Scientia Agraria Paranaensis

Scientia Agraria Paranaensis – Sci. Agrar. Parana.
ISSN: 1983-1471 – Online
DOI: https://doi.org/10.18188/sap.v22.31717

CONSEQUENCES OF CLIMATE CHANGE ON BRAZILIAN SOYBEANS PRODUCTION

Merilyn Taynara Accorsi Amorim[1*], Marina Rodrigues dos Reis[1], Renan Caldas Umburanas[1]

SAP 31717 Received: 14/01/2023 Accepted: 08/05/2023
Sci. Agrar. Parana., Marechal Cândido Rondon, v. 22, e202331717, p. 01-09, 2023

ABSTRACT - Climate change is a current problem in agricultural production. Soybean is one of the main crops produced in the world, the main source of oil and vegetable protein, and contributes to the planet's food security. However, soybeans are sensitive to climate variations, such as extreme temperatures and water excess or deficit. Studies with simulation of the future climate and its impact on soybean yield reported that increased temperature and instability in the rainfall regime harm the production of this crop, as it alters the physiology of the plant and limits the attainable yield. Meanwhile, studies report that a higher concentration of CO_2 in the atmosphere can increase yield, but that would be limited to conditions in which the temperature does not exceed the optimum range for the crop. In simulation studies, it has been reported that climate change in the medium to long term will reduce both the planted area and soybean production in Brazil, due to climate variables being above the optimal limits for the crop. However, there is still room for genetic improvement to adapt future cultivars to future scenarios and mitigate this problem. In this context, the development of new technologies and their transfer to rural producers will play an important role in guaranteeing future agricultural production in a climate change scenario.
Keywords: Land use, extreme weather events, climate projections.

CONSEQUÊNCIAS DAS MUDANÇAS CLIMÁTICAS NA PRODUÇÃO DE SOJA BRASILEIRA

RESUMO - As mudanças climáticas são um problema atual na produção agrícola. A soja é umas das principais culturas produzidas no mundo, principal fonte de óleo e proteína vegetal, e contribui para segurança alimentar do planeta. Porém a soja é sensível as variações climáticas, como temperaturas extremas e excesso ou déficit de hídrico. Estudos com simulação do clima futuro e seu impacto sobre a produtividade da soja reportaram que o aumento da temperatura e a instabilidade no regime de chuvas prejudica a produção dessa cultura, uma vez que altera a fisiologia da planta e limita a produtividade atingível. Por outro lado, estudos reportam que a maior concentração de CO2 na atmosfera pode aumentar a produtividade, mas isso seria limitado para condições que a temperatura não ultrapassasse o intervalo ótimo da cultura. Em estudos com simulações tem sido reportado que as mudanças climáticas no médio a longo prazo reduzirão tanto a área plantada quanto a produção da soja no Brasil, em virtude das variáveis climáticas se encontrarem acima dos limites ótimos para a cultura. Porém ainda existe espaço para o melhoramento genético adaptar as futuras cultivares aos futuros cenários e mitigar este problema. Neste contexto, o desenvolvimento de novas tecnológicas e a transferência destas para o produtor rural terá um papel importante para garantir a produção agrícola futura no cenário de mudanças climáticas.
Palavras-chave: Uso da terra, eventos climáticos extremos, projeções climáticas.

INTRODUCTION

Soybean is an essential crop for food security and its demand is growing. Still, due to the limitation of the expansion of the cultivated area, increase on its production relies more and more on increasing yield (AYALA et al., 2016; BATTISTI et al., 2018; SILVA et al., 2021). It is expected that soybean yield in Brazil need to grow above the world average to be able to supply the demand. This presents ongoing challenges for Brazilian soybean because most of it is grown in rainfed areas (BATTISTI; SENTELHAS, 2019). Soybean is a plant sensitive to extreme climatic variations, such as temperatures above 40°C or below 10°C, water deficit and excessive solar radiation (ALSAJRI et al., 2020; TAN et al., 2021; ZHAO et al., 2021).

The increase in greenhouse gas emissions contributed to global warming and various impacts on agricultural crops (TANURE et al., 2020). Climate change can modify soybean production negatively, and this affects the supply and price of soybeans in the main markets, causing difficulties, especially for the most vulnerable consumers and for producers (CARAUTA et al., 2021). Furthermore, since Brazil is one of the largest soybean producers in the world, possible impacts and risks associated with climate change need to be estimated so that preventive control measures can be adopted and thus

[1]Escola Superior de Agricultura "Luiz de Queiroz" - Universidade de São Paulo (ESALQ/USP), Piracicaba, SP, Brasil. E-mail: merilyn.accorsi@usp.br. [*]Corresponding author.

guarantee global food security (CAETANO et al., 2018; GOULART et al., 2023).

The objective of this review was to summarize some demands of soybean in relation to climate variables, to analyze future scenarios about climate change and how these changes affect soybean production in Brazil. To achieve this, searches were carried out within the main known databases, with the keywords 'soybean and environmental needs', 'soybean ecophysiology', 'impacts of climate change on soybean' and 'consequences of climate change of Brazilian soybean'. Below, the results of the main verified studies are presented.

Historical and ecophysiological aspects of soybean crop

Soybean (*Glycine max* L. Merril) belongs to the Fabaceae family and has its center of origin in the Asian continent, on the banks of the Yangtze River, in China. It is an annual plant, with epigeal germination and has herbaceous size (EMBRAPA, 2023). Its grain is rich in oils (around 18% to 23%) and proteins (around 33% to 42%) UMBURANAS, et al., 2022).

In Brazil, soybeans were introduced in Bahia in 1882 by Gustavo D'utra, but the crop did not develop well due to the lack of cultivar adaptation to the tested environment. At the same time, the Agronomic Research Institute (IAC) began studies on this crop. Around 1910, soybean cultivars were introduced in Brazil in Rio Grande do Sul from the southern region of the United States, where it showed good adaptation due to the similarity of latitude with the region of origin of the introduced cultivars (BONATO; BONATO, 1987).

Until the 1970s, soybean production was concentrated in the southern region of Brazil, due to the cultivars and edaphoclimatic conditions in the region. In the following decades, the area cultivated with soybeans expanded in the Brazilian Cerrado region with the development of more adapted cultivars. The area cultivated with soybeans in the 2022/2023 growing season was 43.3 million ha (IBGE, 2023).

Commercial soybean cultivars are classified according to the development cycle, being grouped, and characterized by the maturity groups, which ranges between 5 to 9 among Brazil territory (Figure 1). This classification considers the interaction between genotype and environment (MATSUO et al., 2016; KASTER; FARIAS, 2012).

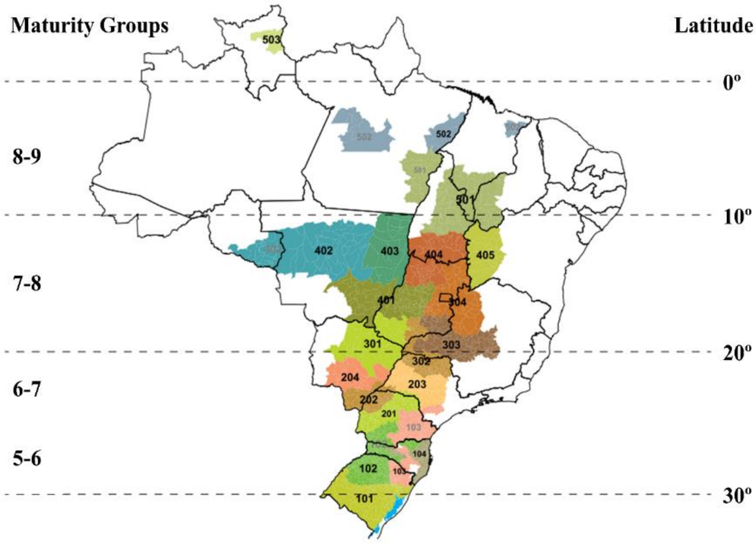

FIGURE 1 - Distribution of relative maturity groups of soybean cultivars in Brazil. Source: Kaster e Farias (2012).

For each maturity group there are recommendations regarding the best location and sowing date, mainly. These recommendations are based on agricultural zoning of climate risk (ZARC). The ZARC indicates the best sowing date for the crop to have its full development without suffering the effect of extreme climatic events. In general, the soybean sowing in Mid-South Brazil runs from mid-September to December, and until February in some regions in North Brazil areas. Each federation state regulates this sowing window according to the sanitary break to prevent Soybean Rust (*Phakopsora pachyrhizi*) disease. There are several meteorological factors that impact the agronomic performance of soybeans, such as the incidence of light (radiation and photoperiod), humidity, temperature, CO_2 concentration, mainly.

The incidence of light in the soybean crop is directly linked to photosynthesis, growth and setting of pods and grains, among other processes. Saturation of photosynthetically active radiation happens in 1800 µmol m^{-2} s^{-1}. Under conditions of low radiation, the soybean crop reduces the number of pods per plant, the total soluble sugar content, accumulates less biomass, as well as reduces biological nitrogen fixation (LIU et al., 2011).

As for the photoperiod, the soybean crop is a short-day plant, whose flowering occurs when the plant finds a photoperiod condition below the critical photoperiod and represents the transition from the vegetative period to the reproductive period. As for humidity and precipitation, the soybean crop needs about 400 to 800 mm of water well distributed during its growth cycle, the most critical periods being the germination and emergence phase, as well as flowering and grain filling (BREVEDAN; EGLI, 2003; SILVA et al., 2015). During the reproductive period the demand for water is around 7 to 8 mm day (FARIAS et al., 2007). Significant water deficiencies, during flowering and grain filling, cause stomatal closure and a reduction in the photosynthetic rate of the plant, consequently, decreases nitrogenase activity and nitrogen assimilation (TAIZ et al., 2017). In addition, there is curling and premature fall of leaves and flowers, and pod abortion (BREVEDAN; EGLI, 2003), which decreases seed quality, affects germination and vigor.

Temperatures between 20ºC and 30ºC are optimal for soybean crop (ALSAJRI et al., 2020). The optimal temperature for soybean seed germination is 32ºC, with the minimum temperature tolerated for germination being 8ºC and the maximum being 40ºC (LAMICHHANE et al., 2020). At temperatures below 10ºC the vegetative and reproductive development of the soybean crop is null, and temperatures above 40ºC harm flowering and pod fixation. The minimum temperature for flowering is 13ºC. Another important process affected by temperature is the biological nitrogen fixation, the appropriate soil temperature for the formation of nodules is 27ºC. High temperatures (>40ºC) can also impair grain/seed maturation (SILVA et al., 2015).

Projected climate change for Brazil

Soybean is a highly sensitive plant to climate adversity (BATTISTI et al., 2018; ODEY et al., 2022), which can be responsible for yield losses in the order of 46 to 74% (BATTISTI; SENTELHAS, 2019). For Brazil, between 1980 and 2018, there was average increase in temperature of 0.5ºC per decade, for all regions of the country, and this value continues to rise (SANTOS et al., 2020). In the most pessimistic scenarios of CO_2, from the *Representative Concentration Pathways* (RCP 8.5), the temperature increase in the Brazilian regions may be 2ºC by 2052. However, this projection would not be uniform for all regions of the country, with the North and the Midwest regions having the highest probability of severe changes in temperature (CARVALHO et al., 2020; SANTOS et al., 2020).

This changes in the temperature of the country can harm soybean cultivation (Figure 2), among which overheating of plant tissues, lower fixation of flowers (ODEY et al., 2022), extending pods formation duration, grain filling duration, as well as decrease potential leaf area index of the crop (CAETANO et al., 2018; KOTHARI et al., 2022). Excessive temperatures (>35ºC) also reduce the survival of diazotrophic bacteria, responsible for biological nitrogen fixation (LI et al., 2016; SITA et al., 2017; SOARES et al., 2021).

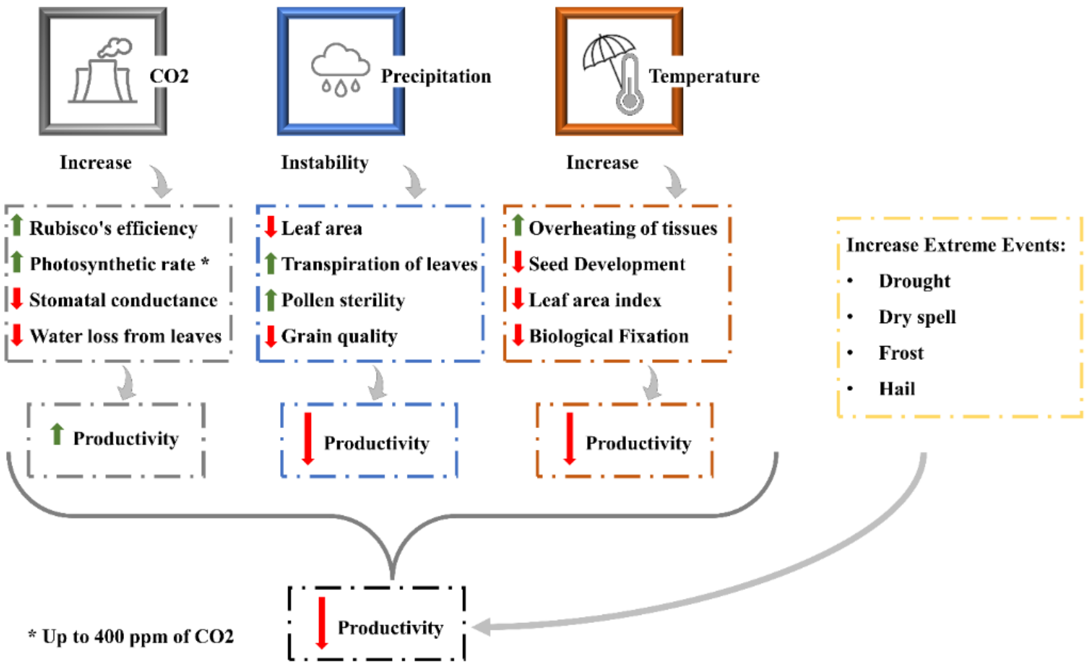

FIGURE 2 - Consequences of climate change on soybean yield.

It is expected that in Brazil, a reduction in rainfall and, consequently, drought events occur more frequently (SOARES et al., 2021). However, as well as for temperature, rainfall presented a regionalized aspect throughout the country. The pattern of rainfall in the country proved to be variable, in the period between 1980 and 2018, for the north of the North region, central-east of the Northeast region and in the South region there was an increase in the accumulated rainfall (SANTOS et al., 2020; ZILLI et al., 2020).

Whereas a scenario of reduced rainfall for the entire South region, as well as for the Southeast and Midwest were also reported (FERNANDES et al., 2022; ZHANG et al., 2021). This represents risks associated with soybean cultivation, since traditionally the Midwest and Southeast regions represent most of soybean production areas (CONAB, 2023; SILVA et al., 2021). Surveys by the Intergovernmental Panel on Climate Change (IPCC, 2023) indicate that, by 2100, rainfall could reduce by 22% in the Northeast region and part of the Midwest and increase by 25% in the South region. These changes in rainfall can lead to water scarcity, which reduces leaf area and hinders plant transpiration, due to stomatal closure, in addition to promoting pollen sterility and decreasing grain quality (ODEY et al., 2022).

The enrichment of the atmosphere with CO_2 also affects the soybean crop (Figure 2). As a C_3 metabolism plant, Rubisco is not close to saturation, so soybean can have a positive response to the increase in CO_2 in the atmosphere (BUNCE, 2015; KUMAGAI et al., 2015). Even in scenarios where the CO_2 concentration is 800 μmol mol^{-1}, basically double the current level, yield would be able to increase by up to 40%, without metabolic changes occurring in the culture, which indicates an improvement in photosynthetic efficiency, if only the CO_2 was changed (CASALI et al., 2021; LI et al., 2016). This is in accordance with the works of Ainsworth and Long (2021), according to them, if there is an increase of 200 ppm of CO_2 in the atmosphere, soybeans would be able to increase production by 18%, however, even in this scenario, if the temperature increase by 2ºC, yield can drop by 10%. The increase in CO_2 can help preserve water by reducing stomatal conductance and, thus, water loss from leaves (SILVA et al., 2021). However, morphological studies have shown that photosynthesis tends to reduce in environments with a CO_2 concentration greater than 400 ppm, as well as morphological changes in stomata, in leaf distribution and anatomical changes in leaves (ZHENG et al., 2019).

Climate change, in addition to causing changes in rainfall and temperature patterns, also increase the occurrence of extreme meteorological events (Figure 2) that can harm soybean cultivation (CARVALHO et al., 2020; MCTI, 2023; ORTIZ et al., 2021; REN et al., 2018; SILVA et al., 2021; ZILLI et al., 2020). The areas of the Caatinga and part of Mato Grosso, Piauí and Bahia states (MATOPIBA) may experience a higher frequency of drought, and the South and Southeast may experience a higher frequency of drought, frost, and hail (CARVALHO et al., 2020; RIO et al., 2016). Problems with heat and drought already affect soybean yield by 12.4% around the world (MATIU et al., 2017).

In addition, heavy rainfall events are also expected to occur in the main producing regions of the country. It is known that soybeans have a certain degree of tolerance to waterlogging (PASLEY et al., 2020). However, if this event occurs in great intensity, mainly in places with more fragile soils and, with few conservationist practices, it will cause high damage to the crop such as loss of seeds, soil dragging and deposition in lowland areas, erosion and reduced fertility (CASALI et al., 2021; POWLSON et al., 2016). This soil degradation that can occur in extreme events harms agricultural crops, mainly in places without irrigation because they provide high loss of water retention capacity of these soils (CASALI et al., 2021).

Impacts of climate change on the Brazilian soybean area

Around the world, climate change already has negative impacts on soybeans, in some cases making cultivation in previously favorable locations unfeasible (CAETANO et al., 2018; PASLEY et al., 2020; ZHAO et al., 2021). In Brazil, this problem can be intensified since the area cultivated with soybeans has expanded to regions considered marginal (CAETANO et al., 2018; CARUATA et al., 2021; CASALI et al., 2021; FERNANDES et al., 2022; ZILLI et al., 2020). The impact of these changes has been shown to be specific depending on the agricultural culture and the region considered. Therefore, there is a need to evaluate between the agricultural areas that allow the continuity of soybean planting or that may be new areas for cultivation, in view of the realities of climate change.

There is a risk of reducing the attainable yield of Brazilian soybean areas by up to 65%, by 2050, the South region would be the most affected, it would lose a large part of its capacity to support the crop and the Southeast part of the Amazon would be a compensation region for this loss (Figure 3b and Figure 3c) (ASSAD et al., 2016). This could lead to greater pressures in this biome. By 2100, 72% of the Brazilian territory may be considered unviable for the crop, mainly in the North and Northeast regions, but also in part of the Midwest (Figure 3a, Figure 3b, Figure 3c) (CAETANO et al., 2018). The Southeast region is the one with the greatest possibility of gains, due to its technological contribution (ASSUNÇÃO; CHEIN, 2016; CAETANO et al., 2018). The North of Brazil would benefit or be less impacted by climate change because of the more constant temperature and smaller rainfall variation in them, despite lower accumulated rainfall (TANURE et al., 2020).

To compensate for yield losses, there may be an expansion of soybean cultivation in the South of the Cerrado and the Atlantic Forest and in the Pampas. The new agricultural frontier of current soybean , MATOPIBA and the North of the Cerrado would not be suitable for the expansion of production (ZILLI et al., 2020) (Figure 3a, Figure 3b, Figure 3c, Figure 3d). In addition, despite the expansion of the cultivated area in some places, the total area of the crop in the country can fall by up to 38% and yield by up to 36%. This projected expansion towards the southernmost regions can be problematic, due to the great variability of the water cycle in this region, despite the large volume of rainfall (BATTISTI; SENTELHAS, 2019; RIO et al., 2016; ROESCH et al., 2009). Impacts on soybeans would be more limiting for cultivation in the MATOPIBA region, since they would make this region more like the Caatinga (FERNANDES et al., 2022; SILVA et al., 2023). Observing these data, climate changes can accentuate regional disparities between municipalities (ASSUNÇÃO; CHEIN, 2016), since places that are already traditional in relation to soybean cultivation have greater capacities to remain as strong producers and expanding sites can become even more vulnerable.

Most producing regions in Brazil take advantage of the sowing period to grow two crops throughout the year (first and second season), with soybeans generally being the first. The decrease in the rainfall window and in the amount of rain predicted for some regions may make this practice unfeasible (SILVA et al., 2023). For different future scenarios in Mato Grosso, the occurrence of two harvests would be difficult and economically unviable.

Measures to mitigate the impacts of climate change on soybean

The advance in soybean yield in recent decades was mainly due breeding new cultivars and improved agricultural practices and technologies (ODEY et al., 2022; SOARES et al., 2021; ZILLI et al., 2020). In the current scenario, soybeans in Brazil could be 80% more efficient, yet poor management causes large crop losses every year (BATTISTI et al. 2018). Thus, to avoid adding agricultural inefficiencies to the climate change scenario, it is necessary to improve management.

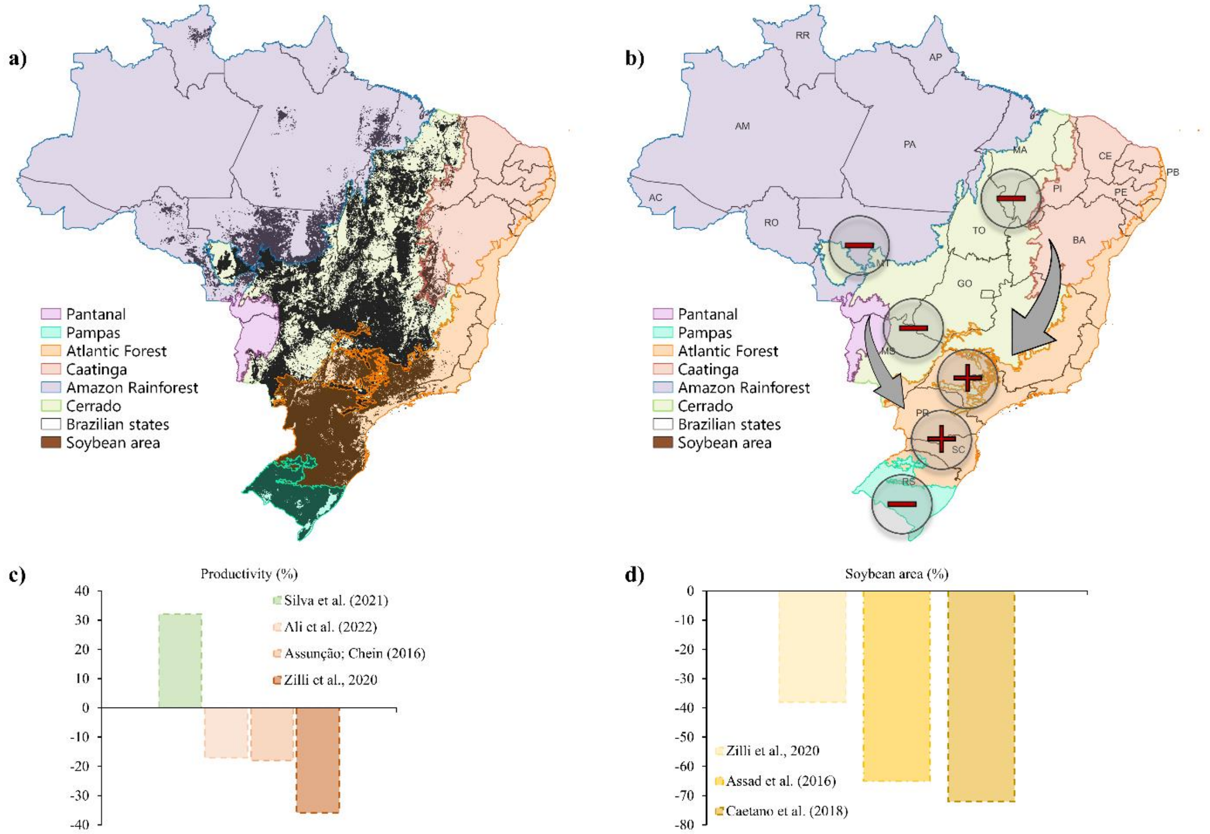

FIGURE 3 - a) Map of Brazil containing the current soybean area in each Brazilian biome and state, modified from MapBiomas (2023), b) scenarios for changing soybean production areas, the '+' sign indicates the areas where possible production increases will occur, or maintenance of the productive potential, the sign of '-' indicates the areas with possibilities of reduction of the productive capacity in face of the problems caused by the climatic changes and the arrows, indicate the preferential flows of migration of the cultures, adapted from Caetano et al. (2018) and Zilli et al. (2020), c) main projections of change in soybean yield in the country and d) main projections of change in the country's cultivated area.

Considering homogeneous zones according to water availability can be a solution (BATTISTI; SENTELHAS, 2019), since, in this regard, management can be adjusted according to the water needs of crops at the best sowing dates, including selection of resistant cultivars drought, adequate planting time in relation to rainfall and irrigation adjustments, when necessary. In addition, concentrating cultivation in more suitable regions allows agricultural and environmental resources to be used in the best possible way (GOULART et al., 2023).

Genetic improvement can modify the leaves to be smaller, to improve heat dissipation and to have a deeper root system (SILVA et al., 2021). In this respect, smaller leaves could also cause less water loss, together with roots that react better to compacted soil, causing better water use by the crop. Developing cultivars that are more tolerant to abiotic stresses will help minimize the impacts of droughts and high temperatures (CAETANO et al., 2018; SOARES et al., 2021). However, this tolerance must be accompanied by increases in yield, since for soybeans to reach the expected targets, average yield should be 4.1 ton ha^{-1} by the end of the century (ZILLI et al., 2020).

The introduction of management technologies also helps in this process (CAETANO et al., 2018). Changing the sowing date is one of the most effective and accessible ways to carry out (RIO et al., 2016; TAN et al., 2021;

ZHANG et al., 2021), however, in scenarios where rainfall becomes scarcer and variable over time, its effectiveness may decrease, especially for rainfed agriculture, as is the case with most soybeans in Brazil. In addition, the need for a sanitary break to reduce the incidence of key pests and diseases in the crop and the occurrence of two crop cycles in the rainy season reduce the flexibility of this method. However, it is expected that, due to the increase in temperatures, soybeans cycle will shorten, and crop water consumption will increase (SILVA et al., 2021; TAN et al., 2021; ZHAO et al., 2021).

The reduced cycle helps in agricultural planning and, if the water requirement is met, it can help maintain economic viability in some areas (CARAUTA et al., 2021). Irrigation can mitigate part of the risk of crop failure due to water scarcity (CASALI et al., 2021; FERNANDES et al., 2022; TAN et al., 2021). However, with lower rainfall scenarios for most of the country, access to surface and subsurface waters may become limited (SILVA et al., 2023; ZILLI et al., 2020). The use of sustainable agricultural practices, such as green fertilizers, crop rotation, maintenance of natural vegetation cover and no-tillage are alternatives to try to maintain soybean yield (CAETANO et al., 2018; FOGUESATTO et al., 2019; GOULART et al., 2023; SILVA et al., 2021). One of the ways of managing to reduce the water footprint is to use no-tillage systems, since, by preserving the soil structure, evapotranspiration is reduced (AYALA et al., 2016). There are still many producers who are not convinced of the needs of these practices (FOGUESATTO et al., 2019), therefore, conservationist agricultural practices should be more widely used.

Limitations of climate change in the Brazilian region, studies, and practical needs

Most studies address the relationships between how climate can affect crops, and often do not address the economic aspect and the need for farmers to adapt to the market (CAETANO et al., 2018; CARAUTA et al., 2021; NTIAMOAH et al. al., 2022; ZHAO et al., 2021; ZILLI et al., 2020). When using econometrics to study the future modifications of soybeans in Ghana, it was observed that farmers who manage to access credit, even if it is just a little, have an 8% more chance of increasing their technical efficiency and consequently their production in the long term and mitigating losses. of climate change (NTIAMOAH et al., 2022). A study reported how climate change can negatively impact the relationship between the marketing of soybeans between Brazil and China. The Chinese market is the largest buyer of Brazilian soybeans and uncertainties associated with possible crop failures can lead to declines of up to 15% in grain exports (ALI et al., 2022).

Many farmers still disbelieve in the impacts of climate change (SILVA et al., 2023). For this reason, they are reluctant to adopt conservation measures for crops, which can help to reduce the impacts of these changes. Therefore, more studies with producers would be necessary, to draw persona profiles, for public policies or extension activities for the dissemination of information and the necessary strategies for improving agricultural activities in the face of adverse scenarios (FOGUESATTO et al., 2019).

Many studies use simulation models to estimate the behavior of crops in the face of climate change, however, many use only one or another parameter without standardization (CAETANO et al., 2018; KOTHARI et al., 2022; SILVA et al., 2021). Thus, some scenarios are inconsistent or cannot be compared. In addition, many consider only climate information and not the relationship between climate and soil (NTIAMOAH et al., 2022; SILVA et al., 2021), especially considering the relationship between rainfall and water capacity in the soil . It is necessary to know the dynamics of water within soils as soils with greater drainage capacity are more susceptible to climate variations, and the variation in surface water content, and soil texture, influences soybean yield (MOREIRA et al., 2023). Soil degradation is an important factor to simulate soybean yield in climate change scenarios and should be better considered (CASALI et al., 2021).

CONCLUSIONS

The vast majority of climate scenarios projected for this decade agree that, in Brazil, temperatures are likely to grow by up to 2ºC on average. However, this growth would not be uniform in all producing regions. In addition, rainfall is estimated to be increasingly unpredictable, and for most producing regions total rainfall tends to decrease, especially for the new areas of soybean agricultural expansion, which are marginal production zones. The occurrence of extreme events tends to be higher. Therefore, even if the increase in CO_2 contents can be positive for the increase in yield, to a certain extent, it is most likely counterbalanced by the higher temperature and the higher frequency of excessive and uneven precipitation.

Most of the scenarios projected for this century indicate that the production areas will become more unfavorable for soybean production in the country. Soybean has specific needs for temperature, precipitation, CO_2, and photoperiod. In the country, soybean management has continuous technologies and genetic improvement aimed at yield and adaptation to the environment. With the greater occurrence of adverse weather conditions, producers are increasingly dependent on these management technologies and cultivars that are more resistant to abiotic stress, to mitigate the negative impacts on crops. However, these increments must be accompanied by good agricultural practices, which allow the preservation of natural resources, optimize the use of water, and maintain good health for the crop.

It is important to have studies in this area, to allow planning and actions that consider how to adjust the culture to the changing environment. However, most of them consider only climatic variables and their interaction with the local culture. Thus, there is a need to include other variables that directly impact agricultural decisions, such as economic variables and the perception of producers in the face of climate problems, so that more assertive strategies can be considered.

REFERENCES

AINSWORTH, E.A.; LONG, S.P. 30 years of free-air carbon dioxide enrichment (FACE): what have we learned about future crop productivity and its potential for adaptation? **Global Change Biology**, v.27, n.1, p.27-49, 2021.

ALI, T.; ZHOU, B.; CLEARY, D.; XIE, W. The impact of climate change on China and Brazil's soybean trade. **Land**, v.11, n.12, p.2286, 2022.

ALSAJRI, F.A.; WIJEWARDANA, C.; IRBY, J.T.; BELLALOUI, N.; KRUTZ, L.J; GOLDEN, B.; GAO, W.; REDDY, K.R. Developing functional relationships between temperature and soybean yield and seed quality. **Agronomy Journal**, v.112, n.1, p.194-204, 2020.

ASSAD, E.D.; OLIVEIRA, A.M.; NAKAI, E.; PELEGRINO, G.; MONTEIRO, J.E. Impactos e vulnerabilidades da agricultura brasileira às mudanças climáticas. In: TEIXEIRA, B.S.; ORSINI, J.A.M.; CRUZ, M.R. (Eds.). **Modelagem Climática e Vulnerabilidades Setoriais à Mudança do Clima no Brasil.** Ministério da Ciência, Tecnologia e Inovação. p.127-187, 2016.

ASSUNÇÃO, J.; CHEIN, F. Climate change and agricultural productivity in Brazil: future perspectives. **Environmental and Development Economics**, v.27, n.6, p.581-602, 2016.

AYALA, L.M.; EUPEN, M.V.; ZHANG, G.; PÉREZ-SOBA, M.; MARTORANO, L.G.; LISBOA, L.S.; BELTRAO, N.E. Impact of agricultural expansion on water footprint in the Amazon under climate change scenarios. **Science of The Total Environment**, v.569-570, [s.n.], p.1159-1173, 2016.

BATTISTI, R.; SENTELHAS, P.C.; PASCOALINO, J.A.L.; SAKO, H.; DANTAS, J.P.S.; MORAES, M.F. Soybean yield gap in the areas of yield contest in Brazil. **International Journal of Plant Production**, v.12, [s.n.], p.159-168, 2018.

BATTISTI, R.; SENTELHAS, P.C.; Characterizing Brazilian soybean-growing regions by water deficit patterns. **Field Crops Research**, v.240, [s.n.], p.95-105, 2019.

BONATO, E.R.; BONATO, A.L.V. **A soja no Brasil:** história e estatística. Londrina: EMBRAPA-CNPSo, 1987. 61p. (Embrapa-CNPSo. Documentos, 21).

BREVEDAN, R.E.; EGLI, D.B. Short periods of water stress during seed filling, leaf senescence, and yield of soybean. **Crop Science**, v.43, [s.n.], p.2083-2088, 2003.

BUNCE, J.A. Elevated carbon dioxide effects on reproductive phenology and seed among soybean cultivars. **Crop Science**, v.55, n.1, p.339-343, 2015.

CAETANO, J.M.; TESSAROLO, G.; OLIVEIRA, G.; SOUZA, K.S.; DINIZ-FILHO, J.A.F.; NABOUT, J.C. Geographical patterns in climate and agricultural technology drive soybean productivity in Brazil. **PLoS ONE**, v.13, n.1, e0191273, 2018.

CARAUTA, M.; PARUSSIS, J.; HAMPF, A.; LIBERA, A.; BERGER, T. No more double cropping in Mato Grosso, Brazil? Evaluating the potential impact of climate change on the profitability of farm systems. **Agricultural Systems**, v.190, [s.n.], p.103104, 2021.

CARVALHO, A.L.de; SANTOS, D.V.; MARENGO, J.A.; COUTINHO, S.M.V.; MAIA, S.M.F. Impacts of extreme climate events on Brazilian agricultural production. **Sustainability in Debate**, v.11, n.3, p.211-224, 2020.

CASALI, L.; HERRERA, J.M.; RUBIO, G. Modeling maize and soybean responses to climatic change and soil degradation in a region of South America. **Agronomy Journal**, v.113, n.2, p.1381-1393, 2021.

CONAB. COMPANHIA NACIONAL DE ABASTECIMENTO. **Acompanhamento da safra brasileira de grãos.** 2023. Disponible in: <https://www.conab.gov.br/info-agro/safras/graos/boletim-da-safra-de-graos?limitstart=0>. Access at: 07 jun. 2023.

EMBRAPA. EMPRESA BRASILEIRA DE PECUÁRIA E ABASTECIMENTO. **História da soja.** 2023. Disponible in: <https://www.embrapa.br/soja/cultivos/soja1/historia>. Access at: 05 jun. 2023.

FARIAS, J.R.B.; NEPOMUCENO, A.L.; NEUMAIER, N. **Ecofisiologia da soja**. 2007. Disponible in: <https://www.infoteca.cnptia.embrapa.br/handle/doc/470308>. Access at: 05 jun. 2023.

FERNANDES, R.D.M.; MELO, D.M.; ELLI, E.F.; BATTISTI, R. Climate change impacts on rainfed and irrigated soybean yield in Brazil's new agricultural frontier. **Theoretical and Applied Climatology**, v.147, n.1, p.803-816, 2022.

FOGUESATTO, C.R.; BORGES, J.A.R.; MACHADO, J.A.D. Farmers' typologies regarding environmental values and climate change: Evidence from southern Brazil. **Journal of Cleaner Production**, v.232, n.20, p.400-407, 2019.

GOULART, H.M.D.; WIEL, K.; FOLBERRTH, C.; BOERE, E.; HURK, B. Increase of simultaneous soybean failures due to climate change. **Earth's Future**, v.11, n.4, e2022EF003106, 2023.

IBGE. INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA. **Levantamento sistêmico da produção agrícola.** 2023. Disponible in: <https://sidra.ibge.gov.br/tabela/1618#resultado>. Access in: 24 jun. 2023.

IPCC. INTERGOVERNAMENTAL PANEL ON CLIMATE CHANGE. 2023. **Food, Fibre and Other Ecosystem Products**. Disponible in: https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_Chapter05.pdf. Access at: 04 de maio de 2023.

KASTER, M.; FARIAS, J.R.B. **Regionalização dos testes de Valor de Cultivo e Uso e da indicação de cultivares de soja - Terceira Aproximação**. Londrina: Embrapa Soja, 2012. 70p. (Documentos, 330). Disponible in: <https://www.embrapa.br/busca-de-publicacoes/-/publicacao/917252/regionalizacao-dos-testes-de-valor-de-cultivo-e-uso-e-da-indicacao-de-cultivares-de-soja---terceira-aproximacao>. Access at: 31 jan. 2024

KOTHARI, K.; BATTISTI, R.; BOOTE, K.J.; ANCHONTOULIS, S.V.; CONFALONE, A.; CONSTANTIN, J.; CUADRA, S.V.; DEBAEKE, P.; FAYE, B.; GRANT, B.; HOOGENBOOM, G.; JIN, Q.; SILVA, F.A.M.; MARIN, F.R.; NEHBANDANI, A. Are soybean models ready for climate change food impact assessments? **European Journal of Agronomy**, v.135, [s.n.], p.126482, 2022.

KUMAGAI, E.; AOKI, Y.; SHIMONO, H. Phenotypic plasticity conditions the response of soybean seed yield to elevated atmospheric CO_2 concentration. **Plant Physiology**, v.169, n.3, p.2021-2029, 2015.

LAMICHHANE, J.R.; CONSTANTIN, J.; SCHOVING, C.; MAURY, P.; DEBAEKE, P.; AUBERTOT, J.N.; DÜRR, C. Analysis of soybean germination, emergence, and prediction of a possible northward establishment of the crop under climate change. **European Journal of Agronomy**, v.113, n.2, p.125972, 2020.

LI, M.W.; XIN, D.; GAO, Y.; LI, K.P.; FAN, K.; MUÑOZ, N.B.; YUNG, W.S.; LAM, H.M. Using genomic information to improve soybean adaptability to climate change. **Journal of Experimental Botany**, v.68, n.8, p.1823-1834, 2016.

LIU, B.; LI, Y.S.; LIU, X.B.; WANG, C.; JIN, J. HERBERT, S.J. Lower total soluble sugars in vegetative parts of soybean plants are responsible for reduced pod number under shading conditions. **Australian Journal of Crop Science**, v.5, n.13, p.1852-1857, 2011.

MAPBIOMAS. MAPEAMENTO ANUAL DO USO E COBERTURA DA TERRA NO BRASIL. **Mapa de coleções MapBiomas, Soja.** 2023. Disponible in: <https://mapbiomas.org/download>. Access em: 07 jun. 2023.

MATIU, M.; ANKERST, D.P.; MENZEL, A. Interactions between temperature and drought in global and regional crop yield variability during 1961-2014. **PLoS One**, v.12, n.5, e178339, 2017.

MATSUO, N.; FUKAMI, K.; TSUCHIYA, S. **Effects of early planting and cultivars on the yield and agronomic traits of soybeans grown in southwestern Japan**. Plant Production Science, v.19, n.3, p.370-380, 2016.

MCTI. MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E INOVAÇÕES. **Quarta comunicação nacional do Brasil à convenção:** quadro das Nações Unidas sobre mudança do clima. 2023. Disponible in: <https://www.gov.br/mcti/pt-br/acompanhe-o-mcti/sirene/publicacoes/comunicacoes-nacionais-do-brasil-a-unfccc/arquivos/4comunicacao/4_com_nac_brasil_web.pdf.>. Access at: 31 jun. 2023.

MOREIRA, V.S.; CANDIDO, L.A.; MOTA, M.C.; WEBLER, G.; OLIVEIRA, E.P.; ROBERTI, D.R. Impacts of climate change on water fluxes and soybean growth in southern Brazil. **Revista Ciência Agronômica**, v.54, e20228398, 2023.

NTIAMOAH, E.B.; LI, D.; APPIAH-OTOO, I.; TWUMASI, M.A.; YEBOAH, E.N. Towards a sustainable food production: modelling the impacts of climate change on maize and soybean production in Ghana. **Environmental Science and Pollution Research**, v.29, n.4, p.72777-72796, 2022.

ODEY, G.; ADELODUN, B.; CHO, G.; LEE, S.; ADEYEMI, K.A.; CHOI, K.S. Modeling the influence of seasonal climate variability on soybean yield in a temperate environment: South Korea as a case study. **International Journal of Plant Production**, v.16, n.3, p.209-222, 2022.

ORTIZ, A.M.D.; OUTHWAITE, C.L.; DALIN, C.; NEWBOLD, T. A review of the interactions between biodiversity, agriculture, climate change, and international trade: research and policy priorities. **One Earth**, v.4, n.1, p.88-101, 2021.

PASLEY, H.R.; HUBER, I.; CASTELLANO, M.J.; ANCHONTOULIS, S.V. Modeling flood-induced stress in soybeans. **Frontiers in Plant Science**, v.11, [s.n.], [s.p.], 2020.

POWLSON, D.S.; STIRLING, C.M.; THIERFELDER, C.; WHITE, R.P.; JAT, M.L. Does conservation agriculture deliver climate change mitigation through soil carbon sequestration in tropical agro-ecosystems? **Agriculture, Ecosystems & Environment**, v.220, [s.n.], p.164-174, 2016.

REN, F.M.; TREWIN, B.; BRUNET, M.; DUSHMANTA, P.; WALTER, A.; BADDOUR, O.; KORBER, M. A research progress review on regional extreme events. **Advances in Climate Change Research**, v.9, n.3, p.161-169, 2018.

RIO, A.; SENTELHAS, P.C.; FARIAS, J.R.B.; SIBALDELLI, R.N.R.; FERREIRA, R.C. Alternative sowing dates as a mitigation measure to reduce climate change impacts on soybean yields in southern Brazil. **International Journal of Climatology**, v.36, n.11, p.3664-3672, 2016.

ROESCH, L.F.W.; VIEIRA, F.C.B.; PEREIRA, V.A.; SCHÜNEMANN, A.L.; TEIXEIRA, I.F.; SENNA, A.J.T.; STEFENON, V.M. The Brazilian Pampa: a fragile biome. **Diversity**, v.1, n.2, p.182-198, 2009.

SANTOS, D.J.; PEDRA, G.U.; SILVA, M.G.B.; GUIMARÃES JUNIOR, C.A.; ALVES, L.M.; SAMPAIO, G.; MARENGO, J.A. Future rainfall and temperature changes in Brazil under global warming levels of 1.5ºC, 2ºC and 4ºC. **Sustainability in Debate**, v.11, n.3, p.74-90, 2020.

SILVA, A.F; SEDIYAMA, T.; BORÉM, A. Exigências edafoclimáticas. In: SEDIYAMA, T.; SILVA, F.; BORÉM, A. (Eds.). **Soja:** do plantio a colheita. Viçosa, Editora UFV, p.54-65, 2015.

SILVA, D.S.; ARIMA, E.Y.; REIS, T.N.P.; RATTIS, L. Temperature effect on Brazilian soybean yields, and farmers' responses. **International Journal of Agricultural Sustainability**, v.21, n.1, p.2173370, 2023.

SILVA, E.H.F.M.; ANTOLIN, L.A.S.; ZANON, A.J.; ANDRADE JUNIOR, A.S.A.; SOUZA, H.A.; CARVALHO, K.S.; VIEIRA JUNIOR, N.A.; MARIN, F.R. Impact assessment of soybean yield and water productivity in Brazil due to climate change. **European Journal of Agronomy**, v.129, [s.n.], p.126329, 2021.

SITA, K.; SEHGAL, A.; HANUMANTHARAO, B.; NAIR, R.M.; PRASAD, P.V.V.; KUMAR, S.; GAUR, P.M.; FAROOQ, M. SIDIQUE, K.H.M.; VARSHNEY, R.K.; NAYYAR, H. Food legumes and rising temperatures: effects, adaptive functional mechanisms specific to reproductive growth stage and strategies to improve heat tolerance. **Frontiers in Plant Science**, v.8, p.1658, 2017.

SOARES, J.R.S.; RAMOS, R.S.; SILVA, R.S.; NEVES, D.V.C., PICANÇO, M.C. Climate change impact assessment on worldwide rain fed soybean based on species distribution models. **Tropical Ecology**, v.62, n.1, p.612-625, 2021.

TAIZ, L.; ZEIGER, E.; MOLLER, I.M.; MURPHY, A. **Fisiologia e desenvolvimento vegetal.** 6.ed. Porto Alegre: Artmed, 2017. 888p.

TAN, Q.; LIU, Y.; DAI, L.; PAN, T. Shortened key growth periods of soybean observed in China under climate change. **Scientific Reports**, v.11, n.1, p.8197, 2021.

TANURE, T.M.P.; MIYAJIMA, D.N.; MAGALHÃES, A.S.; DOMINGUES, E.P.; CARVALHO, T.S. The impacts of climate change on agricultural production, land use and economy of the legal Amazon region between 2030 and 2049. **Economia**, v.21, n.1, p.73-90, 2020.

UMBURANAS, R.C.; KAWAKAMI, J.; AINSWORTH, E.A.; FAVARIN, J.L.; ANDERLE, L. Z.; DOURADO-NETO, D.; REICHARDT, K. Changes in soybean cultivars released over the past 50 years in southern Brazil. **Scientific Reports**, v.12, n.1, p.508, 2022.

ZHANG, M.; ABRAHAO, G.; THOMPSON, S. Sensitivity of soybean planting date to wet season onset in Mato Grosso, Brazil, and implications under climate change. **Climatic Change**, v.168, n.2, p.15, 2021.

ZHAO, J.; WANG, C.; SHI, X.; BO, X.; LI, S.; SHANG, M.; CHEN, F.; CHU, Q. Modeling climatically suitable areas for soybean and their shifts across China. **Agricultural Systems**, v.192, e103205, 2021.

ZHENG, Y.; LI, F.; HAO, L.; YU, J.; GUO, L.; ZHOU, H.; MA, C.; ZHANG, X.; XU, M. Elevated CO_2 concentration induces photosynthetic down-regulation with changes in leaf structure, non-structural carbohydrates and nitrogen content of soybean. **BMC Plant Biology**, v.19, [s.n.], p.255, 2019.

ZILLI, M.; SCARABELLO, M.; SOTERRONI, A.C.; VALIN, H.; MOSNIER, A.; LECLÈRE, D.; HAVLÍK, P.; KRAXNER, F.; LOPES, M.A.; RAMOS, F.M. The impact of climate change on Brazil's agriculture. **Science of The Total Environment**, v.740, [s.n.], p.139384, 2020.