Special Supplement: Climate Change in Agriculture

Prospective analysis of soybean distribution in the Tocantins state considering climate change scenarios[1]

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ABSTRACT

Soybean is one of the agroenergy crops of greatest supply and demand in the Brazilian economy. Even though positive slopes in the productivity curves are constantly perceptible, the demands for arable land are evolving wildly, inevitably promoting deforestation actions and deleterious effects on the natural biogeochemical cycles, such as the carbon cycle. Several environmental models are used to explain these complex phenomena, whose variables change spatially and temporally as a function of economic, social and natural factors. Therefore, this study aimed at prospecting the soybean cultivation area using a territorial dynamics model (Dinamica EGO), in regions where sustainable use conservation units are located in the Tocantins state, considering different climate risk scenarios based on the water requirement satisfaction indexes (WRSI), calculated using daily average rainfall and temperature data from the MIROC5 global climate model. The WRSI contributed to a greater exploitation of natural resources around the environmental preservation areas of Ilha do Bananal/Cantão, Lago de Palmas and Serra do Lajeado. Furthermore, a possible decrease in the soybean area in some recognized producing centers was prospected, as well as a scenario of greater distancing of this species cultivated areas, in a near future, from the mosaic of conservation units of Jalapão, which has become of high climatic risk for the soybean grain yields usually demanded by the market.

KEYWORDS: Water availability, climate risks, conservation units.

RESUMO

Análise prospectiva da distribuição da soja no estado do Tocantins, considerando-se cenários de mudanças climáticas

A soja é uma das culturas agroenergéticas de maior oferta e procura na economia brasileira. Embora sejam constantemente perceptíveis inclinações positivas nas curvas de produtividade, as exigências por terras cultiváveis evoluem desenfreadamente, inevitavelmente promovendo ações de desmatamento e agravos deletérios nos ciclos biogeoquímicos naturais, como no ciclo do carbono. Uma série de modelos ambientais são utilizados para explicar esses fenômenos complexos, cujas variáveis se modificam espacial e temporalmente em função de fatores econômicos, sociais e naturais. Neste intuito, almejou-se a prospecção da área de cultivo da soja por intermédio de um modelo de dinâmica territorial (Dinamica EGO), em regiões onde localizam-se unidades de conservação de uso sustentável no estado do Tocantins, considerando-se cenários de riscos climáticos fundamentados nos índices de satisfação das necessidades de água (ISNA), calculados a partir dos dados de precipitação e temperatura médias diárias do modelo climático global MIROC5. Os ISNA influenciaram em uma maior exploração dos recursos naturais no entorno das áreas de preservação ambiental da Ilha do Bananal/Cantão, Lago de Palmas e Serra do Lajeado. Prospectou-se, também, uma possível redução de área de soja em alguns centros produtores reconhecidos, bem como um cenário de maior distanciamento das áreas cultivadas da espécie, em um futuro próximo, do mosaico de unidades de conservação do Jalapão, que se tornou de alto risco climático para os rendimentos em grãos de soja normalmente demandados pelo mercado.

PALAVRAS-CHAVE: Disponibilidade hídrica, riscos climáticos, unidades de conservação.

INTRODUCTION

The Brazilian export demand for soybean, soybean meal and soybean oil (averaging 12 % per year) increased between 2007 and 2018 (Abiove 2019). As a result, the country has become one of the leading players in this productive chain's global market. Expectations regarding the biodiesel industry show the growing interest in this oleaginous crop due to the legal percentages assigned to the commercialization of diesel fuels, whose advance in production has been at 3 % per year (Guiducci & Laviola 2019).

The growing demand for this crop may amplify the deforestation dynamics and, as a result, contribute to greater emissions of atmospheric pollutants. According to Escobar et al. (2020), forest cover loss is the main factor in this product's life cycle

[1] Received: May 31, 2022. Accepted: Aug. 10, 2022. Published: Oct. 19, 2022. DOI: 10.1590/1983-40632022v5272969.
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carbon footprint, especially in the states belonging to Matopiba (an acronym designating the states of Maranhão, Tocantins, Piauí and Bahia).

The Tocantins government has made significant investments in the soybean crop. The platform of municipal agricultural productions (IBGE/PAM) estimates that, in Tocantins, soybean has generated the highest income (63.27 % of the revenue generated by temporary and perennial crops) and occupied the largest area (67.52 % of the planted land) in the 2017/2018 crop season. Corn and rice crops represent 24.29 % of the hectares grown, while other crops account for 8.19 % (IBGE 2018).

Even though relevant yield increases have been achieved due to genetic breeding, climate risk zoning and improvement of agricultural management techniques, production systems are still expanding in areas previously covered by natural vegetation and inhabited by a rich biodiversity. Among the considered scenarios, Aguiar (2016) found that, even when complying with the federal law nº 9.985/2002, which establishes the national system of environmental conservation units, 14 % of the state's area may be deforested by 2050, probably to develop soybean farming.

There is a considerable range of models for determining the spatially explicit variation of several environmental factors over time. However, spatial modeling softwares are commonly employed: IDRISI® Selva associated with LCM and CA_MARKOV models (Eastman 2012), CLUE-S (Verburg et al. 2002) and Dinamica EGO (Soares-Filho et al. 2009). They all have examples of agricultural activities prospection (Lacher et al. 2018). However, it is known that the Dinamica EGO, developed by the Universidade Federal de Minas Gerais, has a greater user recursiveness and availability of input parameters for the stochastic learning of the model regulating the behavior of changes in uses and occupations, and it is, therefore, more appropriate to reflect regional circumstances and conditions (Mas et al. 2015).

According to the Intergovernmental Panel on Climate Change (IPCC), climate change has shown increases in temperature and fluctuations in average monthly rainfall due to greenhouse gas emissions resulting from changes in land use and occupation, exposing an alarming probability of regional vulnerabilities, regarding production (IPCC 2014).

The rainfall and average daily temperatures projected by a representative concentration pathway in the atmosphere, which reflects the radiative forcing of 4.5 W m^{-2} (RCP 4.5), reveal a 2 ºC increase in the average temperature (this scenario is considered optimistic). From a pessimistic perspective, in which these pollutants concentration would be significantly higher (RCP 8.5 W m^{-2}), the temperature could increase by 3 ºC. Chou et al. (2014) performed simulations that indicate a decrease in rainfall for the Tocantins state from 5 to 15 % by the end of this century.

Considering the climate change and its impact on production systems, it is possible to hypothesize that the demand for land for soybean planting in the near future will possibly lead to a greater pressure for deforestation in conservation units. Therefore, this study aimed to predict the growth dynamics of soybean cultivation areas in conservation unit regions between 2021 and 2050, using the LUCC model (Dinamica EGO), considering two future climate scenarios. The risk zonings of the water requirement satisfaction indexes (WRSI) define these scenarios with an 80 % probability of occurrence, calculated using the climate variables estimated by forcing RCP 4.5, the trend scenario, RCP 8.5, and the pessimistic scenario of the MIROC5 model (model for interdisciplinary research on climate).

MATERIAL AND METHODS

The study area is the Tocantins state (between 05º10'06"S and 13º27'69"S, and 45º41'46"W and 50º44'33"W). According to Collicchio et al. (2015), the highest temperatures coincide with the driest months, between May and September, at around 27.1 ºC, while the lowest temperatures reach 24.7 ºC. Figure 1 details the Tocantins state and its main conservation units.

Figure 2 illustrates the diagram of the adopted methods. They were stratified into two stages. The first corresponds to the elaboration of climate risk scenarios, and the second refers to the simulation stages of land use and coverage, to analyze the soybean in the Tocantins state in the near future.

The mapping of altitude classes (classes from 1 to 7, with intervals of 200 m, with minimum altitude of 73 m and maximum of 1,400 m) was extracted from the SRTM digital elevation model (USGS 2014) under the resolution of 1 arc second (approximately 30 m pixel size, with the spatial scale also adopted in this project). This data is bound as a

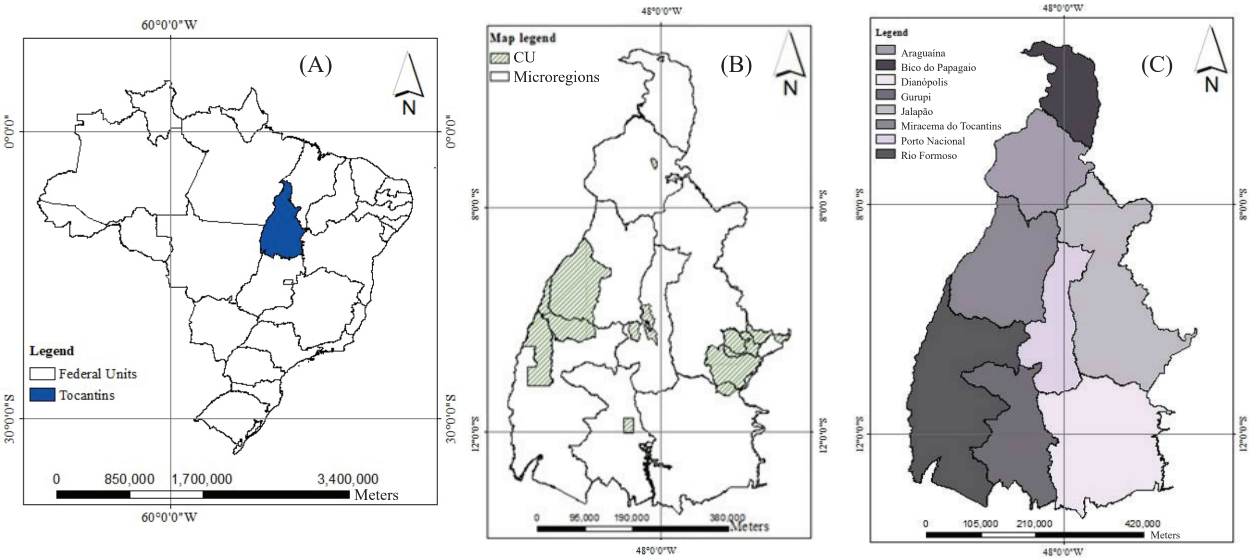

Figure 1. Location of the Tocantins state (A) and its main conservation units (CU; B) and microregions (C).

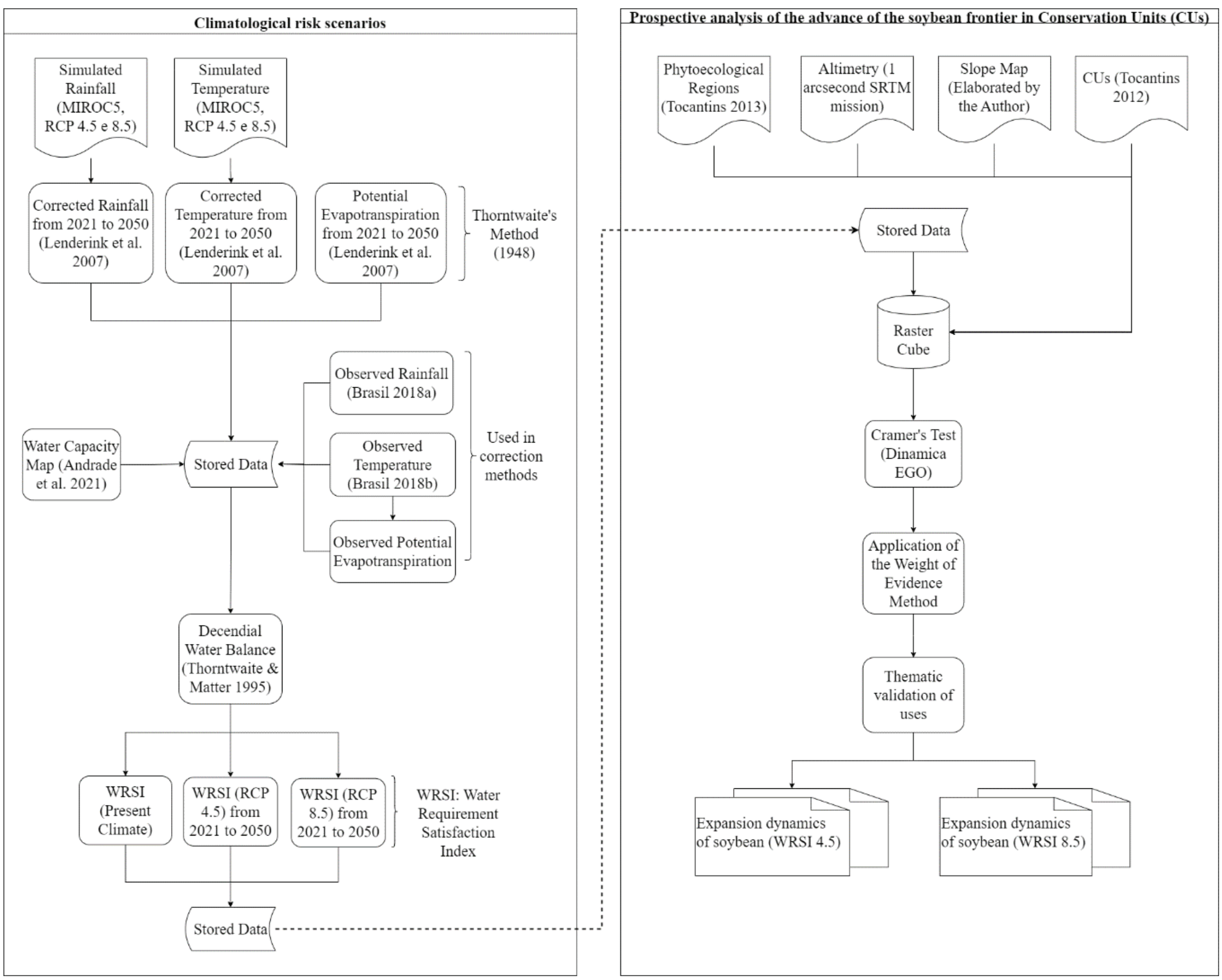

Figure 2. Flowchart of the methods adopted for the prospective analysis of soybean in the Tocantins state.

static input into the land-use and land-cover change (LUCC) model.

The daily average rainfall and air temperatures observed from the Brazilian National Water Agency (Brasil 2018a) and National Institute for Space Research (Brasil 2018b) were used to correct the RCP 4.5 and RCP 8.5 future scenarios of these same climatic conditions using the method proposed by Lenderink et al. (2007), characterized by the following equations: $T_{cor,m,d} = T_{sim,m,d} + \mu(T_{obs,m}) - \mu(T_{sim,m})$ and $P_{cor,m,d} = P_{sim,m,d}$ x $[\mu(P_{obs,m})/\mu(P_{sim,m})]$, where $T_{cor,m,d}$ and $P_{cor,m,d}$ are, respectively, the corrected simulated temperature (ºC) and rainfall (mm) of the month "m" and the 10-day period "d" in the interval from 2021 to 2050; while $T_{sim,m,d}$ and $P_{sim,m,d}$ are the simulated temperatures and rainfall of the MIROC5 model for the month "m" and the 10-day period "d" in the series of the same temporal space. The µ values will be the 10-day averages of the months "m" of these constraints in the time fraction called baseline, which served as a reference for the forecast model (Oliveira et al. 2015). These averages are from the simulated $[\mu(T_{sim,m})$ and $\mu(P_{sim,m})]$ and observed $[\mu(T_{obs,m})$ and $\mu(P_{obs,m})]$ temperatures and rainfall, over the period between 1986 and 2005.

Then, the 10-day water balance was automated in an algorithm developed in Python for processing several samples using the method proposed by Thornthwaite & Mather (1955).

The water requirement satisfaction indexes (WRSI) for the current climate (RCP 4.5 and RCP 8.5) result from the water balance calculation simulations for 36 sowing dates from 130 rainfall stations of the Brazilian National Water Agency (Brasil 2018a), considering a soybean cultivar of medium development cycle, Group II, with crop coefficients indicated by Evangelista et al. (2017) (Table 1) and using available water capacity (AWC) mapping. The latter spatial variable was estimated using a pedotransfer function (PTF), defined from modeling the van Genuchten retention curves of 157 soil density and clay, silt and sand concentration samples (Andrade et al. 2021).

The WRSI and the ratio between actual and maximum crop evapotranspiration during the phenological phase of flowering and grain filling were searched, corresponding to the risk level of 20 % (Evangelista et al. 2017, Brasil 2019) of water deficiency of this indicator's frequency distribution for each simulated planting season and in all the 130 rainfall stations for the corresponding climate change scenarios.

The present study consisted of spatializing low climate risk areas containing at least one sowing date among the 36, with WRSI higher than 0.65 for the current climate and the evaluated scenarios. The same criterion was defined for the mapped areas of medium (0.55 < WRSI < 0.65) and high risk (WRSI < 0.55), which must have at least one planting date in the WRSI range considered for their classification. These data are also considered input parameters for the LUCC model (Monteiro et al. 2015).

The aforementioned matrix and vector layers were transferred to a multidimensional data extent, whose weights of evidence in the terrain transformations were calculated using the Bayes theorem. The correlation (Cramer's test) between the chosen variables aimed to eliminate any redundancy in the weights of evidence, an elementary requirement for this cellular automata modeling (Mas et al. 2015).

Finally, a prospection of the uses of soybean crops in the last ten years in the Tocantins state and regions of conservation units located in this territory was conducted. Therefore, the uses and occupation maps were sampled from the MapBiomas platform in its fourth collection (Mapbiomas 2020) from 2008 to 2018. The use class for annual and perennial crops was entirely based here, as a mask for the soybean crop, given its predominance in terms of production, area and potential deforestation, when compared to other crops.

The land uses and occupations model (LUCC) simulation was performed by calibrating the coefficients of the weights of evidence from the soybean development climate risk mappings for the period between 2008 and 2018. This redefinition of the measured weights makes the low WRSI and higher climate risk areas less attractive to crop implementations. The validation was performed using the Fuzzy similarity between the neighboring

Table 1. Duration of the soybean crop development cycles in 10-day periods by relative maturity group (RMG).

RMG	10-day periods												
	1	2	3	4	5	6	7	8	9	10	11	12	13
Group II	0.4	0.6	0.7	0.8	1.0	1.2	1.4	1.5	1.4	1.3	1.2	0.9	0.8

cells of the two mappings, estimated and observed in 2013 according to the method adapted from Hagen (2003). It should be noted that this procedure was performed for the current climate WRSI, WRSI with RCP 4.5 and WRSI with RCP 8.5. Therefore, simulations of uses and occupations for each climate scenario were performed between 2019 and 2050.

The transitions from the area of natural vegetation to the area potentially occupied by soybean crops were measured by the overlay mapping method, provided by a Geographic Information System for each of the prospected WRSI scenarios (current climate WRSI, WRSI with RCP 4.5 and WRSI with RCP 8.5). The spatial cross-referencing of the carbon stock maps (Tocantins 2013) with the deforested area allowed the visualization of the carbon content removed for cultivation purposes. This value of carbon tons was multiplied by the ratio between the atomic masses of CO_2 and carbon (44/12) to estimate the emissions, in tons, of equivalent carbon dioxide (CO_2e) generated as a result of the agricultural frontier advance for each of the mentioned scenarios (Salmona et al. 2016).

RESULTS AND DISCUSSION

The mapping of risk areas from current rainfall and daily temperature data over the past 30 years (Figure 3a) is similar to that defined by Evangelista et al. (2017). In both, it is clear that there is at least one sowing season in which water deficiency will not occur in the evaluated phenological phase. Some WRSI, mainly in the southern region, were characterized as high climate risk under RCP 4.5 and 8.5 scenarios (Figures 3B and 3C, respectively). Fidelis et al. (2007), through four trials in the municipality of Gurupi, with twenty genotypes of this legume, validated the high risk, once they found grain yields below the relativized viability per cultivar.

There is a possibility that the lower AWC estimated by the PTF between 30 and 40 mm in the protected area of Jalapão, if compared to the Tocantins state, whose average is 40-50 mm (Andrade et al. 2021), have acted as co-causers of the low WRSI, just as the rainfall regime.

After calibration of the model of land uses and occupations (Dinamica EGO), the minimum degree of similarity observed in the comparison map between observed and simulated differences by the method adapted from Hagen (2003) was 0.70 for the modeling that involved the WRSI of RCP 4.5 as a statistical variable and 0.69 in RCP 8.5 for a comparison window size of 11 x 11 pixels of resolution. This value is above what is normally used as an acceptability standard (between 45 and 50 % of similarity).

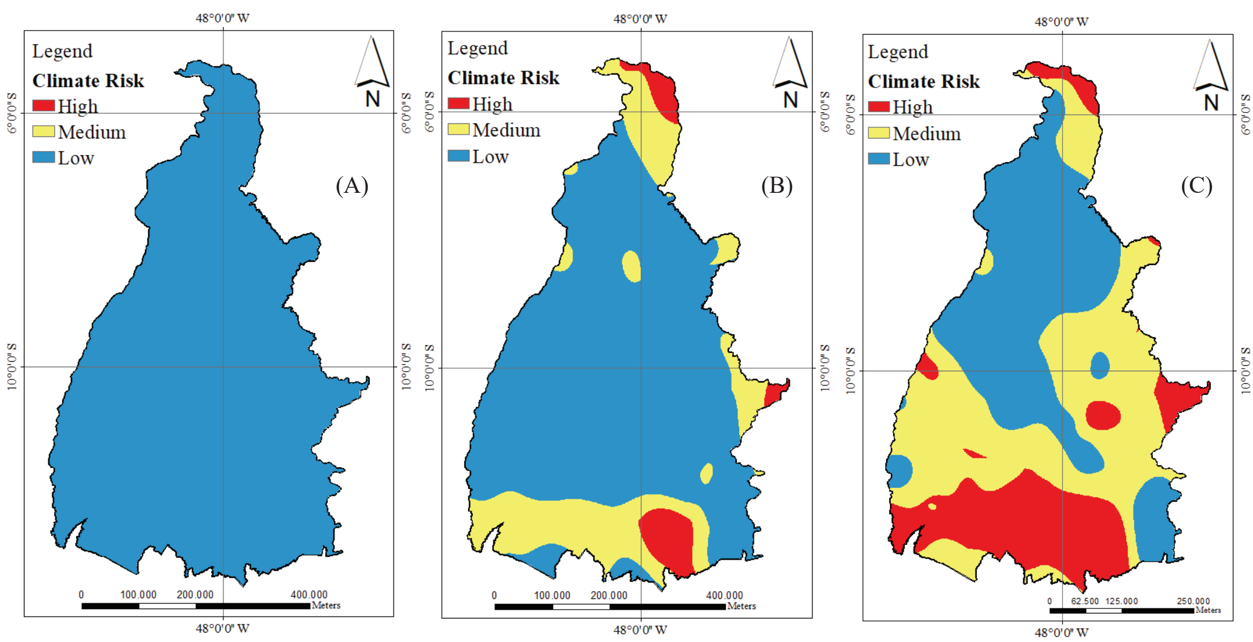

Figure 3. Low, medium and high climate risk areas for the historical rainfall and temperature series observed between 1986 and 2017 (A), and estimated by the MIROC5 model between 2021 and 2050 for the RCP 4.5 (B) and RCP 8.5 (C) scenarios.

Figure 4 illustrates the similarity coefficients exposed by the Dinamica EGO. There is a certain similarity between the perspectives adopted for the windows below 7 x 7. Above this value, a slight difference is observed, characterizing a greater similarity for the RCP 4.5 forcing compared to the other, relatively pessimistic scenario, RCP 8.5.

The soybean production system advanced in 29.54 % of the natural vegetation areas in the territory of the Tocantins state in both the studied scenarios. However, a higher value of CO_2e emissions is portrayed for a trend climate risk scenario (RCP 4.5). Therefore, the climate model exposing a wide range of low WRSI values (WRSI RCP 8.5) provided a perspective of lower equivalent carbon emissions due to this agricultural activity.

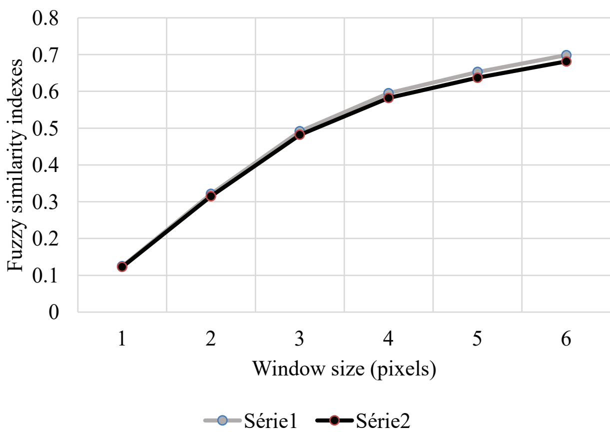

Figure 4. Fuzzy similarity indexes between simulated and observed difference maps for different window sizes and soybean expansion scenarios in the Tocantins state.

Figure 5 shows that deforestation rates decrease and stabilize in 2040, at 260,000 ha, by the end of the defined time horizon. For RCP 8.5 W m^{-2}, this decrease follows the decrease in the CO_2e emissions. Beuchle et al. (2015) also characterized this rate decrease (from 1,294.9 to 1,181.2 thousand ha $year^{-1}$), between 2000 and 2010, in the Cerrado biome. The Ministry of the Environment (Brasil 2009) has deferred a figure close to 1,250,000 ha $year^{-1}$. Based on these references, Tocantins is responsible for approximately 20.8 % of the phytophysiognomic losses in this biome. Carneiro Filho & Costa (2016) and Bolfe et al. (2017) extended this opinion to Matopiba and Tocantins, respectively.

The soybean evolution for the RCP 4.5 scenario of the MIROC5 model (Figures 6A and 6B) shows that the most optimistic version of the water availability distributions in the Tocantins state, with lower greenhouse gas emissions, leads to area competitiveness in the south-central part of this federative unit. For RCP 4.5, the Jalapão microregion, which has significant municipal agricultural productions of the analyzed species (IBGE 2018),

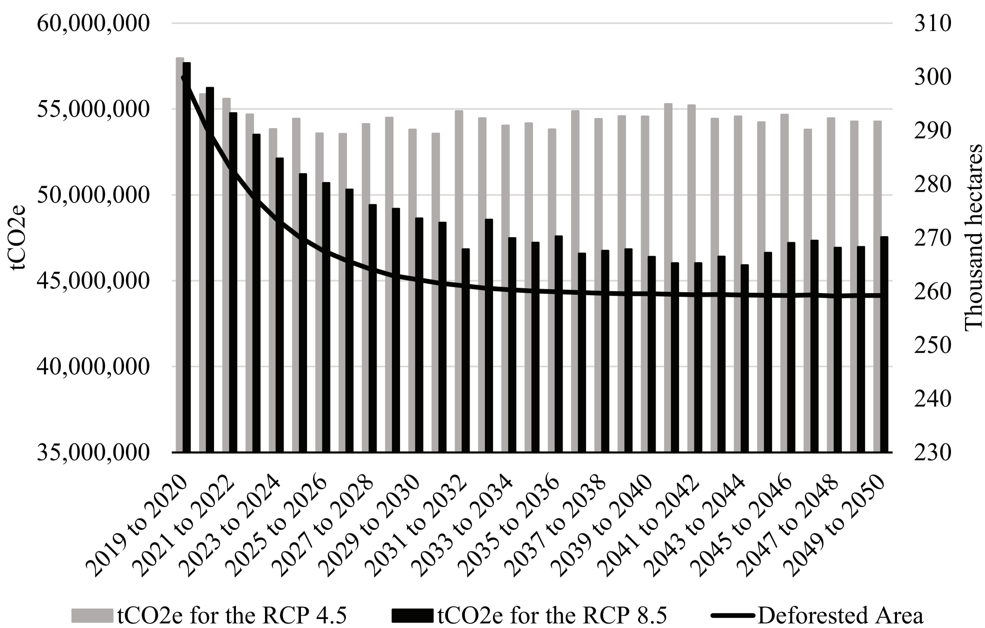

Figure 5. Cumulative CO_2e emissions by climate scenario and accumulated deforested area between 2009 and 2050.

may suffer losses of areas planted with soybean of around 99 %, between 2019 and 2050.

For RCP 8.5, the overlap between the Figures 6C and 6D simulates a possible advance of the species in the Araguaína microregion, which almost quintupled its area cultivated with soybean between 2019 and 2050. This territorial dynamics ratifies a possible soybean expansion toward the Amazon biome. Moura et al. (2018) proved, using a principal component analysis, that the relationship between southern ocean oscillation indexes and climate variables best explains the rainfall regime of the legal Amazon. The

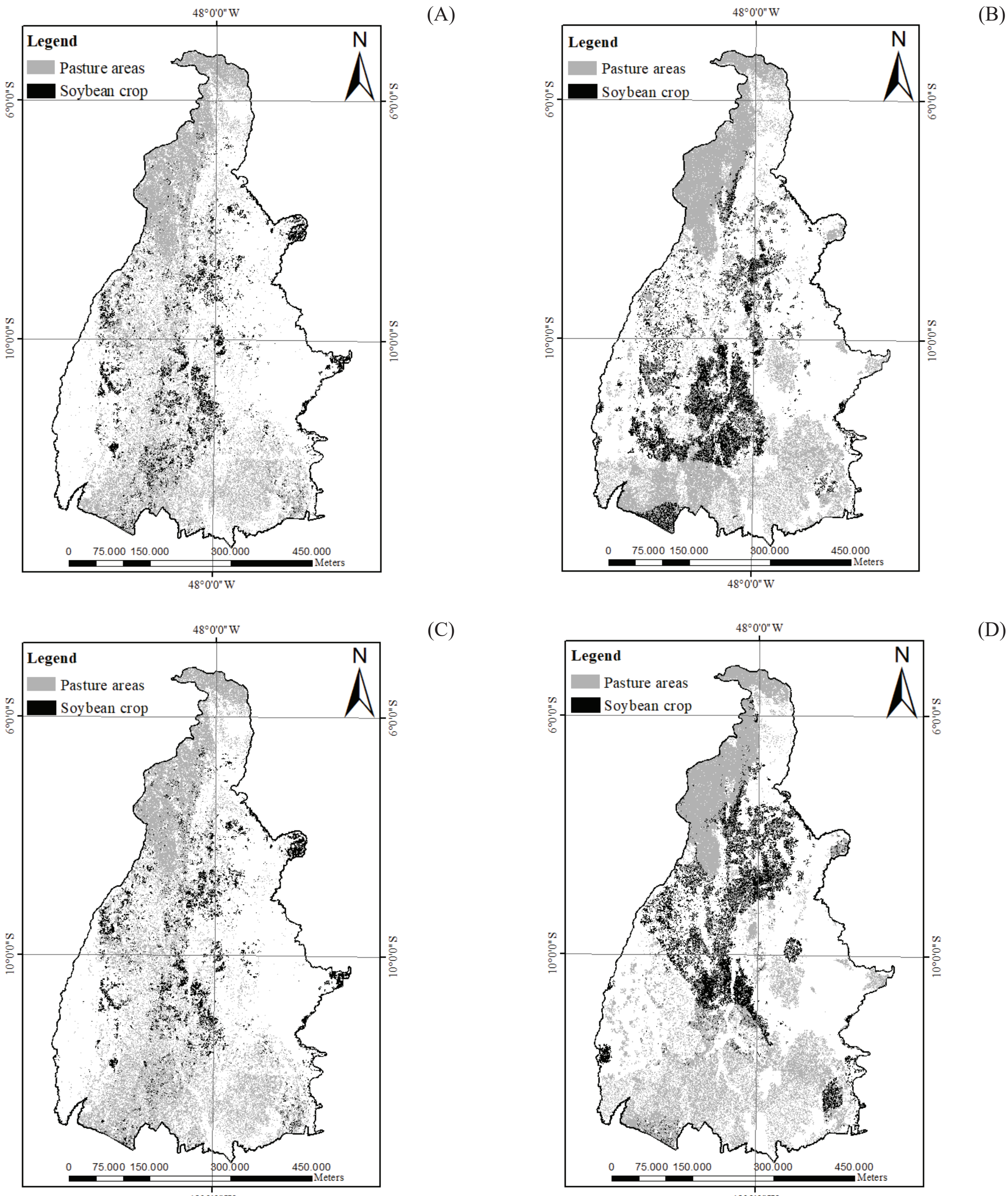

Figure 6. Soybean crop MIROC5 model estimation in the Tocantins state for the RCP 4.5 scenario in 2020 (A) and 2050 (B), and RCP 8.5 in 2020 (C) and 2050 (D).

authors exposed that the convective phenomenon of the South Atlantic Convergence Zone generates this rainfall distribution, positively impacting the soybean industry in the southeast of the legal Amazon, which is in the Tocantins Amazon biome (Moura et al. 2018).

The municipalities of Mateiros and Campos Lindos, belonging to the Jalapão microregion, are the first and third agricultural hubs of the Tocantins state, according to the indicative number of plantations, in ha, from the 2018 municipal agricultural production census detailed by the IBGE (2018). Campos Lindos may lose 93.42 % of its cultivated area if the MIROC5 model climate projection with RCP 4.5 is validated, and may have 5,224 ha by 2050. Mateiros had the second highest soybean production revenue in 2018 and may dissolve 70.43 % of its soybean domains. This loss may be higher (approximately 85 % of its sown area) if the RCP 8.5 scenario is confirmed.

The municipality of Campos Lindos may obtain, according to Silva (2018), who used the same model used in this study, a decreasing green water footprint over the century, while the crops may demand greater amounts of water from the applied irrigation systems. It justifies a possible drop in the planting of this crop in dryland, the agricultural method advocated by this study, in the municipality of Campos Lindos (Silva 2018).

The only municipality benefiting from the two simulations of land uses and land cover in the executed LUCC model is Porto Nacional, which was ranked fourth in the municipal ranking of planted areas in 2018 and is the eighth economy in the Tocantins state in this sector.

The Bananal island/Cantão conservation unit may have its annual suppression rate of native vegetation area growing linearly from 1.26 to 3.38 % over the next 30 years. It gives a soybean crop occupancy of 12.87 % in 2050, with a greater record in 2030 of approximately 22.11 % of farmland for the WRSI theme ranges explored by the MIROC5, RCP 4.5 model. These numbers are similar to the future scenario proposed by Aguiar (2016) in the Tocantins state, which creates the hypothesis of the non-existence of conservation units and their sustainability principles, referring to the national system of conservation units (Brasil 2000). The absence of integral protection and the prerogatives created in the legislations for this conservation unit noted by Moreira & Collicchio (2017) equally support the possibility of these indexes in the near future.

Cross-referencing the geographic information on carbon stock and the area deforested by soybean planting, multiplied by the conversion factor of 44/12, allowed the estimation that between 0.21 and 0.47 million tCO_2e are emitted per year in the two evaluated WRSI scenarios (RCP 4.5 and RCP 8.5), in the surroundings of this conservation unit. Given the RCP 8.5 within the Ilha do Bananal, it was found that 11.93 % of the state emissions occurred in 2019. By 2050, 28.37 % of emissions may come from this conservation unit.

The Serra do Lajeado conservation unit, which houses the Lajeado state park, resulting from the creation of the Luiz Eduardo Magalhães hydroelectric power plant in Lajeado, between 2019 and 2020, was devastated by 756 ha (0.61 % of the area). In the last prospected years, this rate may reach 0.91 %, devastating 1,124 ha $year^{-1}$. During thirty years, a deforestation equivalent to 20.66 % of the area may be accumulated (average of 819 ha $year^{-1}$). Supposing that a more intense climate change is considered (RCP 8.5), the situation changes radically, as diagnosed by the Student's t-test at 1 % of significance, exhibiting an average over the same time interval of 1,022.97 ha $year^{-1}$, degrading the equivalent of 25.82 % of the area.

The Jalapão mosaic of conservation units had an area anthropized by the species cultivation of 28,608 ha in 2019 (2.67 % of its total area). For the RCP 4.5, this area may decrease to 5,344 ha (0.50 % of the conservation units) in 2050, and, for the RCP 8.5, may reach 340 ha (0.03 % of the conservation units). The stresses exerted by agriculture on the surroundings of these units may also decrease by 44.08 % of the planted areas for the RCP 4.5 and 73.56 % for the RCP 8.5. These indexes imposed an emission rate of 0.11 % CO_2e in 2019 and 0.05 % in 2050. For the radiation forcing of 8.5 W m^{-2} in the MIROC5 model, the same depreciation rate was found, with less expressive results than for the RCP 4.5, with different annual averages at 1 % of significance.

CONCLUSIONS

1. A greater deforestation pressure is predicted in the conservation units of Bananal island/Cantão, Lago de Palmas and Serra do Lajeado in the near future, with Ilha do Bananal/Cantão standing out, where deforestation rates derived from soybean

planting may increase from 1.26 to 3.38 % between 2021 and 2050, according to the less pessimistic scenario (RCP 4.5), corresponding to an increase of 0.21 to 0.47 million tons of CO_2e;

2. The complex of protected areas in the Jalapão micro-region showed decreasing deforestation rates (reduction from 44.08 to 73.56 % in the surrounding conservation units) and CO_2e emissions (around 0.11 % in 2019 and 0.05 % in 2015). The possible reduction of soybean areas in this region is due to the soils physical-hydric characteristics, relatively low available water capacity (around 30-40 mm) and the average annual rainfall regime estimated by the corrected MIROC 5 model, which jointly quantified the water requirement satisfaction indexes below the average value (< 0.55);
3. Climate change may reduce the soybean planted areas in one of the largest municipal producers of the Tocantins state, Campos Lindos, located in the Jalapão micro-region, which may lose 93.42 % of its cultivated area between 2021 and 2050, according to the RCP 4.5.

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