atmospheric CO_2 emission scenarios demonstrate the continuity and increase in emissions in the future, and the soybean crop will benefit from this. This trend is more evident when analyzing the studies [59,62,63,68] in which time frames are compared within the same studies, assuming the same research variables. This fact demonstrates an increasing soybean yield in Brazil since future climate changes must increase over the years.

The forecast is that the phenological cycle of soybeans will be reduced due to future climate changes. All the studies that made this assessment corroborate this statement. However, there are some discrepancies regarding the amount of time reduction, ranging from 2 to 13 days, with the majority showing a reduction from 2 to 7 days. Nevertheless, the soybean's phenological cycle will be less affected than the corn cycle. The crop sensitivity to the photoperiod mainly regulates the soybean cycle, but the temperature also fulfills this function. Therefore, when the air temperature is above or below the optimum temperature for the crop, the physiological cycle is shortened or lengthened [82]. Therefore, the increase in temperature evidenced by the authors explains why the cycle will become shorter.

Contrasting the cycle reduction caused by increasing temperature, ref. [79] showed that when CO_2 increases and other climatic variables are held constant, the phenological cycle of soybeans tends to lengthen and produce more biomass. This explanation can be applied to [57], which stated that the soybean cycle tends to become 16% longer, on average, in future scenarios.

Several authors have demonstrated that management adaptations can positively impact crop yield compared to the practices currently used. Among the most mentioned adaptation practices are the adequacy of sowing time, choice of cultivars with a longer cycle, irrigation, and adequacy of fertilization [58,60,62,65,66,68]. According to [33], sowing on the ideal date and choosing appropriate genetic material can mitigate yield losses by temperature.

Concerning management adaptations and the possible increase in yield under future climate change scenarios, ref. [62] brings some interesting considerations to the debate. They evaluated irrigation, sowing date, different groups of cultivar maturation, and plant density in the conditions of the South, comparing two scenarios of future climate change with the base year. The findings suggest that when the management adaptations are optimized, they can increase the crop yield. However, the yield increases resulting from these adjustments were manifested both in the future scenarios and in the base scenario, except for irrigation, which provided a slightly greater increase in future scenarios (~21%)

than in the base year (16%). They concluded that changes in crop management would not increase soy's resilience to future climate changes compared to current conditions.

3.2. Expected Impacts of Future Climate Changes on Corn

Initially, it is highlighted that most studies showed a reduction in the corn yield under scenarios of future climate change, as shown in Figure 3. Most of the studies suggest only the occurrence of yield losses or greater probabilities of yield losses rather than yield gains in future scenarios. The losses reached up to 88%, while the biggest positive increase variation was 33%. Note that the variations shown in Figure 3 refer to those found in the studies, assuming the numerous variables used as a method for their simulation, except for the management adaptations tested.

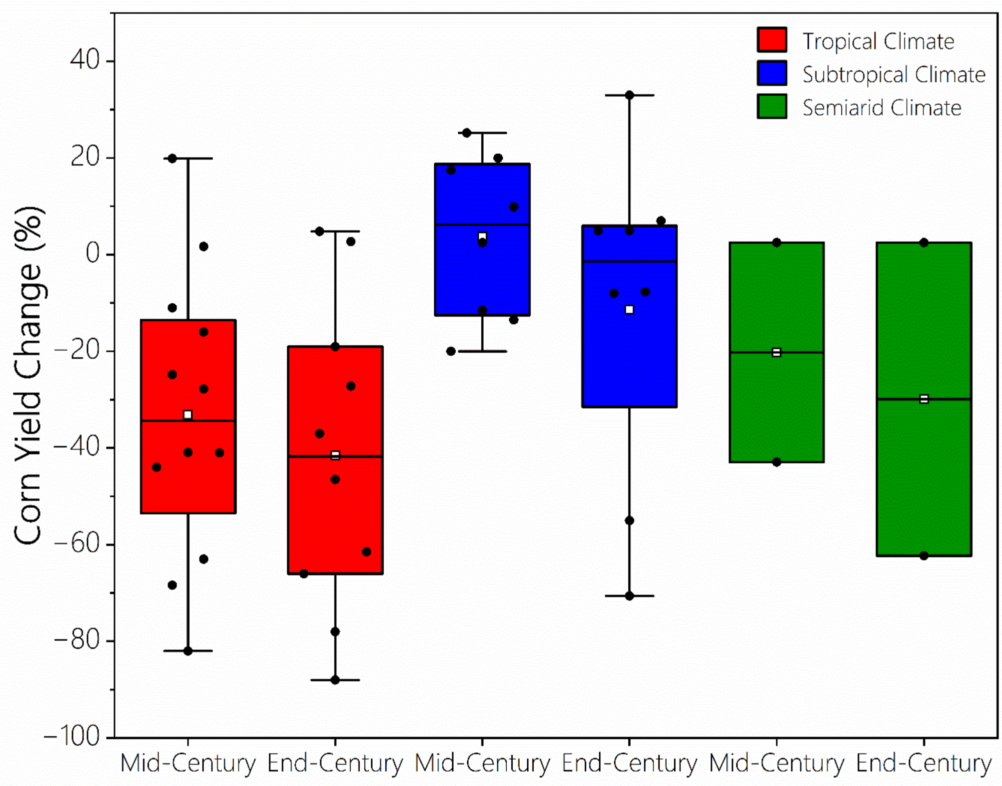

Figure 3. Studies that evaluated the impact of future climate changes on the corn yield and phenology in different Brazilian climatic zones and time frames. Variations according to treatments and variables used in each study. Source: prepared by authors.

The corn yield losses were more accentuated in tropical and semi-arid climates. In these two climate zones, yield behaved similarly, and the maximum positive variation was 20%. Only four studies showed the possibility of increasing yield, while the others showed generalized yield losses. Average losses vary between −20% and 30% for the semi-arid climate and between −30% and −40% for the tropical one. In experiments conducted in a controlled environment similar to tropical and semi-arid climates, ref. [83] found that grain yield was reduced by 48% with an increase of 3 °C in the temperature, while ref. [84] found a yield reduction of 15% and 23.5% for a 1.5 °C and 3 °C temperature increase, respectively. Such a finding is corroborated by [85], who evaluated the effects of climate change on corn yield in a semi-arid climate and identified a 9% decrease in yield for each 1 °C increase in temperature. Another study [49] identified yield losses of 0.5 to 1.0 t ha^{-1} for a 1 °C increase in temperature in Brazil.

Yet another study [67] was the only one to analyze the impacts of climate change in two different climate zones and present them separately. It is possible to perceive both the possibility of gain and loss in the tropical climate, while the yield is projected to increase in the subtropical region. The cited study evaluated several sowing times of second-crop corn from January 13th. The yield results in these regions were negatively affected by the delay in sowing. In the tropical region, the yield reduction in the later sowing periods was due to the increase in temperature and the shortening of the rainy season, while in the subtropical climate, the increase in temperature had less of an effect on late sowing since the milder warming can be beneficial.

There was a greater diversity of results for the subtropical climate, from an increase in yield of up to 33% to losses of up to −70%; average losses varied between 0 and −10%. However, the greatest yield losses appeared in [54,56] conducted in Southeastern Brazil. These studies were carried out under the Cwa (subtropical dry winter) climatic classification, while the other studies were carried out in South Brazil under the Cfa (humid subtropical) climate.

Analyzing the Cfa-south and Cwa-southeast climate classification, it is possible to verify a tendency varying from neutrality to a slight increase in yield in the southern region since just one study showed yield reduction. Southern Brazil is the country region with the lowest average temperatures during the year. Evaluating corn yield using crop modeling in similar climates, ref. [86] found an increase in yield between 4% and 7%, while the yield found by [87] varied from 1.5% to 18.7%, both up to the middle of the century. These results agree with the findings presented here. In a controlled environment experiment, the corn yield increased by 25% when the temperature increased by 2.1 °C, and the CO_2 concentration was maintained at 700 ppm [78].

Some studies report that there were no yield gains for corn subjected to higher concentrations of atmospheric CO_2 [88,89]. However, some studies indicate that under conditions of water stress, maize shows yield gains under high CO_2 concentrations. These gains come mainly from the stomatal regulation of C4 plants [87,90–93]. Such an explanation is corroborated by other studies that concluded that the WUE might increase for the first and second corn-growing seasons in Brazil under future climate change scenarios [48,53]. Data that counter these findings reporting lower efficiency in the use of water by corn crops are also found [49]. The trend in yield loss found in the last study was the highest among all studies evaluated, up to 88%. Higher yield loss may have affected the final WUE since it represents the ratio between crop yields and water consumption.

It is possible to clearly observe that corn yield losses are accentuated at the end of the century for all climates. When comparing time horizons within the same studies, we can identify a tendency to maximize losses in yield over time. Studies reported in [48,49,55,57] carried out in tropical and semi-arid climates showed yield reduction up to the middle of the century, and it can be observed that the losses are accentuated until the end of the century. In [49], the losses are 55% up to the middle of the century for the off-season corn sown at the earliest possible time. For the end of the century, losses vary between 63% and 78%, reaching 88% when the late sowing is analyzed.

As for corn's phenological cycle, it is possible to establish that there will be a reduction in the number of days for the crop to complete its cycle, which was observed in all studies analyzing it. However, the cycle reduction varied between studies, with a minimum cycle reduction of 2 days and a maximum of 29 days. This result can be explained by the fact that the corn crop cycle is regulated by the thermal sum, where the accumulation of degree days must occur to reach its phenological development stages.

Many authors, such as [48,49,52,55,56,65,66], point out that the reduction in the physiological cycle of corn crops in Brazil due to the increase in temperature will be the leading cause of yield losses in the future. Both agree that cultivars with longer cycles can alleviate this problem and mitigate productivity losses, as they remain longer in crops, producing and accumulating biomass, compensating for losses due to shortened cycles. Given the evidence presented and their agreement, it is possible to state that using genetic materials with a longer cycle can reduce the negative impacts of increasing temperature on corn crops.

Other management adaptations recommended as efficient alternatives to mitigate losses caused by climate change and to increase yield were irrigation, recommended by [49,53,55,66], and an appropriate sowing date, cited by [49,50,52,66,68]. Modeling corn crops in India for the future, ref. [32] identified yield losses of 16%. They reported that by changing the sowing date, the losses would be much reduced, and when combined with irrigation, there would be an increase in yield. Thus, good crop-management techniques have proven to be efficient tools for mitigating the impacts of climate change on corn. Future studies should consider these as variables, as well as the interaction between them, since different regions require different crop adaptations in the face of these scenarios.

3.3. Expected Impacts of Future Climate Changes on the Double-Cropping System

In addition to individually affecting the development and yield of soybean and corn crops, future climate changes may affect the dynamics of cropping systems. Some of the studies cited in Sections 3.1 and 3.2, in addition to individually analyzing soybean and corn, analyzed how future climate changes will affect the double-cropping system of these crops. In the present section, we extend the discussion about the interactions between soybean–corn crops and climate change scenarios.

In several regions of Brazil, mainly in Matopiba, Midwest, Southern Amazon, and Central Brazil, all located in the tropical climate zone, the current climatic patterns provide conditions for the cultivation of soybean and corn within the same growing season, giving rise to the double-cropping system. The double-cropping system is based on early soybean sowing at the beginning of the rainy season (September–October). Immediately after the soybean harvest, the corn is sown (January–February), extending its cycle until there is moisture in the soil at the end of the rainy season, as shown in Figure 4.

Sowing soybeans soon after the end of the sanitary void and the beginning of the rainy season and subsequent growing of corn has proved interesting for farmers, given the enormous expansion in the land area under this system throughout the national territory. Furthermore, the higher prices received for soybeans harvested earlier and the lower incidence of Asian rust make the double-cropping system economically attractive to farmers, compensating for the risks inherent to the system [58].

However, some studies analyzed have shown that future climatic conditions will decrease the ability of tropical regions to support the double-cropping system, as shown in Figure 4. Basically, the double-cropping system will be affected by reducing both the rainfall, shortening of the rainy season, and the yield potential of corn sown after soybean, caused by the increase in temperature. The evidence for this claim will be discussed as follows. Thus, ref. [64] suggests a reduction in precipitation of 16.9% and 13.5% for the first and second growing seasons, respectively, because of modeling the future climate scenarios. This suggests by the middle of the century a delay of 7 and 20 days is expected in sowing for soybean and corn, respectively.

One study [57] showed a general tendency to delay the sowing of corn because the sowing and harvesting of soybeans are delayed in the first part of the cropping cycle, making corn unfeasible as a second crop in some treatments. This is justified by pointing out negative precipitation anomalies at the beginning of the rainy season and increasing temperatures between 2.2 °C and 4.8 °C. Complementing this, ref. [58] affirms that there is a high probability that the double-cropping system could be successfully cultivated if the soybean reaches physiological maturity in early January and a mean probability of success if the physiological maturity is reached by mid-January. After these dates, the double-cropping system is considered unfeasible. It is suggested that early soybeans be sown by mid-October in order for corn sowing to take place within the expected season.

Maintaining the sowing of early soybean varieties right at the beginning of the rainy season can result in yield losses for this crop under future climate change scenarios. According to the trend previously demonstrated, yield losses decrease when sowing delays and longer cycle varieties are used and can be converted into yield gains [58]. Yield losses mainly occur due to the delay and irregularity of the rainy season and possible reductions in precipitation during crop development. The discussion about maintaining the double-cropping system in Brazil is grounded in the following paradox: it is important to sow soybean earlier to enable a second crop with corn, even though it incurs a higher weather risk, or sow a single crop with the probability of obtaining higher yields at lower weather risk.

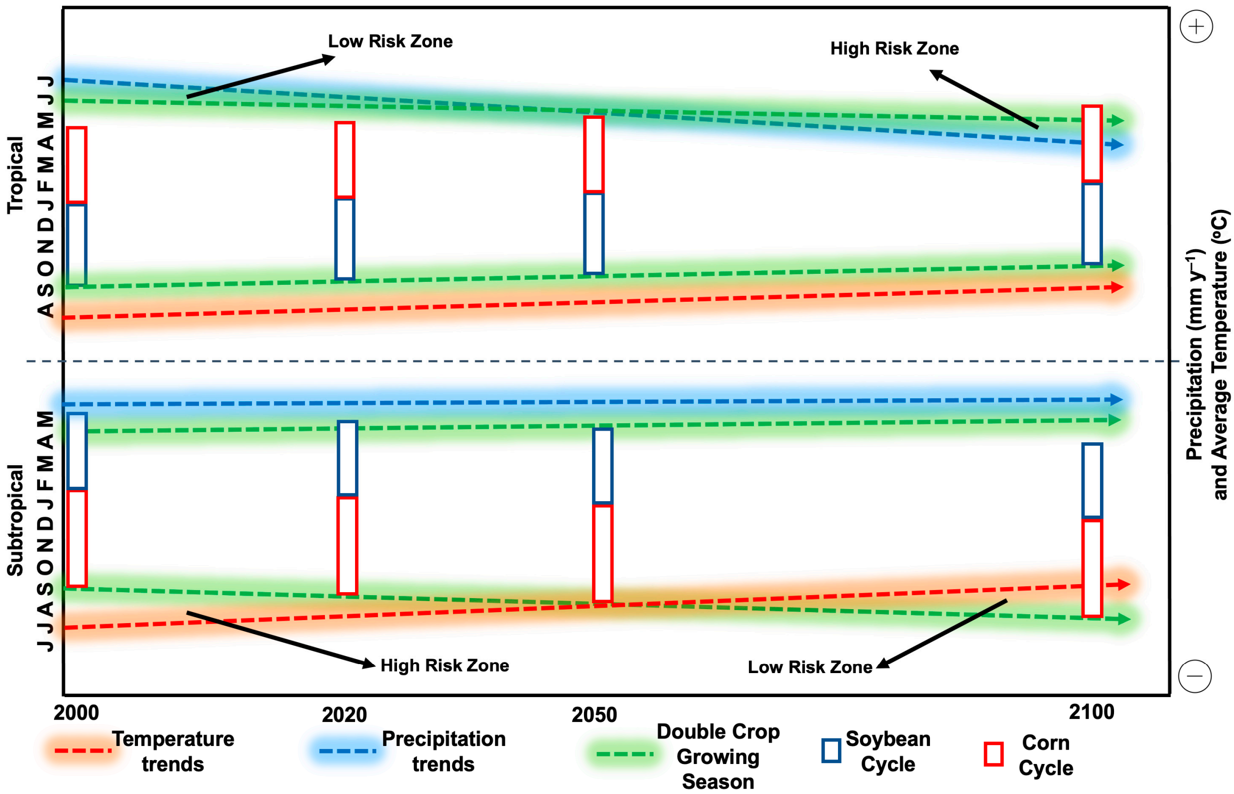

Figure 4. Time window perspectives for the use of a double-cropping system in tropical and subtropical climate regions while considering the effect of climate change on precipitation and temperature. Average temperature and precipitation are plotted against the right axis, showing that in tropical climate regions, average temperature tends to increase and annual precipitation tends to decrease, while in subtropical climate regions, average temperature also tends to increase, but precipitation tends to remain stable. As a result, the time window for the use of the double-cropping system tends to become narrower in tropical climate regions and wider in subtropical climate regions over time. The time window is plotted against the left axis, indicating the time interval whose weather conditions are most favorable for the development of the soybean + corn crop from sowing to harvest. Considering that the length of the soybean and corn crop cycle does not change over the following decades, the time required (days) for the full completion of the soybean + corn cycles tends to exceed the time window in tropical climate regions, increasing the weather and yield loss risks. On the other hand, in subtropical climate regions, the weather and yield loss risks tend to be progressively reduced over time and as the time window for soybean + corn cultivation becomes wider due to climate change. Technological advances in the development of corn and soybean varieties better adapted to future weather conditions and with shorter cycles may change this scenario. Source: prepared by the authors.

In the Midwest and Southern Amazonia regions, the yield in the double-cropping system is simulated to decrease by 10% and 41% for soybean and corn, respectively [64]. In this study, sowing dates were allowed to freely adjust to the optimum. It was the only study to implement this. These results differ significantly from those of [58], mainly because the latter assumed that farmers would adjust their sowing dates to climate changes. They used fixed sowing dates and found a reduction in the yield of soybean sown at the beginning of the growing season of 45% in Matopiba and 20.8% in the Midwest region.

Analyzing the producing regions of Mato Grosso state, ref. [57] found an increase in soybean yield of 20% to 35%, justified by the extra CO_2 fertilization and the rainfall data simulated by these authors, as previously mentioned. The corn yield is assumed to be reduced between 15% and 35% as a second crop. The authors found differences in corn yield between the regions of the same state; that is, in a comparatively smaller geographical area than the other studies. This raises questions about the limitations in the quality of information from studies that go beyond their geographical limits to larger areas, using homogeneous blocks of climate and soil in their simulations. Once again, the importance of carrying out localized studies is emphasized, taking into account the specific characteristics of each region.

One study [56] conducted in the main corn-producing regions in Brazil indicated corn as a second crop, sown on 15 February, showed yield variation between an increase of 5% to losses of up to −55%. These results are similar to those found by [48], where the negative yield variation was −1.6% to −27.8% for corn sown on February 10 in Mato Grosso, Mato Grosso do Sul, and Goiás.

The most accentuated losses for corn as the second crop were found by [49] in a study at Mato Grosso do Sul, where the losses varied from 80% for sowing on January 25th to 88% for sowing on February 25th. There is agreement among the previous authors that the yield of second-crop corn will substantially decrease in all the evaluated regions, which is accentuated as the sowing of this crop is delayed. The increase in temperature and low water availability at the end of the cycle are pointed out as the main future aggravating losses in the yield of second-crop corn.

In addition, the differentiation of sowing times and the use of cultivars with cycles compatible with the double-cropping system was previously recommended by the authors as an adaptation measure to reduce yield losses caused by future climate changes. Other management adaptation possibilities can be adopted, such as drought-tolerant cultivars [64], irrigation [49], and optimization of sowing and harvesting operations [58]. The latter authors also suggest the development of new cultivars with high yield potential and shorter cycles. Technological development will be decisive for the maintenance of the double-cropping system. New technologies will compensate for the losses caused by climate change and generate a yield increase of 40% for soybeans and 68% for corn [64].

The double-cropping system adopted mainly in the Brazilian Cerrado region is responsible for increasing the national production of grains, primarily corn that was previously cultivated in a smaller area compared to soybean. In the past, soybean and corn competed for the same land area. Technological developments and revolutions in management practices have made it possible for these two crops to be grown within the same growing season, helping to increase food security worldwide. The challenges for the future prosperity of this system are enormous and will again require cooperation between producers, policymakers, and research organizations, both public and private.

So far, it has been discussed how climate change will affect the dynamics of the double-cropping system of soybean + corn in the Brazilian tropical climate regarding crop yields. It will become even more difficult to successfully grow both crops in the same growing season. However, climate change will also affect the cropping system in the subtropical region of Brazil. As shown in Section 3, the temperature is projected to increase in all scenarios, and the rains tend to be neutral to slight increases, enabling better conditions for the adaptation of a double-cropping system, in this case, a double-cropping system of corn + soybean.

The Cfa climate classification of the subtropical climate prevails in the three southern states of Brazil. The subtropical climate is characterized by four seasons that are well defined for the year, with hot summers and cold winters, and with the formation of frosts. There is no dry season, and rains occur throughout the year with high rainfall volumes [46]. The double-cropping system of corn + soybean consists of sowing corn soon after the end of winter frosts (August), and immediately after harvesting (December/January), the sowing of soybean takes place. The low temperatures at the end of winter and the shortening of the photoperiod tend to reduce the yield potential of corn and soybean, respectively, compared to the best sowing time for each crop.

The growing window for summer crops tends to be wider in the subtropical region as the increase in the temperature predicted by future climate change scenarios is confirmed (see Figure 4). A wider growing window would provide better conditions for earlier sowing of corn and its better development, shortening its cycle due to the increase in temperature. Thus, soybean sowing could also be anticipated for the period just after the corn harvest, providing better conditions for soybean development. As the temperature increases, the result tends to be a progressive reduction in the weather risks and an increase in the yields achieved by the double-cropping system of corn + soybean compared to current climate conditions.

3.4. Limitations of the Study

This study is limited to evaluating the impacts that climate change has on the yield of soybeans and corn crops and their cropping systems. Many other crops are grown in Brazilian climates. We chose corn and soybeans arbitrarily, according to our own interests. Thus, there is room to expand the analysis of climate change to the yield of other crops.

We used secondary data estimated from different crop models and CO_2 concentration scenarios. Thus, our findings and conclusion are based on computational data generated from crop models fed with climate data from climate models. The use of computational mathematical models brings with it several uncertainties to studies. Even though such tools are suitable for carrying out such studies, the models are undoubted sources of error. Although crop and climate models have evolved rapidly in recent years, improving their ability to accurately predict physical systems, continued studies must be performed to demonstrate the effects of climate change on agricultural crops.

Another limitation concerns the relatively low number of articles that met the selection criteria defined in the methodology. In addition, the numerous variables associated with the type of study made it difficult to collect enough data to conduct a more sophisticated statistical analysis, such as a meta-analysis.

Finally, our analysis lacks a more comprehensive contrast of the effects of climate change on soybean and corn yields in Brazil with those in other regions with similar Köppen climate classifications. This discussion would allow us to see whether the same climate would also affect crop yields.

4. Conclusions

Simulated future climate changes, mainly the increase in temperature expected to occur in the coming years, will affect corn crops negatively. The tropical and semi-arid regions will be more affected than the subtropical regions. The corn's physiological cycle will be reduced, and consequently, yield will decrease, becoming more accentuated over the years. Long-cycle cultivars, irrigation, and choosing the best sowing date can be used as alternatives to minimize these negative impacts. Being a C4 plant, corn will not benefit from an increase in yield from increasing CO_2, but this can make the corn crop more efficient in water use, increasing yield by the quantity of water, especially when exposed to water scarcity conditions.

For soybean cultivation in Brazil, future projections indicate that there will be a considerable increase in yield. The leading cause is that the beneficial effects of the higher atmospheric CO_2 concentration will outweigh the deleterious effects of the increase in temperature. This fact is accentuated up to the end of the century in the evaluated scenarios. There will be a reduction in the phenological cycle of the soybean caused by the increase in temperature. Strategies that can further increase crop yields need to be studied and recommended carefully but will possibly positively impact crop development and production.

In addition to the direct impacts on the yield of soybean and corn crops, future climate changes will affect the dynamics of the double-cropping system for these crops in different regions of the country, with negative implications. In the tropical climate, the projection for early soybean sown at the beginning of the rainy season is of reduced yield. However, yield increases when sowing is delayed and longer-cycle varieties are sown. Yet, adopting these techniques benefiting soybean delays the sowing of corn as the second crop, reducing its yield and making the system unviable. The shortening and delay in the beginning of the rainy season, reduction in the volume of precipitation, and increase in temperature are indicated as the leading causes of these changes in the system. The use of new studies that allow the sowing dates to freely adjust to the optimum in the double-cropping system is necessary to obtain data closer to reality. Meanwhile, there is the possibility that a new double-cropping system will emerge and expand in the subtropical climate region under climate change scenarios.

The climate changes expected to occur in the coming decades will affect the yield of corn and soybean crops. The yield of soybeans is projected to increase, while that of corn is projected to decrease. Likewise, this will affect the dynamics of growing these crops, especially in regions with a tropical climate, where they are grown using the double-cropping system. The difficulties in continuing with the double-cropping system, considering the results presented and that historically, soybeans have always been the main crop when competing with corn, there may be a reduction in the area cultivated with corn in tropical regions. When this happens, the supply chains based on these two crops, like meat and biofuel production, will be severely impacted. These stand out among other economic and technical impacts that will occur because of such changes. Scientists, farmers, and political actors must pay attention to this fact and seek ways to minimize the negative impacts, counterbalancing the losses by promoting opportunities for gains, like the adoption of the double-cropping system of corn + soybean in subtropical climate areas. The possibility of adopting the double-cropping system in subtropical areas suggested here needs to be further explored, which is a suggestion for future studies.

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Appendix A

Table A1. Description of the CO_2 emission models considered in the selected articles.

CO_2 Emission Model	Description	Source
SRES A1	The A1 family of scenarios describes very rapid economic growth. The global population peaks at mid-century and declines shortly thereafter. There is also a rapid introduction of new and more efficient technologies. The main underlying themes are convergence between regions, capacity building, and increasing social and cultural interactions, with a substantial reduction in per capita income differences between regions. The A1 family of scenarios is developed into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technology emphases: fossil energy-intensive (A1FI), non-fossil energy sources (AIT), or a balance of all sources (A1B).	[94]
SRES A2	Scenario A2 describes a very heterogeneous world. It is based on national self-sufficiency and the preservation of local identities. Fertility patterns across regions converge very slowly, resulting in a continued increase in the global population. Economic development is primarily regionally oriented, and per capita economic growth and technological change are more fragmented and slower than in other future stories.	[94]
SRES B1	Scenario B1 describes a converging world with the same global population that peaks at mid-century and declines shortly thereafter—as in future story A1—but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technology. Emphasis is on global solutions for economic, social, and environmental sustainability, including increased equity, but without additional climate initiatives.	[94]
SRES B2	The B2 scenario describes a world where the emphasis is on local solutions for economic, social, and environmental sustainability. It is a world with continued global population growth at a slower rate than in the A2 family, intermediate levels of economic development, and slower and more diversified technological change than in the B1 and A1 future stories. Although the scenario is also oriented toward environmental protection and social equity, its focus is local and regional.	[94]
RCP 4.5 RCP 8.5	The Representative Concentration Pathways (RCPs) describe different 21st century pathways of greenhouse gas (GHG) emissions and atmospheric concentrations, air pollutant emissions, and land use. The RCPs cover a wider range than the scenarios from the Special Report on Emissions Scenarios (SRES) used in previous assessments, as they also represent scenarios with climate policy. In terms of overall forcing, RCP8.5 is broadly comparable to the SRES A2/A1FI scenario and RCP4.5 to B1.	[95]

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