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*Scientific Article*
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# Impacts of climate change on water fluxes and soybean growth in southern Brazil[1]

## Impactos das alterações climáticas nos fluxos de água e no crescimento da soja no sul do Brasil

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**ABSTRACT** - Climate is a determining factor in agricultural production and climate change can affect this productivity. This, study aims to analyze the consequences of climatic change in the soil water dynamic and growth soybean in Southern Brazil. Scenarios were created for conditions of a 2 ºC temperature increase, a 20% reduction, and a 50% increase in precipitation rates, representing hot, dry and wet scenarios, respectively. The atmospheric forcing generated were used as input data for the agricultural version of the Integrated Biosphere Simulator model (Agro-IBIS) and simulations were carried out for a soybean growing season in the northwestern Rio Grande do Sul, Brazil. The following variables estimated by Agro-IBIS were analyzed: soil moisture, soybean leaf area index, evaporation, and transpiration. The results showed that the climatic changes projected by the simulations influence soybean growth in the study area. By increasing the temperature in 2 °C, the Agro-IBIS model indicated the occurrence of shorter crop growth cycles and even more impactful results on the leaf area index, with a 70% reduction in the highest values. Furthermore, a 50% increase in precipitation rate showed positive effects on agriculture, indicated by increased LAI in the reproductive period. On the other hand, a 20% reduction in precipitation has a negative effect, as it exposes the crop to water deficit conditions, impacting soil moisture and decreasing LAI. The soil evaporation is also intensified with increased temperatures due to the higher evaporative demand of the atmosphere and a significant decline in LAI. The transpiration for the hot scenario is more strongly impacted during the vegetative growth stage and leaf senescence.

**Key words**: Agroecosystem model. Soil moisture. Evaporation. Transpiration. Leaf area index.

**RESUMO** - O Clima é um fator determinante na produção agrícola e as mudanças climáticas podem afetar esta produtividade. Assim, este estudo tem como objetivo analisar as consequências das mudanças climáticas na dinâmica da água no solo e do crescimento da soja no sul do Brasil. Foram criados cenários para condições de aumento de temperatura de 2 ºC, redução de 20% e aumento de 50% nas taxas de precipitação, representando cenários quentes, secos e úmidos, respectivamente. Os forçamentos atmosféricos gerados foram utilizados como dados de entrada para a versão agrícola do modelo de Simulação Integrada da Biosfera (Agro-IBIS) e simulações foram executadas para uma estação de cultivo de soja no noroeste do Rio Grande do Sul, Brasil. Analisaram-se as seguintes variáveis estimadas pelo Agro-IBIS: umidade do solo, índice de área foliar (LAI) da soja, evaporação e transpiração. Os resultados mostraram que as mudanças climáticas projetadas pelas simulações influenciam o crescimento da soja na área de estudo. Ao aumentar a temperatura em 2 °C, o modelo Agro-IBIS indicou a ocorrência de ciclos de crescimento de safra mais curtos e resultados ainda mais impactantes no LAI, com redução de 70% nos valores mais altos. Além disso, o aumento de 50% na taxa de precipitação mostrou efeitos positivos na agricultura, indicados pelo aumento do LAI no período reprodutivo. Por outro lado, a redução de 20% na precipitação tem efeito negativo, pois expõe a cultura a condições de déficit hídrico, impactando a umidade do solo e diminuindo o LAI. A evaporação do solo também é intensificada com o aumento das temperaturas devido à maior demanda evaporativa da atmosfera e um declínio significativo do LAI. A transpiração para o cenário quente é mais fortemente afetada durante o estádio de crescimento vegetativo e a senescência das folhas.

**Palavras-chave**: Modelo de agroecossitema. Umidade do solo. Evaporação. Transpiração. Índice de área foliar.

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## INTRODUCTION

Climatic conditions are determining factors for favorable agricultural productivity. Research simulating the impacts of climate change on Brazilian agriculture has been developed using mathematical models, such as the one presented by Rosa, Souza and Tsukahara (2020) for wheat, Soler, Sentelhas and Hoogenboom (2007) and Bassu *et al*. (2014) for maize, Battisti, Sentelhas and Boote (2018b) for soybean, Dias and Sentelhas (2017) and Marin *et al*. (2013) for sugarcane, and Rodríguez *et al*. (2011) for coffee. In general, these studies used empirical productivity models, assessing the productivity impacts of climate change, but do not consider the dynamic of the water balance in the soil-plant-atmosphere system according to the physical processes involved.

In this context, a new approach to understanding how different climatic scenarios affect plant growth is proposed using agroecosystem models based on physiological and phenological traits. One of these models of surface-atmosphere interaction is Agro-IBIS, which is widely used to better understand the dynamics of crops in specific regions and conditions.

The Agro-IBIS was developed to model crops and currently includes soybean, maize, wheat, and sugarcane (CUADRA *et al*., 2012; KUCHARIK; BRYE, 2003; VANLOOCKE; BERNACCHI; TWINE, 2010). Agro-IBIS is a dynamic vegetation model and represents the canopy physiology, plant phenology and carbon balance. Furthermore, simulate the soil-vegetation-atmosphere system through the surface processes related to energy, water, carbon, and momentum exchanges. This approach allows coupling of the ecological, biophysical, and physiological processes that occur on different time scales (WEBLER *et al*., 2012). The model output includes LAI, evapotranspiration, carbon flux and other variables (KUCHARIK; BRYE, 2003).

In Agro-IBIS, the mass exchanges are represented by the Farquhar–Ball–Collatz equations, and are governed by stomatal and aerodynamic conductances (BALL; WOODROW; BERRY, 1986; COLLATZ; GRIVET; BERRY, 1991; FARQUHAR; SHARKEY, 1982; FARQUHAR; VON CAEMMERER; BERRY, 1980). In these representations, photosynthesis is a function of absorbed light, leaf temperature, $CO_2$ concentration in the leaf, and the capacity of Rubisco Enzyme (WEBLER *et al*., 2012). The LAI equations are daily solved, through the product between carbon accumulated in the leaf and specific leaf area. For each phenological stage there is a specific fraction of carbon allocated in the pools: root, stem, leaf and grain. The crop development is governed by the accumulated growing degree days (GDD), divided into crop phenological stages: emergence, grain fill and senescence (WEBLER *et al*., 2012). The atmospheric forcing variables necessary to carry out the simulations with the Agro-IBIS model are incident solar radiation, precipitation, air temperature, wind speed, and relative humidity.

Webler *et al*. (2012) validated the Agro-IBIS model against surface fluxes experimentally obtained in soybean agroecosystems located in Cruz Alta, in the northwestern region (NW-RS) of Rio Grande do Sul state (RS), Brazil. This region is responsible for almost 50% of soybean production of this state (RIO GRANDE DO SUL, 2021). Complementing the Webler *et al*. (2012), Moreira *et al*. (2018) evaluated the processes linked to the soil variables. However, no studies have been conducted to understand how the Agro-IBIS model describes the consequences of possible climate change in the soil water and growth soybean. In this sense, this study aims to assess the consequences of possible climate change in these variables over a soybean growing season in NW-RS. The WRF model was used to generate the meteorological forcings for the NW-RS region, under which were imposed climate variations estimated by Intergovernmental Panel on Climate Change (2013). The evaluations were performed on an average over the region under the conditions of the 2009-2010 soybean growing season, the period in which an Agro-IBIS model version has been already improved and evaluated by Moreira *et al*. (2018). Thus, we intend to answer the following questions: (i) Can changes in climatic conditions significantly alter soil water availability for soybean growth? (ii) How do the soil water conditions respond to climate changes associated with precipitation and temperature?

## MATERIAL AND METHODS

### Study area

The soybean crop was introduced in NW-RS in the early 1970s, mainly due to the soil, climatic, and topographic conditions of the region that highly favored soybean growth and had few requirements for its management at the time. Experiments with crop rotation based in soybean in summer have been conducted since 1985 over no tillage (NT) and conventional tillage (CT) managements (BORTOLOTTO *et al*., 2015; CHAVEZ *et al*., 2009).

The experimental observations were carried out at the Experimental Research Center Foundation (CCGL TEC / FUNDACEP) located at - 28° 36’ of latitude and - 53° 40’ of longitude, at an elevation of 425 m, in Cruz Alta, northwest of Rio Grande do Sul, Southern Brazil. The region’s climate is of type Cfa (Köppen), humid subtropical, with average annual precipitation of 1755 mm evenly distributed throughout the year, around 150 mm by month. The average annual daily temperature is 18.7 °C, with the average minimum daily temperature of 8.6 °C in July and an average maximum of 30.0 °C in January.

The soil at the experimental site is Rhodic Ferralsol (FAO Soil Taxonomy) or Typic Haplorthox (USDA Soil Taxonomy) with the following characteristics: clay = 520 g $kg^{-1}$, silt = 240 g $kg^{-1}$, sand 240 g $kg^{-1}$, organic matter = 32 g $kg^{-1}$. The soil is clayey and deep, with a 1% slope.

At CCGL TEC / FUNDACEP an array of 40 m × 60 m plots was arranged in pairs in order to compare NT with CT. The permanent wilting point (WP) and field capacity (FC) were estimated using soil water content at 1500 and 10 kPa tension, respectively. The values found for wilting point and soil field capacity were 0.18 $m^3$ $m^{-3}$ and 0.50 $m^3$ $m^{-3}$, respectively.

The soybean growing season 2009/10 over NT management was evaluated. The soybean cycle started on December 14, 2009 (sowing), and on December 19, emergence occurred. On April 13, 2010, physiological maturity was identified and harvesting was performed on April 28, 2010. The soybean growth stages were determined following the phenological scale proposed by Fehr and Caviness (1977). More details about the experimental design can be found in Webler *et al*. (2012) and Moreira *et al*. (2015).

The climatic average precipitation for the study months (December to April) is 691 mm. However, between December, 2009 and April, 2010, total precipitation was 757 mm. Therefore, the total precipitation was only 9% above the climatic average, mainly because the austral summer 2009-2010 was an El Nino year (NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION, 2021), which tends to increase precipitation in southern Brazil.

## Simulation

### Agroecosystem model

The Agro-IBIS (based on version 2.0 of the IBIS model), simulating the soybean, was evaluated using experimental data collected in 2009-2010 growing season in Cruz Alta - RS over NT and CT management by Webler *et al*. (2012). In NT management, a residual layer from the previous crop is deposited on the soil without being mechanically incorporated into the soil as in the case of CT. As there was no representation of straw residue in the Agro IBIS model, the results of Webler *et al*. (2012) showed that the model better represented surface water flux in CT. A residual layer was incorporated in Agro IBIS model by Moreira *et al*. (2018), including different physical soil properties because of the different long-term soil management systems and the leaf area index (LAI) adjustment to better represent the soybean grain fill to the physiological maturity period using the same Weber *et al*. (2012) dataset. Moreira *et al*. (2018) proposed a LAI expression where it is reduced slowly at the beginning of senescence and then falls more rapidly, until it is annulled at the end of the crop development cycle. The parameters were obtained from the adjustment of the Agro-IBIS model based on LAI observations available for the experimental site of Cruz Alta - RS. They show that the model improved the dynamics of the water exchange and indicate this Agro-IBIS model version in studies to assess the consequences of future climate scenarios in surface atmosphere interaction over soybean. The version of Agro-IBIS model proposed by Moreira *et al*. (2018) is used.

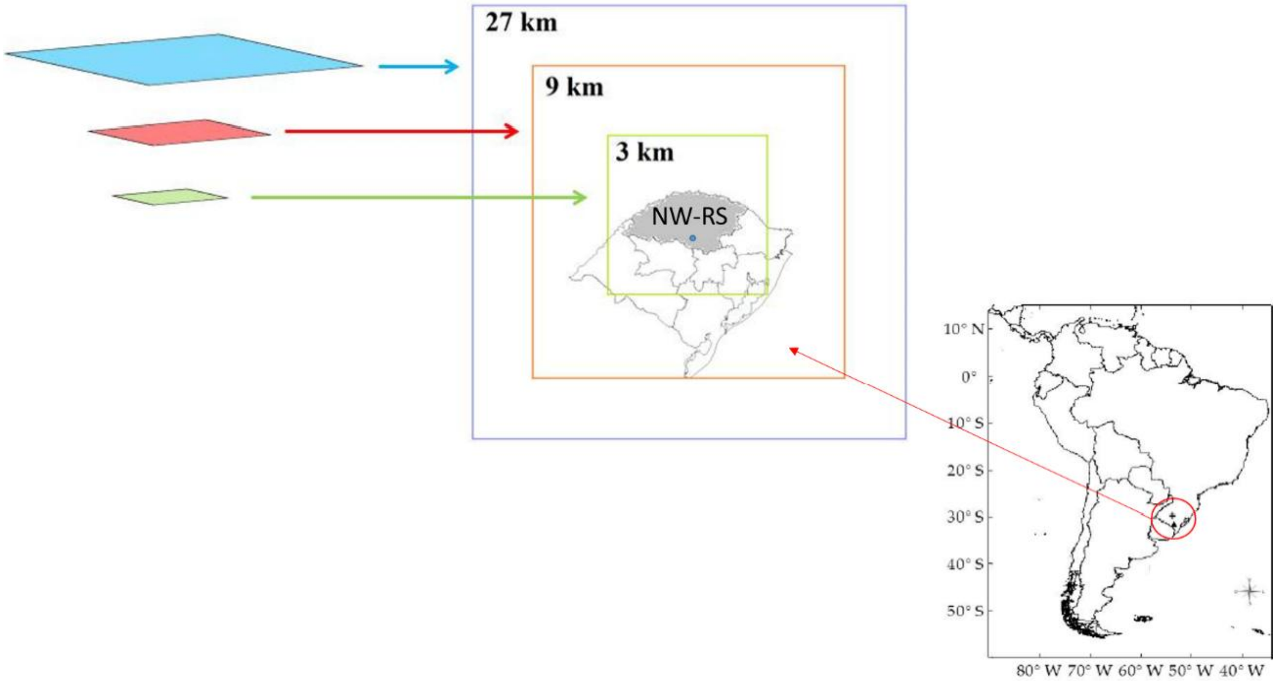
### Generation of atmospheric forcing

Climate downscaling dataset is necessary for agricultural impacts of climate change-variability and assessments because factors that affect crops (soil, surface, topography, and farming practices) vary at finer scales than typical global climate model spatial resolution. To assess the consequences of possible climate change in the dynamic of water and growth of soybean in NW-RS, atmospheric forcings generated to the entire NW-RS region from the WRF daily weather forecast data were used. Numerical weather forecasts were up to 72 h and performed daily from 08 December 2009 to 30 April 2010. This procedure was performed to generate a high spatial resolution and high quality weather database over the NW-RS region during the soybean growing season 2009-2010. Using this strategy allows regionally scaling the application of the Agro-IBIS model, calibrated and validated at local scale by Webler *et al*. (2012) and Moreira *et al*. (2018), using observational data. To this end, dynamic downscaling was performed using the hourly output data of the Weather Research and Forecasting (WRF) model using the same physical configuration as in Sousa *et al*. (2019), which allows the spatial-temporal variability of climatic elements to be represented at a more refined scale.

The lateral boundary conditions were updated every 6 h from daily forecasts of the Global Forecast System (GFS) with a horizontal resolution of 50 km. The WRF model was applied in nested mode at three horizontal resolutions (27, 9, and 3 km; Figure 1). Thus, the predicted precipitation, air temperature, relative humidity, incident solar radiation, and wind speed near the surface of the area of the highest spatial resolution (3 km) were used to force the Agro-IBIS model considering each grid point over the study area.

In this work, to initialize the model (spin-up) forced by hourly average data, a thirty years period with forcing data repeated annually is used in order to stabilize the total column soil moisture and C, N pools.

**Figure 1** - Grids of the WRF model applied in nested mode at three horizontal resolutions (27, 9, and 3 km) for northwestern Rio Grande do Sul. The blue point shows the location of the Cruz Alta experimental site, where the soybean phenological data was obtained




**Temperature and precipitation climate scenarios**

Simulations with Agro-IBIS were performed considering scenarios of change in the average rainfall rate and of air temperature increase following the results of RCP8.5 (Representative Concentration Pathways), (MOSS *et al*., 2010) representing a scenario with very high emissions of greenhouse gases. RCP projections are part of the set of simulations of CMIP5 (Coupled Model Intercomparison Project Phase 5), (INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, 2013; TAYLOR; STOUFFER; MEEHL, 2012). The analysis of the projections of change in precipitation and air temperature in the study area was performed considering the soybean growing season, DJFMA (December, January, February, March, and April), and the RCP8.5 scenario from CMIP5 over the decades from 1986 to 2005. This period is considered the reference period for the current climate condition and for the decades from 2041 to 2060. In this analysis the results produced by 25 models with data availability of at least one member in the set was used. The results were averaged over the study area for the DJFMA station, and considered as variation (changes between the current and future condition of the climate elements), the differences in air temperature and precipitation rate between the decades 2041-2060 and the base period 1986-2005.

The accumulated precipitation measured between December 19, 2009, and April 25, 2010, i.e., 2009/10 soybean growing season in Cruz Alta - RS, was 650 mm. It was used as reference to create the increased and reduced precipitation scenarios. The following scenarios were considered:

- Humid scenario (WET): a 50% increase in precipitation (975 mm);

- Dry scenario (DRY): a 20% reduction in precipitation (520 mm);

For the air temperature, the following scenarios were considered:

- Current scenario (current): the current air temperature.

- HOT scenario (current +2): a 2ºC increase in the current air temperature.

Since the objective of the simulation is to evaluate the sensitivity of the soybean growth cycle simulated by Agro-IBIS under different climatic conditions from those under which the model was calibrated, the phenological characteristics of the soybean were not changed in all scenarios. The simulations were performed for the NW-RS region using the Agro-IBIS model at each grid point of 3 km x 3 km, with atmospheric forcings obtained by forecast data from the WRF model. The results are presented as average values and the region spatial standard deviation for soil moisture at up to 50 cm depth, soybean leaf area index, evaporation, and transpiration.

## RESULTS AND DISCUSSION

### Climatic Scenarios

Most of the CMIP5 earth system models project a trend of increasing air temperature, for the coming decades and during the soybean growing season (Figure 2a). There is a great variation in the projection of air temperature between the results of the models, but when considering the averages of the members that make up these data series it is possible to verify a tendency to increase, with a variation between 1 ºC and 3 ºC, and an average warming of 2 ºC of magnitude at the end of the period from 2041 to 2060 (Figure 2a). Thus, to assess the impact of future warming on soybean cultivation, a most likely 2 °C increase condition was established as a near future climate change scenario.

For precipitation the projections show no trend in terms of the average of the model results for the period 2041 to 2060, given that the relative variations in precipitation occur between values of -30% and +80%. In this case, we proceeded to analyze the relative variation of precipitation for each model, and considered the temporal distribution of precipitation variations over the decades. The result of this analysis is presented in Figure 2b, which shows the distribution of occurrence by year of the relative variations of precipitation, between the years 2041 and 2060, considering separately the positive and negative variations projected by each model.

In the analysis of precipitation intensification conditions, five models project a 40% to 50% increase in precipitation occurring in at least 10 years of the decade, while four models project a 20% to 30% increase in precipitation occurring in at least 10 years of the decade. On the other hand, for the decreasing precipitation conditions, nine models project 19% to 30% reduction in precipitation occurring in at least 10 years of the decade (Figure 2b).

In this sense, as a function of the number of models and more probable quantity of precipitation variation in the decade, two conditions of scenarios of average precipitation patterns alteration that can have impact on the soybean cultivation were established: 1) wet condition, projecting up to 50% increase in precipitation; 2) dry condition, projecting up to 20% decrease in precipitation.

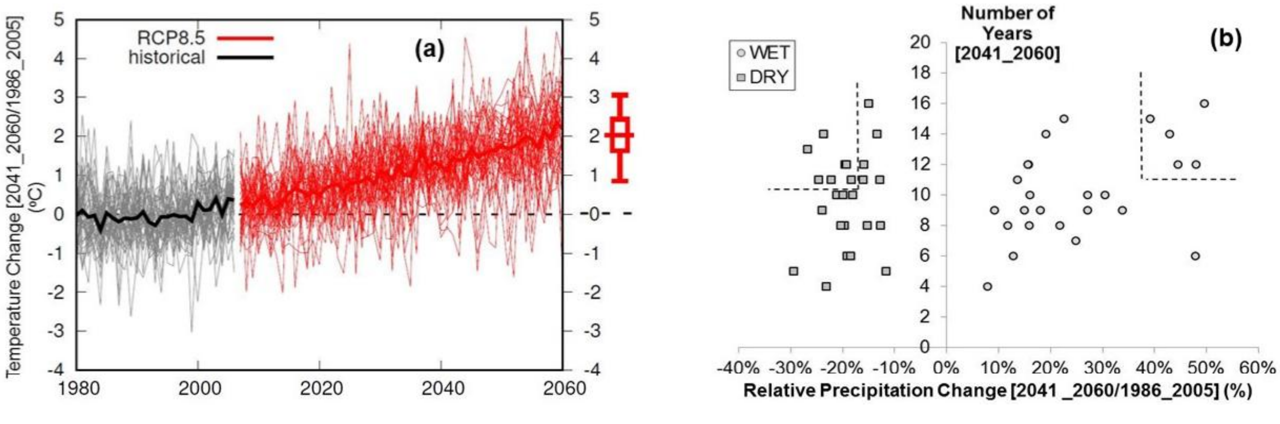
### Dry and Wet scenarios

### Soil moisture

Current soil moisture is fundamental for assessing the availability of water for agriculture and is affected directly by changes in precipitation, and indirectly by air temperature. Reducing precipitation by 20% (DRY scenario) decreases the water content in the soil up to 50 cm depth. At the end of the vegetative stage, 48 Days After Emergency (DAE), soil water value was registered as 150 mm, which represents 23% under the value registered without climate change considerations (current condition). In turn, at the end of the reproductive stage (83 DAE), soil water was 97 mm in contrast with 168 mm registered in the scenario without climate modifications (current condition), meaning 42% less water. Additionally, for the end of the senescence period (115 DAE), 90 mm was registered in the DRY scenario, against 173 mm registered previously. In this case, 48% of moisture reduction occurred (Fig. 3a and 3b). The local soil is a Rhodic Ferralsol (FAO Soil Taxonomy) or Typic Haplorthox (USDA Soil Taxonomy), i.e., typically clayey and deep, which favors the storage and availability of water to plants. It would be expected that in soils with greater drainage capacity the drop in moisture content resulting from the decrease in rainfall would be higher than the values found.

In the scenario with a 50% increase in precipitation (WET), the water stored in the soil remains oscillating between 180 and 240 mm (Figure 3a). This oscillation is related to the phenological stages and may be connected with the clay texture of the soil.

**Figure 2** - Climate scenarios of temperature (a) and precipitation (b) in the study region (NW-RS) for scenario RCP8.5 of CMIP5



In the vegetative stage (between the V4-V13 phases), the soil water content is around 217 mm in the WET scenario and 196 mm in the current scenario, a variation of 21 mm (Table 1) that represents 11% of water increase. In the reproductive stage (stages R1-R5.2), water content was 190 and 168 mm, for WET and current scenarios respectively, a 13% variation. In the leaf senescence stage, the soil water content values reached 192 mm (WET) and 173 mm (current), a variation of 29 mm or 11%. These results are closely associated with LAI changes, as shown in the following, and show greater water content sensitivity to reduced precipitation than increased precipitation.

**Leaf Area Index (LAI)**

The reduced precipitation in the DRY scenario decreased the LAI (Figure 3c; Table 1). Furthermore, crop growth is more evident in the WET scenario, which is related to the optimal condition of soil water availability. In the dry scenario, the vegetative growth stage is delayed and LAI is reduced mainly in the reproductive stage (R stages). Reduced water content in the soil during 51 to 85 DAE in DRY scenario did not cause a condition of water stress for the crop, although there was a small reduction in transpiration. The Agro-IBIS model simulates LAI with dependence on other factors related to the physiology of the plant, which will react in an indirect and non-linear manner to light, humidity, and temperature conditions.

According to Setiyono *et al*. (2008) and Zanon *et al*. (2015a), the evolution of LAI throughout the development cycle depends on sowing time, genotype, plant density, row spacing and phytosanitary management. The sowing season directly affects the availability of meteorological elements throughout the soybean development cycle, which in turn determine the vegetative growth period and the emission of branches in soybean cultivars. Our results show that the change in the amount of precipitation affects the soybean growth cycle (Figure 3c), with emergence occurring 6 days after planting (DAP) in wet conditions (WET), with a significant increase in growth rates occurring after 30 and 32 DAP; and 8 DAP in dry conditions (DRY) with a significant increase in growth rate, approximately after 38 and 40 DAP.

Ohnesorg and Hunt (2015) found, that in agronomic practices, losses of up to 30% in LAI during the vegetative phase and 15 to 20% during the reproductive phase due to biotic factors (insects and diseases) are accepted for soybean cultivation in Brazil. Tagliapietra *et al*. (2018) suggest to farmers that pest and disease management should be reviewed, especially when soybean sowing occurs at different dates than those recommended for the growing region (delayed sowing) and/or when cultivars with maturity groups (MG's) susceptible to degradations by biotic factors are adopted. Therefore, Zanon *et al*. (2015a) recommend conducting studies that address the sowing of cultivars with shorter vegetative phase and longer reproductive phase, in addition to employing cultivars with lower LAI in subtropical environments (ZANON *et al*., 2015b).

The most significant differences in LAI values between the scenarios are verified in the reproductive stage and reach an average of 8 $m^2m^{-2}$, 82 days after emergence (DAE) in the WET scenario, while reaching an average value of 6.5 $m^2m^{-2}$ in the DRY scenario. Moreover, there is also a more significant LAI variation in DRY than in WET (greater deviation bars than the average). The smallest difference between LAI values occurs during leaf senescence. It is important to note that, in the DRY scenario, the crop takes longer to begin leaf development due to the reduced soil water caused by the decreased precipitation, which affects photoassimilate production (TARDIEU, 2013). The Agro-IBIS model captures this mechanism well and suggests seeking a new water balance for soybean crops by reducing the leaf surface (lower LAI) and controlling water loss through transpiration in a situation of low water content. Therefore, the differences in soybean growth between the scenarios are significant and show a notable impact on the condition of reduced precipitation. This result clearly represents the real conditions of losses in productivity due to climate impacts that shorten the period of growth and maturation stage of crops (LIU; BASSO, 2020).

Zhao *et al*. (2018) observed a significant positive correlation between soybean growth uniformity and crop yield, which were associated with improved soil moisture and moderate temperatures (AKHTAR *et al*., 2019). Continuous soil moisture and well-managed soybean cultivars result in favorable plant growth as well as higher LAI conditions, which increases dry matter accumulation. However, air temperatures between 27 °C and 30 °C near the canopy and relative air humidities above 80% trigger attacks by fungi (*Cercospora kikuchii*, *Septoria glycines*, *Colletotrichum truncatum*, *Corynespora cassicola*, *Sclerotinia sclerotiorum*, *Microsphaera diffusa* and *Phakopsora pachyrhizi*, for exemple) (HENNING *et al*., 2014) and insects (*Diabrotica speciosa*, *Megascelis spp.*, *Maecolaspis spp.*, *Anticarsia gemmatalis*, *Pseudoplusia includens*, *Rachiplusia nu*, *Trichoplusia ni*, among others) (SOSA-GÓMEZ *et al*., 2014), which in high infestations, can cause delayed crop development and reduced yields.

According to the simulations, the reduction of water content in the superficial layer of the soil due to reduced precipitation can strongly influence soybean yields, as shown by the temporal evolution of the LAI, delaying its growth in the vegetative stage. The LAI is higher (lower) in the WET (DRY) scenario with values of 3.0, 8.0, and 1.5 $m^2m^{-2}$ (1.9, 6.4, and 1.1 $m^2m^{-2}$), respectively, in the three stages (V4-V13, R1-R5.2, and senescence) (Table 1).

**Figure 3** - Daily variations in soil moisture (a, b), leaf area index (c, d), soil evaporation (e, f), and transpiration (g, h) for precipitation scenarios (left panels) and temperature (right panels) in days after emergence (DAE). Results presented as mean and standard deviation of regional simulation

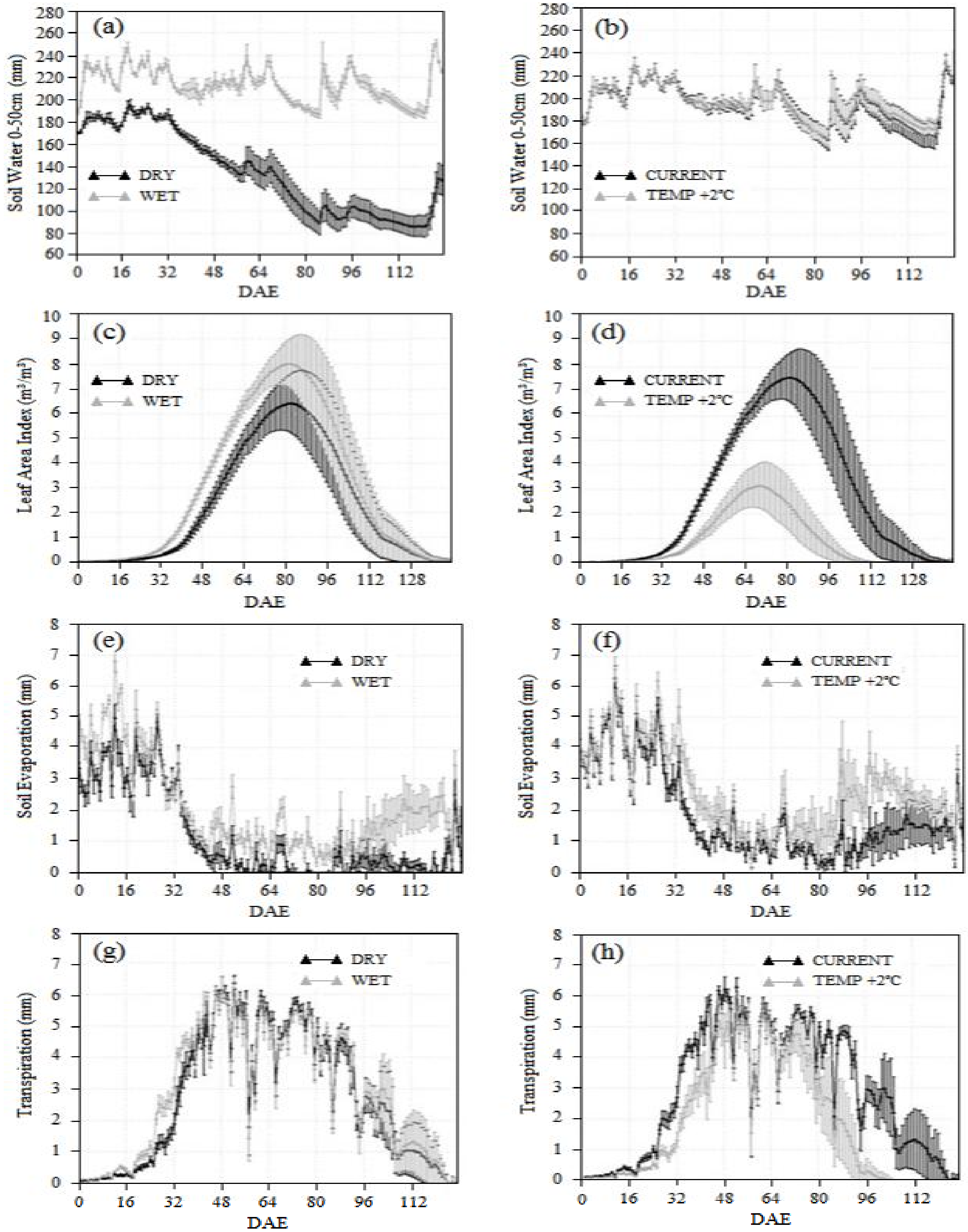


**Table 1** - Average values of leaf area index (LAI), soil moisture in different phenological stages of soybean growth in different simulations. DAE is Day After Emergency

| Scenario | DAE | Phenological stage | LAI ($m^2 m^{-2}$) | Soil moisture (mm) |
|---|---|---|---|---|
| Current condition | 18-48 | Vegetative (V4-V13) | 2.8 | 196 |
| | 51-83 | Reprodutive (R1-R5.2) | 7.6 | 168 |
| | 107-115 | Senescence | 1.5 | 173 |
| Temperature + 2 °C | 18-48 | Vegetative (V4-V13) | 1.2 | 196 |
| | 51-83 | Reprodutive (R1-R5.2) | 2.3 | 168 |
| | 107-115 | Senescence | 0.0 | 178 |
| DRY | 18-48 | Vegetative (V4-V13) | 1.9 | 150 |
| | 51-83 | Reprodutive (R1-R5.2) | 6.4 | 97 |
| | 107-115 | Senescence | 1.1 | 90 |
| WET | 18-48 | Vegetative (V4-V13) | 3.0 | 217 |
| | 51-83 | Reprodutive (R1-R5.2) | 8.0 | 190 |
| | 107-115 | Senescence | 1.5 | 192 |

Reducing precipitation by 20% (DRY scenario) LAI was registered as 1.9 $m^2m^{-2}$ at the end of the vegetative stage (48 DAE), which represents 32% under the value registered without climate change considerations (current condition). In turn, at the end of the reproductive stage (83 DAE), LAI was 6.4 $m^2m^{-2}$ contrast with 7.6 $m^2m^{-2}$registered in the scenario without climate modifications (current condition), meaning a reduction of 16%. Additionally, for the end of the senescence period (115 DAE), 1.1 $m^2m^{-2}$ was registered in the DRY scenario, against 15 $m^2m^{-2}$ registered previously. In this case, 27% of LAI reduction occurred (Figure 3c and 3d).

Between the V4-V13 phases, vegetative stage, the LAI value registered is 3 $m^2m^{-2}$ in the WET scenario and 2.8 $m^2m^{-2}$ in the current scenario, a variation of 0.2 $m^2m^{-2}$ (Table 1) that represents 7% of LAI increase. In the stages R1-R5.2, LAI was 8 and 7.6 $m^2m^{-2}$, for WET and current scenarios respectively, a 5% variation. In turn, at the leaf senescence stage for the WET scenario, any change was registered. Following soil moisture variation, LAI changes in DRY and WET scenarios show greater sensitivity to precipitation reduction than to precipitation increase.

**Evaporation**

Evaporation is determined by water availability on the surface layer and by the fraction of the solar radiation reaching the soil surface. In the initial and final stages of soybean growth, this process contributes to the exchange of water vapor with the atmosphere due to low leaf coverage and the progressive loss of leaves in senescence (ALLEN *et al*., 1998). This behavior is simulated by Agro-IBIS and shown in Figure (3e). During the DRY scenario, the evaporation is lower compared to the WET scenario until 25 DAE. The most significant differences between these scenarios occur after 40 DAE, intensifying at the maturation stage (around 100 DAE) in which there is leaf senescence, increasing soil exposure to solar radiation, representing greater exposure to erosive agents. Moreover, the model simulates more water evaporation from the soil in the WET scenario, which is driven by higher water availability in the soil, despite the increased leaf coverage of the crop. On the other hand, the soil water evaporation is relatively low from the maturation stage until senescence, reacting instantly only to precipitation events.

**Transpiration**

Transpiration has a small difference in values between the scenarios evaluated. Just between 16 and 35 DAE were the differences more significant, which are associated with the reduced leaf cover in the DRY scenario during the vegetative stage of the crop. From the beginning of the emergence until the plant reaches a certain plant stage, the soil is still predominantly exposed to solar radiation, accelerating the evaporation of water present in its structure, as previously reported. As the crop evolves in its growth cycle until maturation, the plants increase the loss by transpiration (5 to 6 mm) and, despite the considerable reduction in soil moisture in the DRY scenario, this process is not significantly affected in the simulation with the Agro-IBIS model. In the leaf senescence stage, the leaf cover decay determines the substantial reduction in transpiration (0.5 to 3 mm).

Even under the reduced precipitation condition, LAI remained high at the maturation stage (51 to 83 DAE, Table 1) which kept the soil largely covered and evaporation low. In the wettest regime, soil moisture oscillated according to the intra-seasonal variation in precipitation, keeping the soil in a condition above field capacity (greater than 0.36 $m^3$ $m^{-3}$) during the entire period. In the dry condition, soil moisture oscillated around 0.36 $m^3 m^{-3}$ until 32 DAE. From this point on, it decreased to around 0.18 $m^3$ $m^{-3}$ until 80 DAE.

This reduction in soil moisture did not imply a marked reduction in transpiration at the maturation stage, because the response factor of stomatal resistance to water stress in the Agro-IBIS model follows a compound-exponential function. It means that considering soil field capacity of 0.50 $m^3$ $m^{-3}$ and wilting point of 0.18 $m^3 m^{-3}$, parameters used in the model, transpiration reduction was a factor of 0.98. In other words, only 2% reduction of transpiration, for a soil moisture of 0.36 $m^3 m^{-3}$. In the wilting point condition, the reduction factor is 0.84, in other words, 16% of reduction in transpiration at 0.18 $m^3$ $m^{-3}$ soil moisture.

Therefore, this low sensitivity of the Agro-IBIS model to low soil moisture explains the little difference in transpiration in the simulation under reduced precipitation conditions. This indicates that a water availability of 0.36 to 0.18 $m^3 m^{-3}$ was shown to be an optimal water interval, which is sufficient to supply the transpiration of the soybean crop in the Agro-IBIS model.

**Temperature + 2 ºC Scenario**

**Soil moisture**

There are no significant differences between the curves at the vegetative and reproductive stages of the soybean crop (up to 96 DAE). A small difference of 3% increase is noted in the stage of leaf senescence (Table 1). This low sensitivity of soil moisture simulated by Agro-IBIS reflects the compensatory effects of reducing transpiration by increasing evaporation of the soil during the stages of vegetative growth and soybean maturation, considering that the precipitation did not change between the simulations.

**Leaf Area Index (LAI)**

The impacts of increasing the temperature on the evolution of LAI is due to the reduction of photoassimilates and the lower incorporation of biomass in all parts of the soybean plant (root, stem, petiole, leaf, and grain), but with a different effect throughout the growth stages and exceptionally in the leaves (TAIZ *et al*., 2015). In the vegetative stage (18-48 DAE), the LAI of the HOT scenario (temperature + 2 ºC) presents low values compared to the current temperature, with a reduction of 57%. LAI at current scenario was 2.8 $m^2m^{-2}$ while at HOT scenario was registered as 1.2 $m^2m^{-2}$ (Table 1). As the soybean plant develops and reaches the reproductive stage (51-83 DAE), there is a greater difference in LAI between the current and HOT scenarios in the order of 5.3 $m^2m^{-2}$. For the current scenario, the maximum LAI is 7.6 $m^2$ $m^{-2}$ at 83 DAE, which represents a 70% of reduction (Table 1).

At the leaf senescence stage (107-115 DAE), LAI values cancel each other out in the HOT scenario and null value was measured. At the current scenario, in turn, LAI value registered was 1.5 $m^2m^{-2}$. Therefore, there was a direct impact on reducing the growth of leaves, pods, and grains, in addition to shorter phenological stages. The two LAI curves (Figure 3c, d) show a significant difference in the soybean growth cycle, with 26 more days for the maximum LAI in the HOT scenario. Therefore, by only considering the effect of the 2 °C increase, the soybean crop simulated by Agro-IBIS has a slower growth and accelerated physiological maturation, resulting in a shorter crop growth cycle. Impacts of soybean LAI reduction with increasing air temperature using the Agro-IBIS model were also verified in El Maayar and Sonnentag (2009).

The higher temperature scenario simulated by the Agro-IBIS model shows significant differences, mainly related to the number of days required to complete the soybean growth cycle. Furthermore, the higher temperature significantly impacted the evolution at all growth stages, causing a 26 -day shortening in the soybean growth cycle. This was associated with the modification imposed in the logistic functions in the different phases that depend on the accumulation of GDD, which generated anticipation of the phases and lower LAI. This implies that a 2 ºC increase delays the growth stage and accelerates the physiological maturation process of the crop, thus shortening the cycle and decreasing the crop yield, as highlighted in other studies (IGLESIAS; ERDA; ROSENZWEIG, 1996; KANG; KHAN; MA, 2009).

Another fact is that the Agro-IBIS model estimates LAI based on leaf carbon by multiplying the leaf biomass carbon by the specific leaf area (SLA). The carbon assimilated by the leaf is distributed to the stem, root, and grain with fixed fractions at each stage of phenology. These parameters were not modified and it was not possible to assess their impact on biomass accumulation and LAI composition.

**Evaporation**

The behavior of the curves indicates that, until 18 DAE, there is no significant difference between soil evaporation for the current temperature and with a 2°C increase, which is mainly due to soil exposure to solar radiation at this stage. After this period, the plant rapidly grows because of increased photosynthesis, while in the HOT scenario, losses due to evaporation are always higher than current conditions of temperature, especially between 26 and 56 DAE and between 86 and 106 DAE (Figure 3f).

**Transpiration**

Transpiration decreases in the HOT scenario throughout the vegetative growth cycle (18-56 DAE), which is directly associated with lower LAI values (Figure 3d). In the maturation stage (57-71 DAE), there are no differences in transpiration rates between the HOT scenario and the current temperature. Furthermore, transpiration decreases more quickly in the HOT scenario during senescence (between 72-104 DAE) until it stops completely (Figure 3h). In the current temperature condition, transpiration only stops at 120 DAE and is a direct consequence of the higher temperature reducing the LAI (Figure 3d). As simulated by the Agro-IBIS, the shorter soybean growth cycle is influenced by the growing degree day (GDD) necessary for the growth of the crop, which reduces as the temperature rises, and, thus, affects the LAI, transpiration (directly), and soil evaporation (indirectly). In the model, the GDD formulation enable too plants development will only occur if the air temperature exceeds a minimum development threshold (called base temperature). If the daily mean temperature is above base temperature, then the accumulated Growing Degree Day are equal the mean temperature minus base temperature.

**Climate scenarios on crops**

According to the Agro-IBIS model, a 2 ºC temperature increase impacts soybean development more significantly (with decreased LAI) than a 20% decrease in precipitation (DRY scenario). On the other hand, the impact on soil moisture reduction is greater in the rainfall decrease scenario than in the temperature increase scenario. In other words, the large decrease that occurs with LAI due to the increase in temperature is not accompanied by the decrease in soil moisture, while the smaller decrease in LAI in the DRY scenario occurs concurrently with the decrease in soil moisture. This is verified for all three phenological stages.

In addition, the variation in LAI and soil moisture are more sensitive to decreasing precipitation than to increasing it. For the three stages, vegetative, reproductive, and senescence, a 20% decrease in precipitation (DRY) caused decreases in LAI and moisture between 16 and 48%, depending on the stage. Streck and Alberto (2006) simulated the impacts of climate change on soil water balance in wheat, soybean, and maize agroecosystems in southern Brazil using mathematical models and demonstrated that water availability in the soil is a limiting factor for summer crops (soybean and maize), which should worsen if the air temperature rises in the future.

A rainfall increase of 50% (WET) caused a LAI increase of less than 10% and moisture increase between 11 and 13%, also depending on the stage. Others authors have reported that variations in precipitation and increased air temperatures are the main factors that lead to changes in agricultural production (LUDLOW; MUCHOW, 1993; ROSENZWEIG *et al.*, 1995). These studies have shown that increased precipitation is beneficial, while increased temperatures are detrimental to crop yields.

For the scenario with 50% increase in precipitation (WET) and defined as the rainy scenario, the crop showed good response, in other words, increased LAI and moisture, resulting in good conditions for soybean development.

However, the scenario of a 2 °C increase in temperature will have a direct negative impact on the crop, as a substantial reduction in LAI values is observed. The result indicates a difference in the crop cycle when the temperature increases, affecting the growth phase of the crop, accelerating the physiological maturation process, shortening the crop growth cycle, reducing resource retention, and affecting crop yields. Due to the increase in temperature, the negative impacts on the shortening of the soybean cycle can be offset by planting more resistant cultivars or changing the planting period. Warmer temperatures generally result in shorter growing seasons, consequently reducing crop yields (CRAUFURD; WHEELER, 2009; ROSE *et al*., 2016).

The responses to precipitation and air temperature changes show that there will be a direct influence on the plant and crop cycle, leading to changes in soybean yields. According to Korres *et al*. (2016), climate change will have significant effects on many activities. However, its effects on agricultural production will be even greater. Estimation of annual damage to agriculture due to rising air temperatures or prolonged periods of drought will be expensive, being that higher temperatures will decrease the yields of temperature-sensitive crops, including soybean, maize, wheat, cotton, among others.

## CONCLUSIONS

1. In the scenario with 50% increase in precipitation (WET), the Agro-IBIS model projects a soybean response with increased LAI and maintenance of soil moisture, resulting in good conditions for crop development. However, a 2 °C temperature increase impacts more significantly on decreasing LAI than a 20% decrease in rainfall (DRY scenario);

2. As expected, the decrease in precipitation generates an impact on soil moisture, with a reduction in water storage more pronounced than in the condition of a 2 ºC increase in air temperature;

3. Thus, the climate changes analyzed presented a direct influence on the soybean agro-ecosystem for the region, which may result in productivity changes;

4. Therefore, the soybean cycle variation may be offset by planting more drought and heat tolerant resistant cultivars or altering the planting period.

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