Soybean yield in future climate scenarios for the state of Rio Grande do Sul, Brazil

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Abstract – The objective of this work was to estimate the yield potential and the water-limited yield of soybean (*Glycine max*) in the state of Rio Grande do Sul, Brazil, in two future climate scenarios, SRES A1B and RCP4.5, using the SoySim and Cropgro-Soybean simulation models. In both models, three maturity groups (4.8, 5.5, and 6.0) and six sowing dates (09/01, 10/01, 11/01, 12/01, 01/01, and 02/01) were considered in the SRES A1B-CMIP3 and RCP4.5-CMIP5 scenarios. The analyzed variable was grain yield at 13% moisture (Mg ha^{-1}). Soybean yield potential in Rio Grande do Sul should increase up to the end of the 21st century, according to both scenarios. Water-limited yield of soybean also increases up to the end of the 21st century, by the SRES A1B-CMIP3 scenario; however, it will decrease in future periods, by the RCP4.5-CMIP5 scenario because of limited soil water.

Index terms: *Glycine max*, climate change, Cropgro-Soybean model, RCP4.5, SoySim model, SRES A1B.

Produtividade de soja em cenários climáticos futuros para o Rio Grande do Sul

Resumo – O objetivo deste trabalho foi estimar a produtividade potencial e a produtividade com limitação de água em soja (*Glycine max*), no Rio Grande do Sul, em dois cenários climáticos futuros, SRES A1B e RCP4.5, por meio dos modelos agrícolas de simulação SoySim e Cropgro-Soybean. Consideraram-se, em ambos os modelos, três grupos de maturação (4.8, 5.5 e 6.0) e seis datas de semeadura (01/09, 01/10, 01/11, 01/12, 01/01 e 01/02), nos cenários SRES A1B-CMIP3 e RCP4.5-CMIP5. A variável analisada foi a produtividade de grãos de soja a 13% de umidade (Mg ha^{-1}). A produtividade potencial de soja no Rio Grande do Sul deve aumentar até o final do século XXI, de acordo com ambos os cenários. A produtividade de soja com limite de água também aumenta até o final do século XXI, pelo cenário SRES A1B-CMIP3; porém, ela decrescerá nos períodos futuros, pelo cenário RCP4.5-CMIP5, em razão do estresse hídrico no solo.

Termos para indexação: *Glycine max*, mudanças climáticas, modelo Cropgro-Soybean, RCP4.5, modelo SoySim, SRES A1B.

Introduction

Soybean is a global commodity, and the United States, Brazil, and Argentina production amounts to about 78% of the world soybean (FAO, 2016). Among the Brazilian states, Rio Grande do Sul is the third in production, with almost 15,000 Gg of soybean harvested in the 2014/2015 growing season, and 2.8 Mg ha^{-1} mean yield (IBGE, 2016).

According to the Intergovernmental Panel on Climate Change (IPCC), the human effect on the climate system is real, and recent greenhouse gas emissions are the highest in history (Solomon et al., 2007; Stocker et al., 2013). The global temperature increased 0.85°C from 1880 to 2012, and the atmospheric carbon dioxide (CO_2) concentration increased from 270 ppm in the industrial era to 404 in February, 2016 (Stocker et al., 2013; NOAA, 2016). Anomalies in the world seasonal mean temperature increased in the 1981–2010 period, in comparison with the 1951–1980 period, mainly during summer (Hansen et al., 2012).

Variations in air temperature, CO_2, and precipitation directly affect soybean yield. Heinemann et al. (2006), in a controlled environment experiment (three different temperatures, and two CO_2 concentrations), in Georgia, observed an increase of soybean yield at an elevated temperature and CO_2; however, the increase rate of yield lowered as the air temperature increased.

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Similar results were found when CO_2 concentration was doubled, and soybean yield increased 50%; nevertheless, the positive effect of the CO_2 increase was offset by the air temperature increase of 3°C, and the final combined effect between CO_2 increase and temperature resulted in 36% increase of soybean yield (Lal et al., 1999).

Yield potential (also called potential yield by some authors) of an agricultural crop is the yield of plants grown under neither biotic (pests, diseases, and weeds) nor abiotic (water and nutrients) stress; therefore, yield is determined only by temperature, solar radiation, and CO_2 during the growing season (Evans & Fischer, 1999). In the field, actual yield is lower than the potential one because biotic and abiotic factors affect the yield potential (Ittersum et al., 2013). The future of food production and global food security will depend on the capacity of farmers to reduce the gap between actual and potential yield, considering that yield potential may decrease due to climate change (Lobell et al., 2009).

Studies on the impact of climate change on soybean in Brazil, particularly in the state of Rio Grande do Sul, have been conducted using crop models, such as Soygro and Cropgro-Soybean, forced by synthetic climate scenarios, and by the SRES A1 and A2 scenarios of CMIP3, considering few sowing dates (Siqueira et al., 1994, 2000; Streck & Alberto, 2006; Justino et al., 2013; Rio et al., 2016). With the update of CMIP5 scenarios (Stocker et al., 2013), new soybean cultivars released annually, and the development of new crop simulation models as SoySim (Setiyono et al., 2010), studies on the impact of future scenarios on soybean in Rio Grande do Sul should be continued, taking into consideration these new tools and technologies.

The objective of this work was to estimate the yield potential and the water-limited yield of soybean in the state of Rio Grande do Sul, Brazil, in two future climate scenarios, SRES A1B and RCP4.5, using the SoySim and Cropgro-Soybean agricultural models.

Materials and Methods

Two dynamic process-based soybean models were used: the SoySim model (Setiyono et al., 2010), on the potential yield conditions; and the Cropgro-Soybean model (Boote et al., 1998), on the potential and water-limited conditions. SoySim is the latest model for soybean, and it requires daily meteorological data such as solar radiation, minimum and maximum temperatures, relative humidity, precipitation, evapotranspiration, and only two genetic parameters: maturity group (MG) from 0.0 to 8.0; and stem termination (indeterminate and determinate). The Cropgro-Soybean model, under the DSSAT platform, is older than SoySim, and it is widely used in numerical studies worldwide, including those with climate change scenarios. To run the Cropgro-Soybean model, the user needs to input daily data of minimum and maximum temperatures, solar radiation, and precipitation (Boote et al., 1998; Ruíz-Nogueira et al., 2001). Cropgro-Soybean differs from SoySim by the greater number of genetic specific coefficients used, which requires five development parameters and seven growth parameters. When water balance is activated, the Cropgro-Soybean model uses the volumetric soil-water content that varies between saturation, field capacity, and permanent wilting points. These physic parameters are calculated based on information regarding the texture of each soil layer. From these data, the model performs the dynamic simulation of water among soil layers, according to the daily hydraulic conductivity, as described in the Ritchie method.

The soybean cultivars used in the present study were NS 4823 RR (MG=4.8), BMX Energia RR (MG=5.5), and BMX Turbo RR (MG=6.0). These cultivars have indeterminate stem termination, are transgenic, and were selected because they represent around 50% of the soybean area in the state of Rio Grande do Sul; during the last five years. The SoySim model was used in the generic mode, in which the MG is informed. The 4.5 version of the Cropgro-Soybean model was used with the calibration of the following genetic-specific parameters for the three soybean cultivars: maximum leaf area, maximum photosynthetic rate, specific leaf area, node number, date of emergence and reproductive stages R1, R3, R5, R7, and yield components (seed number per square meter, and mean weight of grain). Data for the calibration were from field experiments conducted during four growing seasons (2010/2011, 2011/2012, 2012/2013, and 2013/2014), in different locations in Rio Grande do Sul state. The cross-validation method (Baigorria et al., 2010) was used with 21 sowing dates, and consisted of the first date calibration and of the validation with the 20 remaining dates, then the second date calibration, and validation with the remaining 20 dates, and so on, until all sowing dates were used in the calibration and validation.

Two future climate scenarios were used: SRES A1B (SRES-Special Report on Emissions Scenarios) (CMIP3), and RCP4.5 (RCP- Representative Concentration Pathway) (CMIP5), from the fourth and fifth IPCC reports, respectively. The SRES A1B-CMIP3 scenario takes on a balance between the energetic sources in the future, with a peak of the greenhouse gas emissions until a half of the 21st century (Solomon et al., 2007). This method describes an economic scenario of fast growth, with a global population reaching a peak in the first half of the century and that would decline in the next half, and a fast insertion of new and efficient technologies. In this scenario, at the end of the 21st century, CO_2 concentrations would reach 717 ppm, and the mean surface temperature of the planet would be between 1.7 and 4.4°C higher in 2100, compared with the present climate, that is, a scenario of the type "business as usual". These data were generated by the coupled atmosphere-ocean model ECHAM/MPI-OM, with 250 km spatial resolution (Roeckner, 2005), regionalized to the state of Rio Grande do Sul by dynamic downscaling (Hostetler et al., 2011) with the Regional Climate Model version 3 (RegCM3) (Pal et al., 2007), with a 100x100 km grid of latitude/longitude.

With lower emission than SRES A1B-CMIP3, the RCP4.5-CMIP5 scenario of AR5 is also an intermediate scenario, where CO_2 concentration would reach 538 ppm in 2100, and the global surface mean temperature would be between 1.1 and 2.6°C warmer at the end of the century, compared with the present climate. Data were created by the HadGEM-ES global ocean-atmosphere model (Jones et al., 2011), with 250 km of spatial resolution, and served as a bounding condition for downscaling to 100x100 km of resolution with the Regional Climate Model version 4 (RegCM4). The trend increase of the maximum and minimum temperatures (state average) is about 0.28 and 0.22°C per decade, in the SRES A1B-CMIP3, and of 0.18 and 0.16 per decade, in the RCP4.5-CMIP5. The precipitation in the scenario SRES A1B-CMIP3 is high (from 1,000 until 6,000 mm per year), with mean trend around 88 mm per year per decade, while, in the scenario RCP4.5-CMIP5, the precipitation is lower – from 275 until 2,500 mm per year – and without trend throughout the 21st century. The solar radiation is lower in the SRES A1B-CMIP3 than in the RCP4.5-CMIP5.

The time series of meteorological data with seasonal cycle, with 37 grid points distributed across the state of Rio Grande do Sul, was divided into four intervals of 30 years of daily data (Ruane et al., 2014), as follows: baseline (1980–2009); and three future periods (2010–2039, 2040–2069, and 2070–2099). The two soybean models were run for each growing season of each of the four periods. After the annual simulations, the annual grain yield for each model was grouped by the average for each 30-year period. The SoySim and Cropgro-Soybean model were run in the SRES A1B-CMIP3 and in the RCP4.5-CMIP5 scenarios, for three soybean cultivars and six sowing dates – 09/01, 10/01, 11/01, 12/01, 01/01/, and 02/01, which are dates before, during, and after the current recommended period to sow soybean in Rio Grande do Sul (from 10/01 to 31/12). Information on soil texture and depth, which is necessary to run the Cropgro-Soybean, were obtained from the soil physics analysis by the Projeto RadamBrasil (1986). The soil depths for the simulations with the Cropgro-Soybean model varied from 65 to 380 cm, according to each location and soil type. Soybean grain yield at 13% moisture (Mg ha^{-1}) was the main variable analyzed. To evaluate the ability of the two soybean models in simulating the current soybean grain yield in Rio Grande do Sul, the yield simulated by the SoySim and Cropgro-Soybean model was compared with the observed data from IBGE (2016) for the 2008/2009, 2009/2010, 2010/2011, 2012/2013, and 2013/2014 growing seasons. The simulated data are the yield average of three MG (4.8, 5.5, and 6.0) and four sowing dates (10/01, 11/01, 12/01, and 01/01).

Annual soybean yield for each of the three future periods were shown as anomalies calculated by the difference between the yield of each year in the future periods and the mean yield of the baseline period, in each grid point (average of the three MG), for each sowing date (09/01, 10/01, 11/01, 12/01/, 01/01, and 02/01). Maps were also elaborated foryield anomaly for each sowing date, in the three future periods.

Results and Discussion

The soybean mean grain yield in the five growing seasons (2008/2009, 2009/2010, 2010/2011, 2012/2013, and 2013/2014) ranged between 2 and 3 Mg ha^{-1}, in most of Rio Grande do Sul, with a small part in the northeastern region of the state where yield reached 3 to 4 Mg ha^{-1}; in the western region, with shallow soils and small holding capacity, yields were the lowest ones (1 to 2 Mg ha^{-1}). The yield simulated by the SoySim model, forced by the two scenarios, was on average 1 Mg ha^{-1} above the observed values because this model does not consider the effects of low-soil humidity on the crop. The Cropgro-Soybean, forced by the SRES A1B-CMIP3 scenario in the water-limited condition, captured the variation of the observed yield between the regions. These results indicate that the crop models and the climate scenarios are appropriate for this study.

The anomalies of soybean potential yield, simulated with the SoySim model in the two future climate scenarios SRES A1B-CMIP3 and RCP4.5-CMIP5, were positive (from 1.5 to 2 Mg ha^{-1}) until the end of the 20th century (Figure 1 and 2), with a greater increase in the sowing dates of 09/01 and 12/01, mainly in the north and northeast regions of the state, while in the 01/01 and 02/01 sowing dates the yield anomalies were low, as a consequence of the shortening of the crop developmental cycle. In late sowings, soybean tends to benefit from the increase of temperature and CO_2 concentration in future scenarios, despite the shortening of the cycle (Bao et al., 2015a). In some years and sowing dates (09/01, 01/01, and 02/01), the SoySim model interrupted the simulation because it reached low-freezing temperatures. The percentage of years that SoySim did not complete the simulation in the SRES A1B-CMIP3 and RCP4.5-CMIP5, respectively, were as follows: for the baseline period, 76.6 and 83.3%, in the 09/01 sowing date; 3.3 and 0.0% in 10/01; 0.0 and 3.3% in 11/01; 0.0 and 6.6% in 12/01; 3.3 and 13.3% in 01/01, and 3.3 and 26.6% in 02/01. For the future periods, these percentages were for 2010–2099 as follows:12.2 and 22.2%, in 09/01; 0.0 and 8.8%, in 10/01; 5.5 and 10.0%, in 11/01; 11.1 and 21.1%, in 12/01; 13.3 and 43.3%, in 01/01; and 15.5 e 27.7%, in 02/01. These cases were not used for the calculation of the mean yield because the goal was to analyze the potential yield for each period.

Comparing the results of SoySim and Cropgro-Soybean, for the potential condition, and using the scenario SRES A1B-CMIP3, we observed that yield anomalies in the baseline period are greater with the Cropgro-Soybean (Figure 3 A, E, I, M, Q, and U) than with the SoySim model (Figure 1 A, E, I, M, Q, and U). However, for the three future periods, the increase of yield anomalies is greater with SoySim (Figure 1). The yield in the baseline period is greater for the potential conditions (Figure 3), for sowing on 09/01, 10/01, and 11/01, than for yield under water-limited conditions (Figure 4). In the future period of 2070-2099, the 10/01 and 12/01 sowings showed yield anomalies higher for water-limited conditions, and these results are similar to those reported by Bao et al. (2015b), who obtained an increase from 8 to 12% of yield until 2050, in the southeast of the United States, where the climate is similar to that of Rio Grande do Sul state, Brazil.

The yields with the Cropgro-Soybean model in potential condition, for the baseline of the RCP4.5-CMIP5 scenario, vary between 6 and 7 Mg ha^{-1} in almost all the state, for sowings on 09/01, 10/01, and 11/01 (Figure 5). Yield in the same period, simulated with the SoySim model (Figure 2), reaches the maximum of 5 Mg ha^{-1} for sowing on 09/01 and 10/01. This difference probably occurred by the fact that the Cropgro-Soybean model has been calibrated for soybean cultivars currently used in Rio Grande do Sul, while the SoySim model was run from its generic mode with no calibration of the genetic coefficients. The results of yield in the future periods agree with the ones reported by Justino et al. (2013), who found 60% increase for potential yield of soybean in the states of Pará and Mato Grosso, until the end of the 20th century.

The RCP4.5-CMIP5 scenario is drier than the SRES A1B-CMIP3 scenario, and this was well evidenced by comparing simulations by the Cropgro-Soybean, in the potential condition, with the simulations when the model was run with the water balance activated (Figures 5 and 6). For both baseline and the three future periods, under the potential condition the yields would be high (until 7 Mg ha^{-1}); however, under the water-limited condition, yields in the baseline period are below 1 Mg ha^{-1}, in most of the state and in all sowing dates (Figure 6 A, E, I, M, Q, and U). For the future period, only the 09/01 sowing showed anomalies above 0.5 Mg ha^{-1}, in the Central region of the state; the other regions had negatives anomalies, mainly for sowings from October to December (Figure 6). Yield decrease occurs because of the

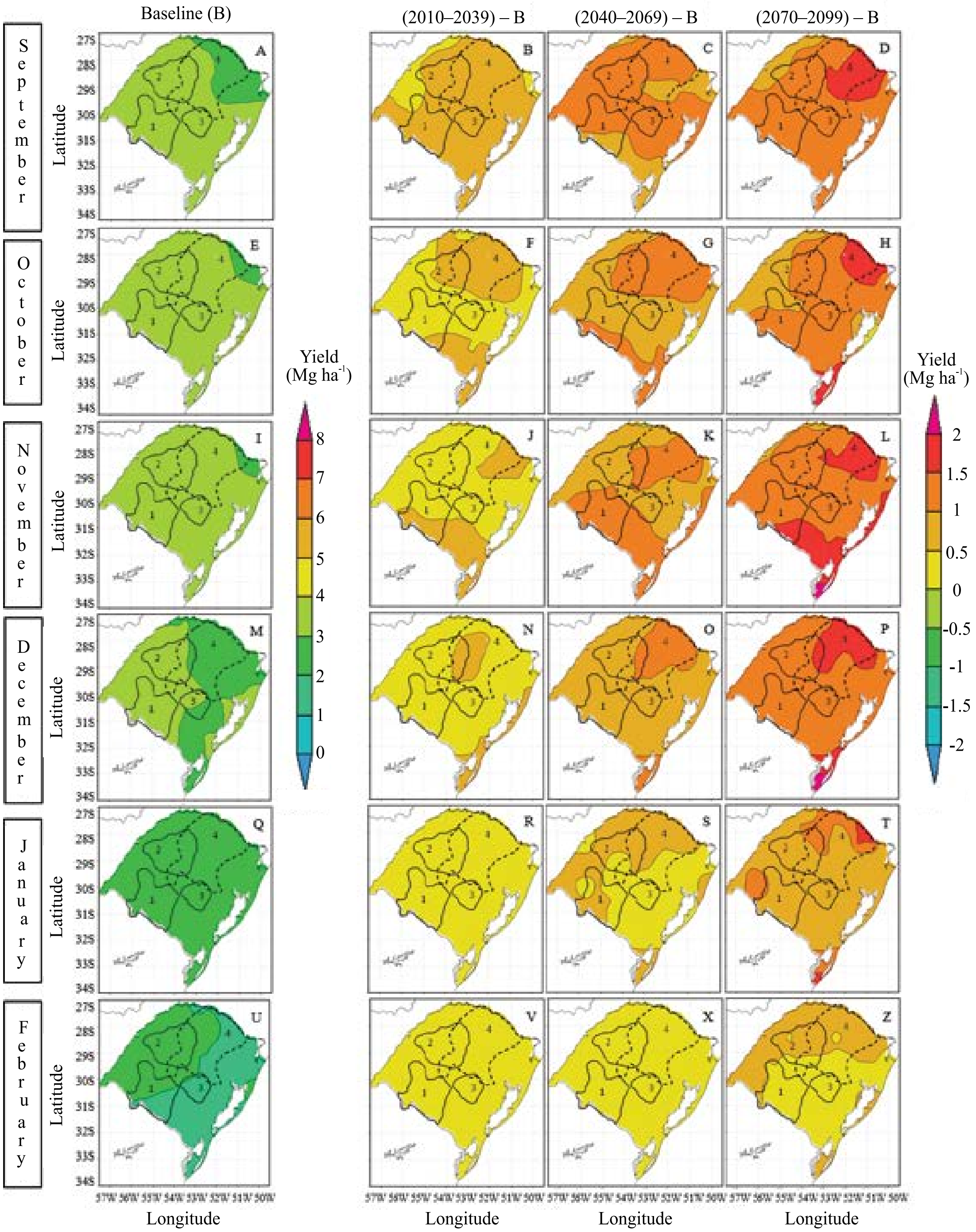

Figure 1. Soybean (*Glycine max*) yield potential at 13% moisture (Mg ha^{-1}), in the baseline period (A, E, I, M, Q, and U), and yield potential anomalies (Mg ha^{-1}) across the state of Rio Grande do Sul, Brazil, simulated with the SoySim model for three future climate scenarios (2010–2039, 2040–2069, and 2070–2099) of the SRES A1B-CMIP3, in six sowing dates 09/01 (B, C, D), 10/01 (F, G, H), 11/01 (J, K, L), 12/01 (N, O, P), 01/01 (R, S, T), and 02/01 (V, X, and Z). Yield is the average of three maturity groups (4.8, 5.5, and 6.0), and the baseline is the period 1980–2009. Areas 1, 2, and 3 are the Campanha, Tupanciretã, and Cachoeira do Sul regions, respectively, with the largest cultivated areas with soybean, and area 4 (dotted line) represents the area with the highest-soybean yield in Rio Grande do Sul, calculated as an average of five growing seasons (2008/2009, 2009/2010, 2010/2011, 2012/2013, and 2013/2014), according to IBGE (2016). The colored ruler on the left-hand side is for yields in the baseline and, on the right-hand side, for yield anomalies.

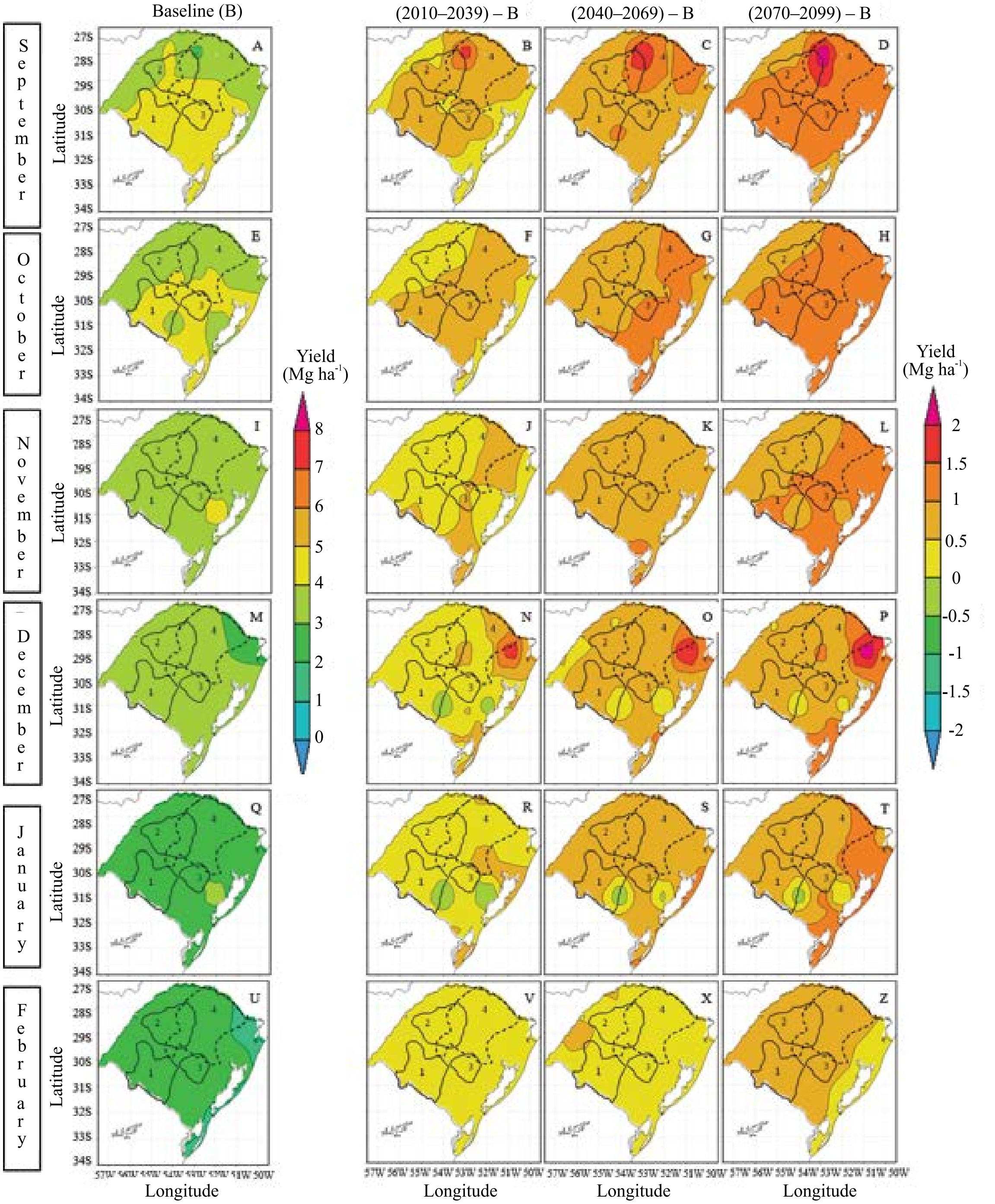

Figure 2. Soybean (*Glycine max*) yield potential at 13% moisture (Mg ha^{-1}) in the baseline period (A, E, I, M, Q, U), and yield potential anomalies (Mg ha^{-1}) across the state of Rio Grande do Sul, Brazil, simulated with the SoySim model for three future climate scenarios (2010–2039, 2040–2069, and 2070–2099) of the RCP4.5-CMIP5, in six sowing dates 09/01 (B, C, D), 10/01 (F, G, H), 11/01 (J, K, L), 12/01 (N, O, P), 01/01 (R, S, T), and 02/01 (V, X, and Z). Yield is the average of three maturity groups (4.8, 5.5, and 6.0), and the baseline is the period 1980-2009. Areas 1, 2, and 3 are Campanha, Tupanciretã, and Cachoeira do Sul regions, respectively, with the largest cultivated areas with soybean, and area 4 (dotted line) represents the area with the highest-soybean yield in Rio Grande do Sul, calculated as an average of five growing seasons (2008/2009, 2009/2010, 2010/2011, 2012/2013, and 2013/2014), according to IBGE (2016). The colored ruler on the left-hand side is for the yields in the baseline and, on the right-hand side, for the yield anomalies.

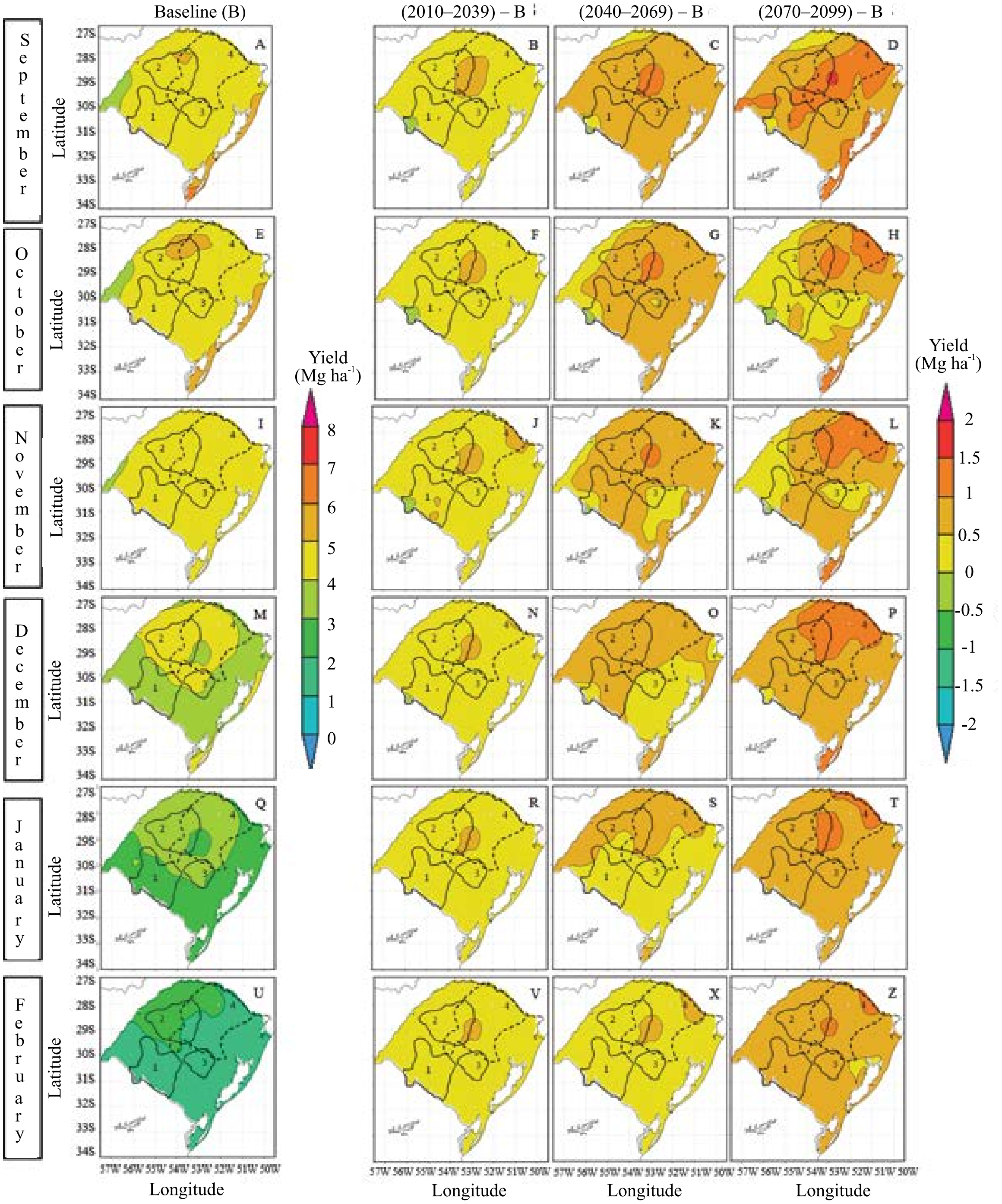

Figure 3. Soybean (*Glycine max*) yield potential at 13% moisture (Mg ha^{-1}) in the baseline period (A, E, I, M, Q, and U), and yield potential anomalies (Mg ha^{-1}) across the state of Rio Grande do Sul, Brazil, simulated with the Cropgro-Soybean model for three future climate scenarios (2010–2039, 2040–2069, and 2070–2099) of the SRES A1B-CMIP3, in six sowing dates 09/01 (B, C, D), 10/01 (F, G, H), 11/01 (J, K, L), 12/01 (N, O, P), 01/01 (R, S, T), and 02/01 (V, X, and Z). Yield is the average of three maturity groups (4.8, 5.5, and 6.0), and the baseline is the period 1980-2009. Areas 1, 2, and 3 are Campanha, Tupanciretã, and Cachoeira do Sul regions, respectively, with the largest cultivated areas with soybean, and area 4 (dotted line) represents the area with the highest-soybean yield in Rio Grande do Sul, calculated as an average of five growing seasons (2008/2009, 2009/2010, 2010/2011, 2012/2013, and 2013/2014), according to IBGE (2016). The colored ruler on the left-hand side is for the yields in the baseline and, on the right-hand side, for the yield anomalies.

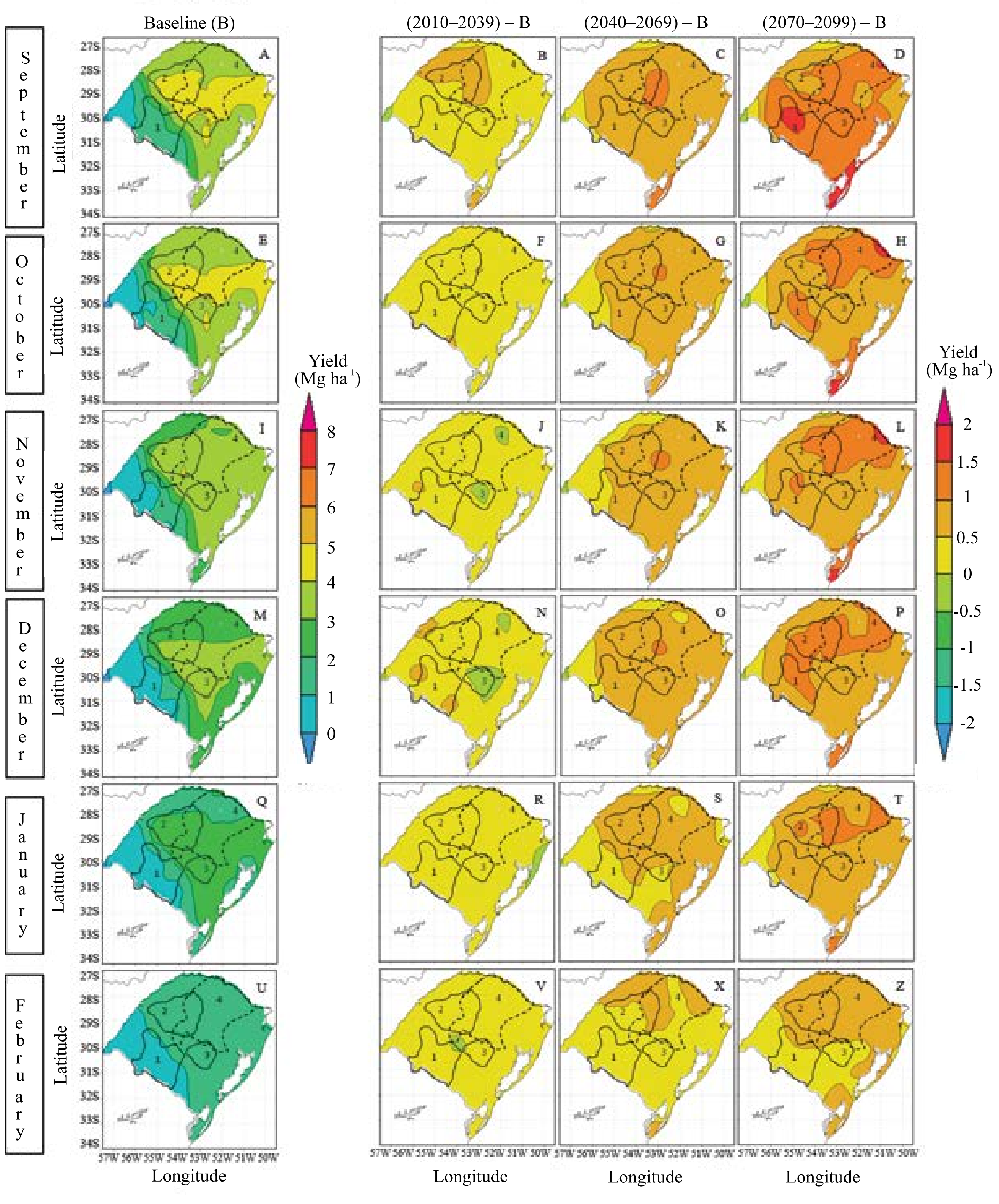

Figure 4. Soybean (*Glycine max*) water-limited yield at 13% moisture (Mg ha^{-1}) in the baseline period (A, E, I, M, Q, and U), and anomalies in soybean water-limited yield (Mg ha^{-1}) across the state of Rio Grande do Sul, Brazil, simulated with the Cropgro-Soybean model for three future climate scenarios (2010–2039, 2040–2069, and 2070–2099) of the SRES A1B-CMIP3, in six sowing dates 09/01 (B, C, D), 10/01 (F, G, H), 11/01 (J, K, L), 12/01 (N, O, P), 01/01 (R, S, T), and 02/01 (V, X, and Z). Yield is the average of three maturity groups (4.8, 5.5, and 6.0), and the baseline is the period 1980-2009. Areas 1, 2, and 3 are Campanha, Tupanciretã, and Cachoeira do Sul regions, respectively, with the largest cultivated areas with soybean, and area 4 (dotted line) represents the area with the highest-soybean yield in Rio Grande do Sul, calculated as an average of five growing seasons (2008/2009, 2009/2010, 2010/2011, 2012/2013, and 2013/2014), according to IBGE (2016). The colored ruler on the left-hand side is for the yields in the baseline and, on the right-hand side, for the yield anomalies.

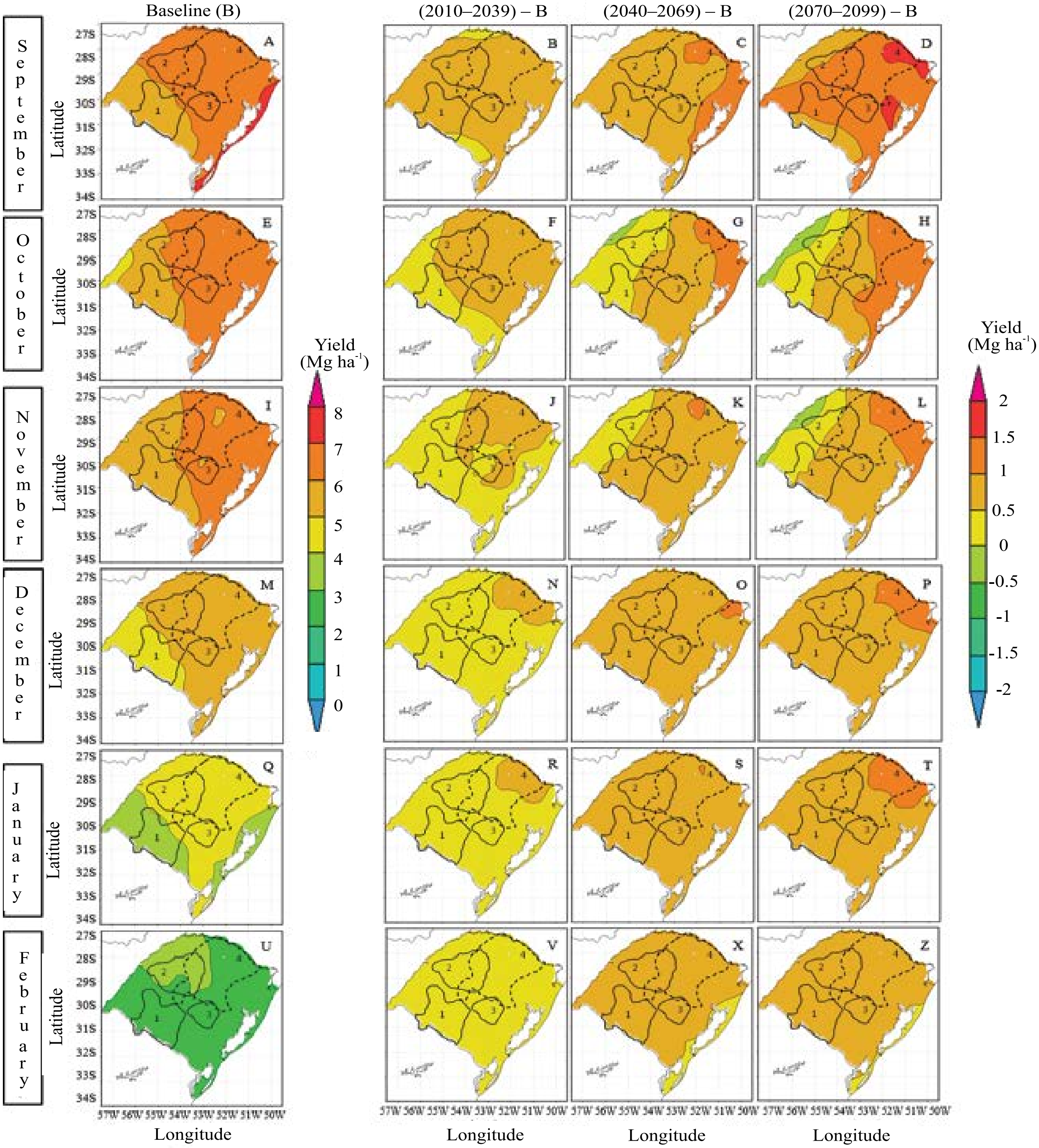

Figure 5. Soybean (*Glycine max*) yield potential at 13% moisture (Mg ha^{-1}) in the baseline period (A, E, I, M, Q, U), and yield potential anomalies (Mg ha^{-1}) across the state of Rio Grande do Sul, Brazil, simulated with the Cropgro-Soybean model for three future climate scenarios (2010–2039, 2040–2069, and 2070–2099) of the RCP4.5-CMIP5, in six sowing dates 09/01 (B, C, D), 10/01 (F, G, H), 11/01 (J, K, L), 12/01 (N, O, P), 01/01 (R, S, T), and 02/01 (V, X, Z). Yield is the average of three maturity groups (4.8, 5.5, and 6.0), and the baseline is the period 1980-2009. Areas 1, 2, and 3 are Campanha, Tupanciretã, and Cachoeira do Sul regions, respectively, with the largest cultivated areas with soybean, and area 4 (dotted line) represents the area with the highest-soybean yield in Rio Grande do Sul, calculated as an average of five growing seasons (2008/2009, 2009/2010, 2010/2011, 2012/2013, and 2013/2014), according to IBGE (2016). The colored ruler on the left-hand side is for the yields in the baseline and, on the right-hand side, for the yield anomalies.

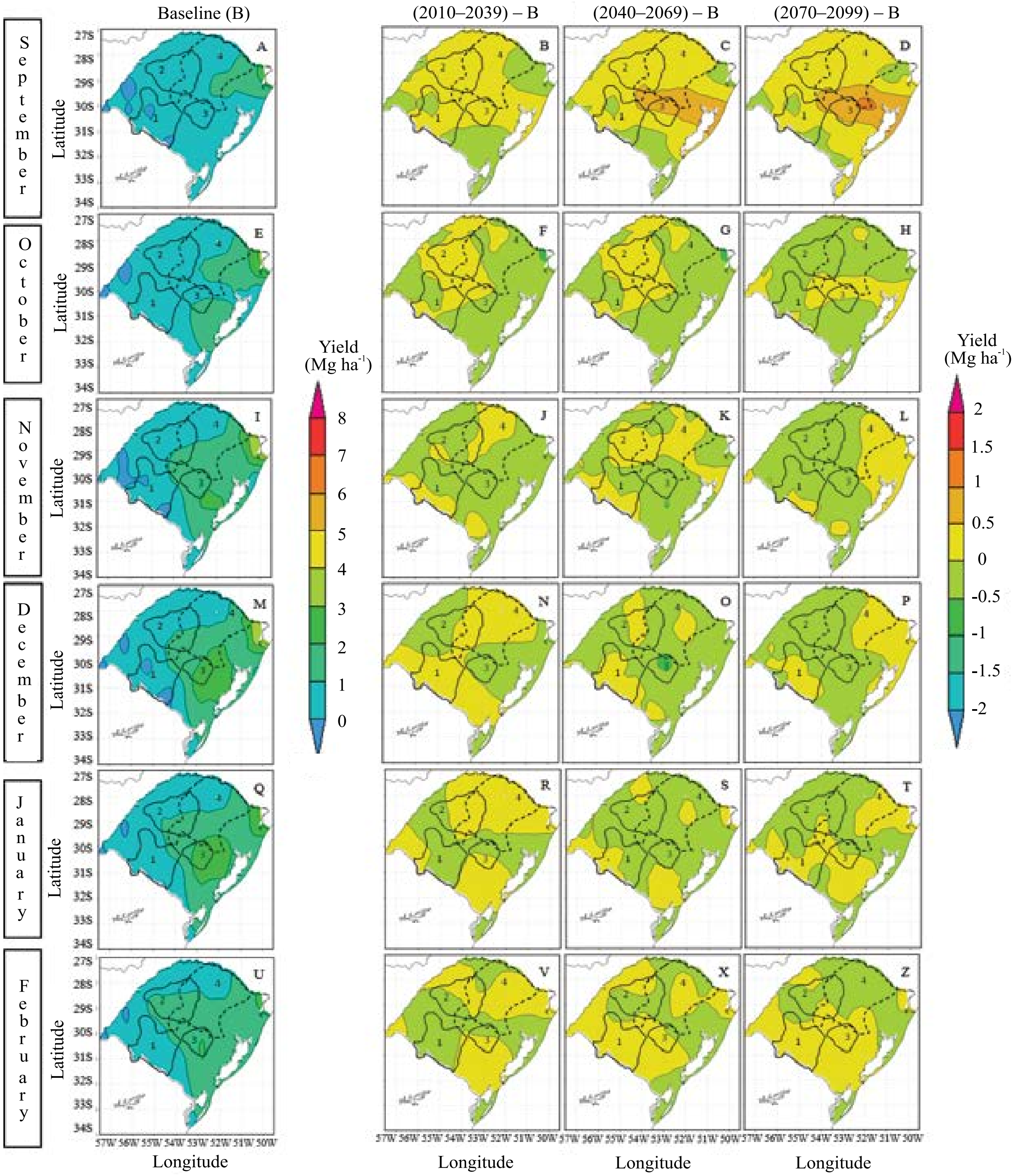

Figure 6. Soybean (*Glycine max*) water-limited yield at 13% moisture (Mg ha^{-1}) in the baseline period (A, E, I, M, Q, and U), and anomalies of soybean water-limited yield (Mg ha^{-1}) across the state of Rio Grande do Sul, Brazil, simulated with the Cropgro-Soybean model for three future climate scenarios (2010–2039, 2040–2069, and 2070–2099) of the RCP4.5-CMIP5, in six sowing dates 09/01 (B, C, D), 10/01 (F, G, H), 11/01 (J, K, L), 12/01 (N, O, P), 01/01 (R, S, T), and 02/01/ (V, X, and Z). Yield is the average of three maturity groups (4.8, 5.5, and 6.0), and the baseline is the period 1980-2009. Areas 1, 2, and 3 are Campanha, Tupanciretã, and Cachoeira do Sul regions, respectively, with the largest cultivated areas with soybean, and area 4 (dotted line) represents the area with the highest-soybean yield in Rio Grande do Sul, calculated as an average of five growing seasons (2008/2009, 2009/2010, 2010/2011, 2012/2013, and 2013/2014), according to IBGE (2016). The colored ruler on the left-hand side is for the yields in the baseline and, on the right-hand side, for the yield anomalies.

lowest-available water content for the plants which is, for instance, 20–40% lowest in the RCP4.5-CMIP5 scenario than in SRES A1B-CMIP3, at 0–15 cm soil depth, in Passo Fundo region, in the northeastern of the state. Rio et al. (2016) also found a yield decrease for the 2041–2071 scenario, for the South of Brazil, with the Cropgro-Soybean forced by the SRES A2 and B2 scenarios, without considering the effect of elevated CO_2. In the RCP4.5-CMIP5 scenario, there are periods without rain during the critical stages of soybean development, R1 and R3, that caused yield reduction during the period of 1980–2099, which agrees with Dogan et al. (2007), who showed that the highest soybean yield losses occur when the irrigation cease in the R3, R5, and R6 stages.

Atmospheric CO_2 is the primary substrate for photosynthesis, and an increase in its concentration has a positive effect on crop yield, mainly in C3 plants such as soybean (Streck, 2005). The largest increase of soybean yield due to elevated CO_2 concentration was simulated with the SoySim model, mainly in the RCP4.5-CMIP5 (Table 1). With the Cropgro-Soybean in the potential condition, the largest increases of yield were also simulated in the RCP4.5-CMIP5 scenario; however, when the model was used with the water balance activated, negative yield anomalies were simulated in the same scenario, even with the increase of CO_2 concentration, as a consequence of limited water in the soil. The lowest increase in yield potential per unity of CO_2 increase in the SRES A1B-CMIP3 scenario is associated with the elevation of higher temperature in this scenario (Table 1), in comparison to the RCP4.5-CMIP5, that is, higher temperatures offset the benefit of the CO_2 concentration increase (Lal et al., 1999; Streck, 2005; Hao et al., 2014).

Table 1. Trends of increase of yield potential (YPot) and water-limited yield (WLY) in soybean (*Glycine max*), per unity of CO_2 increase (kg ha^{-1} ppm^{-1}), simulated by SoySim and Cropgro-Soybean models in two future climate scenarios – SRES A1B-CMIP3 and RCP4.5-CMIP5 –, during the 2010–2099 period. Areas 1, 2, 3 and 4 are indicated in Figures 2 A and 2 B.

Area	Sowing date	Trends in yield (kg ha^{-1} ppm^{-1})					
		SRES A1B-CMIP3			RCP4.5-CMIP5		
		SoySim	Cropgro$_{YPot}$	Cropgro$_{WLY}$	SoySim	Cropgro$_{YPot}$	Cropgro$_{WLY}$
1	09/01	3.52	2.63	3.92	6.25	5.42	3.58
	10/01	3.15	0.64	3.66	6.65	4.14	-0.39
	11/01	3.95	0.85	3.23	6.03	3.52	-0.89
	12/01	3.52	1.59	3.69	4.63	4.58	-2.29
	01/01	2.43	1.78	3.45	4.41	4.75	-2.85
	02/01	0.76	1.48	2.44	3.01	3.63	-0.73
2	09/01	3.18	2.33	2.57	6.09	4.14	0.17
	10/01	2.94	1.43	3.71	5.30	-0.06	-1.12
	11/01	3.92	2.04	4.30	4.91	1.17	-1.45
	12/01	4.08	2.65	3.55	3.91	3.74	-1.96
	01/01	3.39	2.57	3.74	3.63	5.03	-2.07
	02/01	1.51	2.25	2.70	3.46	4.25	-0.78
3	09/01	3.34	2.33	4.67	6.14	3.13	0.34
	10/01	3.23	0.53	2.86	6.09	1.06	-0.34
	11/01	4.18	0.90	2.63	5.47	1.90	-0.5
	12/01	3.60	2.41	2.86	4.69	3.80	-0.56
	01/01	2.96	1.91	2.63	3.29	4.47	-0.22
	02/01	1.06	1.59	1.86	3.07	2.96	0.84
4	09/01	3.71	2.36	3.34	6.42	5.76	1.90
	10/01	3.81	2.20	4.00	6.31	4.47	-0.06
	11/01	4.32	2.41	4.43	5.64	4.30	-0.45
	12/01	4.74	2.49	4.03	4.30	4.64	-0.13
	01/01	3.47	2.55	3.42	5.08	5.25	-2.12
	02/01	1.77	2.28	2.12	3.29	4.64	-1.06

Conclusions

1. Soybean (*Glycine max*) yield potential, in the state of Rio Grande do Sul, Brazil, should increase until the end of the 21th century, according to the SRES A1B-CMIP3 and RCP4.5-CMIP5 future climate scenarios.

2. The water-limited soybean yield, in Rio Grande do Sul, should increase until the end of the 21th century in the SRES A1B-CMIP3 scenario; however, in the RCP4.5-CMIP5 scenario, the soybean yield should decrease, due to limited water in the soil.

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