Assessment of Regional Climate Change Impacts on Brazilian Potato Tuber Yield

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Abstract
Climate models indicate that increasing atmospheric concentrations of greenhouse gases (GHG), mainly CO_2, will alter climate by increasing temperatures and changing rainfall patterns. Considering that potato crop stands out as the most important non-grain crop in the world, it is imperative to understand how climate change will impact this crop and how it will affect global food security. In this sense, crop simulation models are useful tools to estimate crop growth, development and yield in response to climatic conditions, soils, genotype and crop management. Among the several potato crop simulation models, DSSAT-SUBSTOR-Potato is the main one and widely used around the world. The aim of this study was to validate this model for Brazilian conditions and used it to simulate the impacts of projected climate change on potato crop in the main Brazilian producing regions, for different growing seasons, considering an ensemble of different general circulation models, projected for 2040–2069 and 2070–2099 periods, under two GHG Representative Concentration Pathways (RCP4.5 and RCP8.5). The results showed that Brazil will have warmer climate with wetter conditions in the south and less rainfall in the north, which will impact potato crop in different ways, depending on the producing region and growing season. In Southern Brazil, future climate will benefit potato yield, mainly during the 3rd growing season. On the other hand, locations with warmer and drier climates will have lower potato yields in relation to the present, mostly during the 1st growing season, when extremely high temperatures and water deficit will limit plants' growth. These impacts will be less expressive in the most optimist scenario (RCP4.5), while more intense yield losses are expected under the RCP8.5 in the end of the century.

Introduction

Potato is the most important vegetable in Brazil, and the country is ranked as the second biggest producer in South America, with more than 3.6 million ton produced annually in an area of about 119 thousand hectares, with average yield of 29 t ha^{-1} (FAOSTAT 2020). Potato can be grown under a huge range of soil and climate conditions, which makes possible to grow this crop in different Brazilian regions.

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However, the largest producer in the country is the states of the South and Southeast regions, with 86% of the national production, with Minas Gerais state standing out as the main national producer, responsible for 31% of the potato harvested in the country (IBGE 2020) (see Figure S1 in Supplementary Material for further details).

In Brazil, tropical and subtropical conditions allow to have three potato growing seasons, known as rainy, dry and winter seasons, which account for 44%, 34% and 22% of the total harvested area, respectively (IBGE 2020) (Figure S1 in Supplementary Material). The rainy crop season is planted from August to December, harvest from November to March, and conducted under rainfed conditions in places of higher latitudes, where temperature is mild. The dry crop season is planted from January to April and harvest from April to July in places of high and medium altitudes and conducted with complementary irrigation. Finally, the winter crop season is planted from May to July and harvest from

August to October in frost-free regions of the country and also with complementary irrigation (Silva and Lopes 2015).

Considering that future climate projections are indicating warmer conditions and an expected mean annual rainfall changing thorough Brazil (Torres and Marengo 2013; Sánchez et al. 2015; Reboita et al. 2014; Bender and Sentelhas 2018), climate change effect on potato yield will possibly depend on the regional conditions. Furthermore, climate change and population increase will create a pressure over agricultural systems, requiring more food production under more restrictive environmental conditions (Sadras et al. 2009; Mancosu et al. 2015).

As crop models are able to estimate crop growth and development under distinct climate, soil and crop management conditions, they can be used to understand how climate change will impact crops and, consequently, food production (Asseng et al. 2015). However, before their used for any purpose, these models should be calibrated and validated to the most used genotypes (Boote et al. 1996), to ensure that they can adequately simulate the effects of climate, soil, and crop management conditions for the different cultivars used in the region of interest (Angulo et al. 2013; Liu et al. 2015).

In this sense, the DSSAT-SUBSTOR-Potato simulation model, which is part of the Decision Support System for Agrotechnology Transfer (DSSAT) platform, has been widely used for assessing the response of potato crop to climate variability and change around the world (Raymundo et al. 2017a, b; Adavi et al. 2018; Rahman et al. 2018). However, there is a lack of previous studies for potato crop in Brazil for both present and future climate scenarios. Thus, the aim of this study was to test and validate DSSAT-SUBSTOR-Potato model for estimating potato yield under Brazilian conditions and to use this model to quantify the potential impacts of climate change, projected to different Brazilian regions, on potato yield, considering twenty future climate scenarios generated from five general circulation models (GCMs) for two Representative Circulation Pathways (RCP4.5 and RCP8.5) for mid and long term periods (2040–2069 and 2070–2099).

Materials and Methods

Potato Simulation Model

DSSAT-SUBSTOR-Potato model was used to simulate the baseline and future tuber yield and growth characteristics of potato crop in different Brazilian regions, considering three growing seasons (rainy, dry and winter). This model, in its latest version, is included in DSSAT v4.7 (Hoogenboom et al. 2017), and has been used recently for climate change impacts assessments in other countries (Raymundo et al. 2017a, b; Adavi et al. 2018; Rahman et al. 2018).

The DSSAT-SUBSTOR-Potato model defines potato cultivar based on five genetic coefficients, which characterize quantitatively how the cultivar responds to the environmental conditions, including: tuber initiation sensitivity to photoperiod (P2, dimensionless); upper critical temperature for tuber initiation (TC, °C), that affects phenology; leaf area expansion rate (G2, $cm^2 m^{-2} day^{-1}$); potential tuber growth rate (G3, $gm^{-2} day^{-1}$); and the index that suppresses tuber growth (PD, dimensionless), which affects biomass accumulation (Griffin et al. 1993).

Cultivar, Field Experiments and Crop Model Evaluation

Before assessing the future climate impacts on potato yield, the DSSAT-SUBSTOR-Potato was evaluated aiming to determine its ability to accurately predict observed yield data. The genetic coefficients for the Brazilian potato cultivars used in the present study were derived from the literature, adjusted for tropical highlands, in a wide range of soil, climate and crop management conditions, very similar to those observed in the Brazilian producing regions. These coefficients were: G2 = 2000 $cm^2 m^{-2} d^{-1}$; G3 = 30 g $m^{-2} d^{-1}$; PD = 0.9; P2 = 0.9; and TC = 20 °C (Kleinwechter et al. 2016). They were validated with potato tuber yield from two growing seasons (2017 and 2018) at six locations (three in the state of São Paulo and three in the state of Paraná), under irrigated and rainfed conditions. The crop management practices reported at each site, such as planting and harvest dates, irrigation and fertilizer practices, together with measured yield data are summarized in Table 1.

For the potato growth and development simulations, the DSSAT-SUBSTOR-Potato model considers reference evapotranspiration estimated by FAO 56 Penman–Monteith method (Allen et al. 1998). Soil water infiltration according to the soil curve number method (Soil Conservation Service 1972), whereas the soil water balance was determined based on Ritchie method (Ritchie 1998), with soil water evaporation estimated by Suleiman–Ritchie procedure (Suleiman and Ritchie 2003).

The performance of DSSAT-SUBSTOR-Potato was evaluated by comparing simulated and observed tuber fresh weight, using the following statistical indices: coefficient of determination (r^2), as a measure of precision; agreement index (d) (Willmott et al. 1985), as a measure of accuracy; confidence index (c) (Camargo and Sentelhas 1997), which is the product between r and d, being classified as "great" for values higher than 0.85; "very good" for values between 0.76 and 0.85; "good" between 0.66 and 0.75; "median" between 0.61 and 0.65; "suffering" between 0.51 and 0.60; "bad" between 0.41 and 0.50; and "terrible" for values lower than 0.41; mean error (ME), that indicates the bias of the

Table 1 Potato experimental data used for DSSAT-SUBSTOR-Potato model evaluation

Site (city, state)	Palmeira, PR	Lapa, PR	Porto Amazonas, PR
Latitude (°)	− 25.54	− 25.98	− 25.65
Longitude (°)	− 50.06	− 49.86	− 49.95
Altitude (m)	865	908	793
Planting date	2017/03/02	2017/09/08	2018/02/05
Harvest date	2017/06/13	2017/12/27	2018/07/12
Irrigation water applied (mm)	60	60	60
Soil	Clayey sandy	Sandy	Sandy
Fertilizer (planting)	1.8 t/ha (06-27-06)	1.8 t/ha (06-27-06)	1.8 t/ha (06-27-06)
Fertilizer (after planting)	0.8 t/ha (09-00-24)	0.8 t/ha (09-00-24)	0.8 t/ha (09-00-24)
Fresh tuber yield (t ha^{-1})	26.00	30.00	23.00
Site (city, state)	Paranapanema, SP	Itaí, SP	V. Grande do Sul, SP
Latitude (°)	− 23.39	− 23.41	− 21.84
Longitude (°)	− 48.73	− 49.09	− 46.88
Altitude (m)	602	597	730
Planting date	2018/07/12 to 2018/07/23	2018/04/24 to 2018/04/26	2018/06/25
Harvest date	2018/11/12 to 2018/12/10	2018/10/12 to 2018/11/14	2018/11/13
Irrigation water applied (mm)	0	0	258
Soil	Silt	Clayey	Silt
Fertilizer (planting)	1.5 t/ha (06-30-08)	1.5 t/ha (06-30-08)	–
Fertilizer (after planting)	0.5 t/ha (18-00-24)	0.5 t/ha (18-00-24)	–
Fresh tuber yield (t ha^{-1})	34.09	30.09	30.00

errors; and root mean square error (RMSE), which gives the magnitude of the errors (Wallach et al. 2013).

Soil and Weather Data from Experimental Sites

Soil conditions considered in the simulations were grouped in tree mayor soil types, determined according to the texture, as clayey (C), loam (L) and sandy (S), which characterized the average conditions of predominant soil profile over the producing regions, with physical and chemical characteristics being obtained from RADAMBRASIL (1981) and soil water holding capacity determined according to pedotransfer functions of Tomasella et al. (2000). Details about the characteristics of each soil profile are presented in Table S1 in Supplementary Material.

Daily weather data, corresponding to maximum and minimum air temperature, incoming solar radiation, sunshine hours, rainfall, wind speed and relative humidity, were obtained from ground weather stations of the Brazilian National Institute of Meteorology (INMET), Integrated Center of Agrometeorological Information (CIIAGRO) of Agronomic Institute of Campinas (IAC), and Brazilian Agricultural Research Corporation (EMBRAPA). For those weather stations where incoming solar radiation was not available, it was calculated based on sunshine hours, following the method proposed by Ängström (1924) and Prescott (1940), with coefficients *a* and *b* from Glover and

McCulloch (1958). Where or when sunshine hours were missing, incoming solar radiation was estimated by Bristow–Campbell model, as recommended by Bender and Sentelhas (2018).

Assessed Sites for Climate Change Impact on Potato Crop

With a continental dimension, Brazil presents a large spatial climate variability, which will result in different expected increases in air temperature and changes in rainfall pattern (Bender and Sentelhas 2018). Therefore, the impact of climate change on potato crop throughout the country is of great uncertainty. In this sense, assessment of climate change impacts on potato crop was conducted over ten sites, considered as representative of the major potato growing areas in Brazil (IBGE 2020), with contrasting environmental conditions (Fig. 1): São Francisco de Paula, RS (RSSF); Água Doce, SC (SCAD); Guarapuava, PR (PRGP); Itapeva, SP (SPIT); Casa Branca, SP (SPCB); Perdizes, MG (MGPE); Montes Claros, MG (MGMC); Cristalina, GO (GOCR); Ibicoara, BA (BAIB); Jacobina, BA (BAJA).

As local observed weather data are the ideal source of historical climate information (Ruane and McDermid 2017), climate series from 1980 to 2009 were obtained from INMET, with missing data gaps being filled with gridded data from Xavier et al. (2015). This procedure was
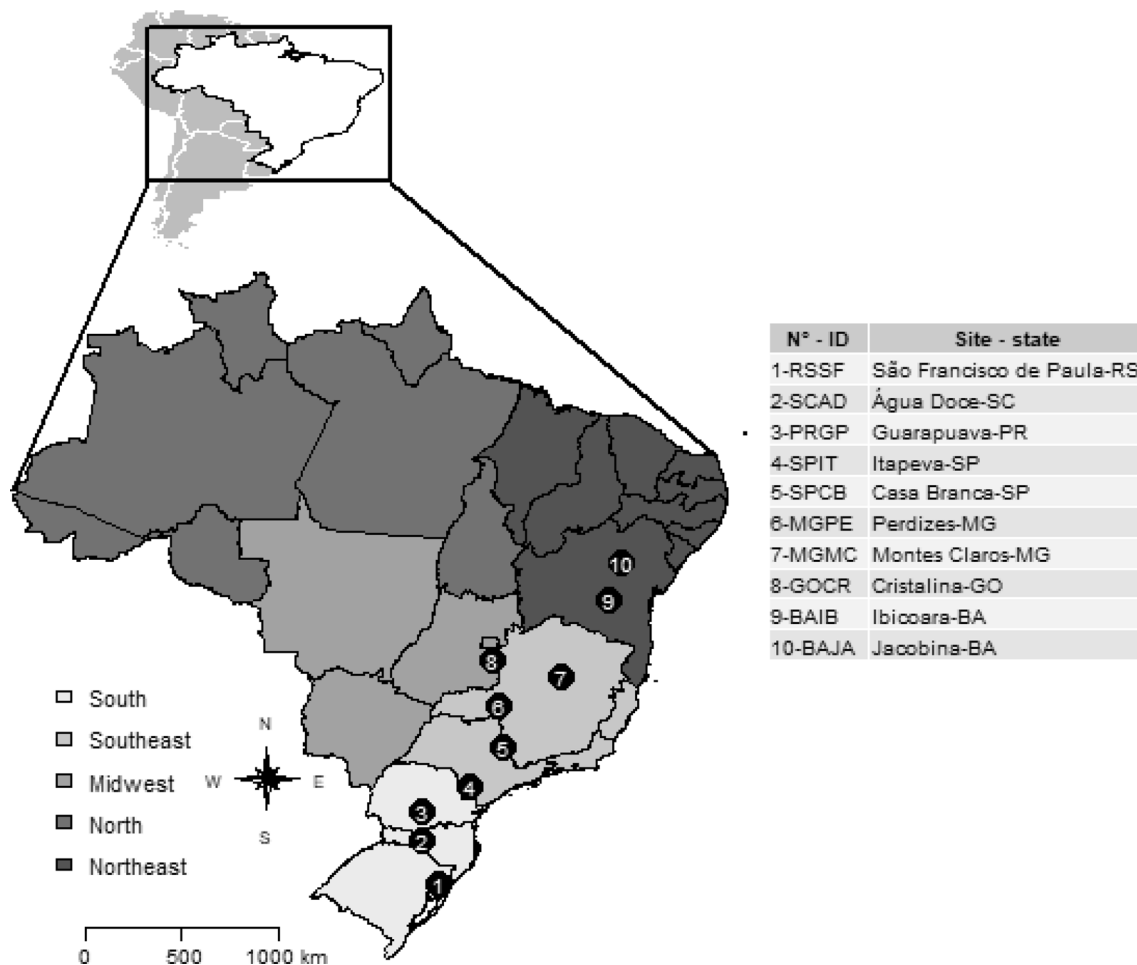
Fig. 1 Assessed locations in Brazil to represent the potato producing regions and used for yield simulations using DSSAT-SUBSTOR-Potato model for present and future climate scenarios

| N° - ID	Site - state
1-RSSF	São Francisco de Paula-RS
2-SCAD	Água Doce-SC
3-PRGP	Guarapuava-PR
4-SPIT	Itapeva-SP
5-SPCB	Casa Branca-SP
6-MGPE	Perdizes-MG
7-MGMC	Montes Claros-MG
8-GOCR	Cristalina-GO
9-BAIB	Ibicoara-BA
10-BAJA	Jacobina-BA

previously tested by Battisti et al. (2018a) for different locations in Brazil and showed a good performance.

The locations selected to represent the potato producing regions in this study are geographically dispersed in four different Brazilian regions (Fig. 1), resulting in an expressive climate variability, as presented in Fig. 2 for air temperature and rainfall. The South region, due to its latitudinal position, is more influenced by frontal systems, which are the main cause of a well distributed rainfall along the year and cooler temperatures during the winter (Grimm 2009). Southeast and Midwest regions are under the influence of tropical and mid latitude systems, presenting a well characterized dry season during the winter and rainy season in the summer (Alves 2009; Nunes et al. 2009). Finally, in Northeast region, the temperatures are higher all year long and rainfall distribution is usually irregular, even during the rainy season.

Climate Change Scenarios

Based on historical database (1980–2009), climate change scenarios were generated under two Representative Concentration Pathways (RPCs; Moss et al. 2010): an intermediate emission scenario (RCP4.5), that appears as the most likely future to happen (Ward et al. 2011); and high emission scenario (RCP8.5) as the worst-case climate scenario, without additional efforts to constrain greenhouse gases emissions (GHG). These scenarios were based on the Agricultural Model Intercomparison and Improvement Project (AgMIP; Rosenzweig et al. 2013) protocols (Rosenzweig et al. 2015), that includes mid-century (2040–2069) and end-of-century (2070–2099) periods. Projections were generated based on mean and daily variability changes for temperature and rainfall, that allowed for changes in both mean climate and its variability (Ruane et al. 2015), following the procedure described by Hudson and Ruane (2015).

To access the impact of global climate models uncertainty, a set of five GCMs was selected based on "The
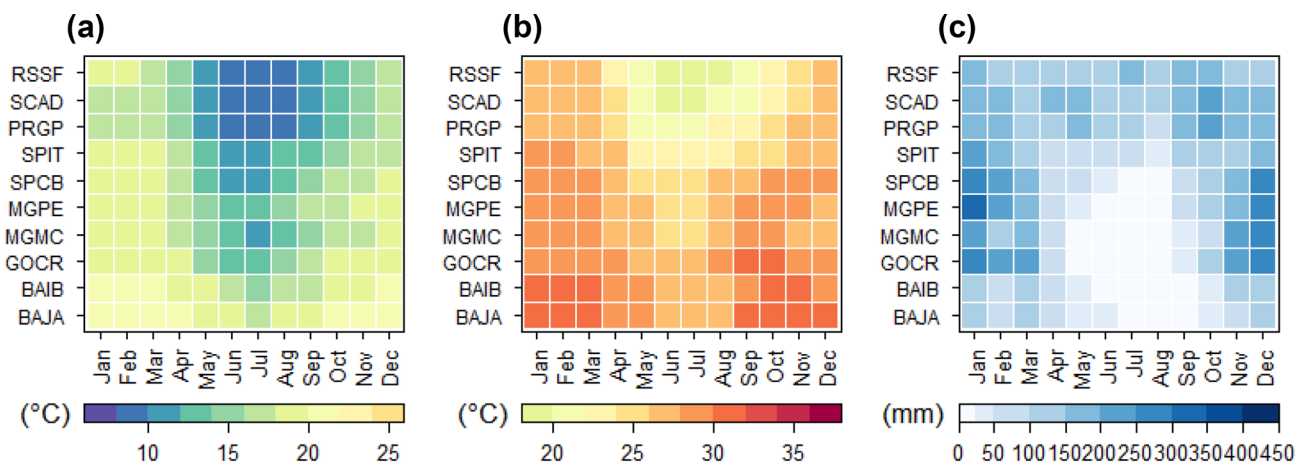
Fig. 2 Monthly averages of minimum (**a**) and maximum (**b**) air temperatures and total rainfall (**c**), from 1980 to 2009, for the ten locations selected to represent the Brazilian potato producing regions: São Francisco de Paula, RS (RSSF); Água Doce, SC (SCAD); Guar- apuava, PR (PRGP); Itapeva, SP (SPIT); Casa Branca, SP (SPCB); Perdizes, MG (MGPE); Montes Claros, MG (MGMC); Cristalina, GO (GOCR); Ibicoara, BA (BAIB); Jacobina, BA (BAJA)

Representative Temperature and Precipitation GCM Subsetting Approach" as described by Ruane and McDermid (2017), developed from similar approaches as reported by Semenov and Stratonovitch (2015) and Lutz et al. (2016), within the AgMIP, which classified GCMs into five quadrants, using median and standard deviation of temperature and rainfall change, from 29 GCMs available through Coupled Model Intercomparison Project—Phase 5 (CMIP5; Taylor et al. 2012), which was used for the Intergovernmental Panel on Climate Changes's (IPCC) fifth Assessment Report (AR5; IPCC 2013). Thus, twenty-one climate scenarios (baseline and twenty future) were used at each local on seasonal analysis (30 years of weather) of DSSAT-SUBSTOR-Potato model. The local GCM projections of growing season's temperature and rainfall change, classified on relatively cold/wet (CW), cold/dry (CD), middle (MI), hot/wet (HW) and hot/dry (HD) classes, are described on Table S2 (Supplementary Material). Atmospheric [CO_2] was set at 360 part per million (ppm) for the baseline, 499 and 532 ppm for the RCP4.5, and 571 and 801 ppm for the RCP8.5 emission scenarios, respectively for mid- and end-of-century periods, with each one representing the concentration in the central year of each 30-year period, as suggested by Rosenzweig et al. (2015) (Table S3 in the Supplementary Material).

Simulations of Climate Change Impacts on Potato Crop

Crop model settings to evaluate regional climate change impacts on potato crop in Brazil were the same used for the present scenario, with the coefficients validated in this study. The planting and harvest dates were fixed for each year,

considering the planting date that reported the greatest mean tuber yield (data not shown) for the baseline historical period in the window from September to December, January to April and May to June, for rainy (1st), dry (2nd) and winter (3rd) potato growing seasons, respectively (Table S4 in Supplementary Material). The model was run with water and nitrogen balances switched on. For fertilizer, two nitrogen applications of 100 kg ha^{-1} at planting and 40 days after planting, in the form of ammonium nitrate, were performed, representing what is currently used by growers and recommended by Silva and Lopes (2015). All simulations were done for rainfed conditions. Once DSSAT-SUBSTOR-Potato model did not include a coefficient to determine senescence or maturity (Griffin et al. 1993), the crop cycle was set as 110 days, from planting to harvesting, for all periods, GCMs and emission scenarios.

Baseline yield was simulated for the historical climate (1980–2009), while for future yields the simulations were performed for each one of the five future climate classes (Table S2 in Supplementary Material), which allow to capture climate variability of each one of the global models projections, arranged by the two emission scenarios and time periods as described in Sect. 2.5, for the ten sites and three growing seasons. The regional percentage of yield changes under future climates were evaluated by the mean yield changes over 30-year period for the five GCMs climate classes in relation to the baseline yield. Under this ensemble approach, the yield change was calculated by:

$$\text{Yield Change (\%)} = \left(\frac{\text{Projected Yield} - \text{Baseline Yield}}{\text{Baseline Yield}} \right) \times 100.$$

Results

Crop Model Validation

The validation process showed, in a wide range of fresh tuber yields, from 23.0 to 34.1 t ha^{-1}, that DSSAT-SUBSTOR-Potato model predicted potato yield well for Brazilian conditions. The mean observed and simulated yields were, respectively, 28.86 t ha^{-1} and 29.38 t ha^{-1}. The results indicated a significant correlation between observed and simulated values ($r^2 = 0.84$), with a d index of 0.91 and a c index of 0.83, which represents "very good" performance, according to Camargo and Sentelhas (1997). The yield errors presented

by the DSSAT-SUBSTOR-Potato model were small, with ME = 0.52 t ha^{-1} and RMSE = 1.74 t ha^{-1}, representing 6% in relation to the average potato yield. The performance of the DSSAT-SUBSTOR-Potato model for Brazilian conditions was even better than that obtained by the studies of Kleinwechter et al. (2016), which used observed yield data from Peru, India, Uganda, Burundi and U.S., and found a relative RMSE of 28.1%, and of Fleisher et al. (2017), which obtained a relative error of about 15% for dry tuber yield, using an ensemble of eight crop simulation models, including DSSAT-SUBSTOR-Potato model, when compared to field data from four countries (Bolivia, Burundi, Denmark

Table 2 Average annual air temperature and rainfall changes in relation to the baseline (1980–2009), as projected by the ensemble of the five future climate classes from Coupled Model Intercomparison Project—Phase 5 (CMIP5; Taylor et al. 2012), under intermediate emission scenario (RCP4.5) at mid (2040–2069) and end-of-century (2070–2099) periods

Site	2040–2069				2070–2099			
	Temperature (°C)			Rain (%)	Temperature (°C)			Rain (%)
	Maximum	Minimum	Mean		Maximum	Minimum	Mean	
RSSF	1.0	1.1	1.1	8	1.4	1.5	1.5	8
SCAD	1.3	1.4	1.3	6	1.8	1.9	1.9	4
PRPG	1.5	1.5	1.5	8	1.9	1.9	1.9	10
SPIT	1.5	1.4	1.5	9	2.3	2.0	2.1	4
SPCB	1.8	1.7	1.7	2	2.3	2.1	2.2	4
MGPE	2.0	1.9	1.9	− 5	2.6	2.4	2.5	− 3
MGMC	1.8	1.7	1.7	− 4	2.4	2.2	2.3	− 9
GOCR	1.9	1.7	1.8	− 13	2.5	2.1	2.3	− 5
BAIB	1.8	1.5	1.7	− 10	2.0	1.8	1.9	− 7
BAJA	1.6	1.4	1.5	− 9	1.9	1.6	1.8	− 11
Mean	1.6	1.5	1.6	− 1	2.1	2.0	2.0	− 1

São Francisco de Paula, RS (RSSF); Água Doce, SC (SCAD); Guarapuava, PR (PRGP); Itapeva, SP (SPIT); Casa Branca, SP (SPCB); Perdizes, MG (MGPE); Montes Claros, MG (MGMC); Cristalina, GO (GOCR); Ibicoara, BA (BAIB); Jacobina, BA (BAJA)

Table 3 Average annual air temperature and rainfall changes in relation to the baseline (1980–2009), as projected by the ensemble of the five future climate classes from Coupled Model Intercomparison Project—Phase 5 (CMIP5; Taylor et al. 2012), under high emission scenario (RCP8.5) at mid (2040–2069) and end-of-century (2070–2099) periods

Site	2040–2069				2070–2099			
	Temperature (°C)			Rain (%)	Temperature (°C)			Rain (%)
	Maximum	Minimum	Mean		Maximum	Minimum	Mean	
RSSF	1.4	1.7	1.6	12	2.6	2.9	2.8	20
SCAD	2.3	2.2	2.2	4	3.7	3.8	3.8	9
PRPG	2.1	2.2	2.1	7	3.6	3.9	3.7	15
SPIT	2.3	2.1	2.2	5	3.9	3.6	3.8	7
SPCB	2.5	2.3	2.4	0	4.3	3.9	4.1	− 7
MGPE	2.6	2.4	2.5	− 12	4.5	4.2	4.3	− 14
MGMC	2.3	2.3	2.3	− 8	4.0	4.1	4.1	− 10
GOCR	2.7	2.6	2.7	− 12	4.5	4.3	4.4	− 14
BAIB	2.3	2.1	2.2	− 12	3.7	3.5	3.6	− 17
BAJA	2.1	1.9	2.0	− 16	3.6	3.2	3.4	− 21
Mean	2.3	2.2	2.2	− 3	3.8	3.7	3.8	− 3

São Francisco de Paula, RS (RSSF); Água Doce, SC (SCAD); Guarapuava, PR (PRGP); Itapeva, SP (SPIT); Casa Branca, SP (SPCB); Perdizes, MG (MGPE); Montes Claros, MG (MGMC); Cristalina, GO (GOCR); Ibicoara, BA (BAIB); Jacobina, BA (BAJA)
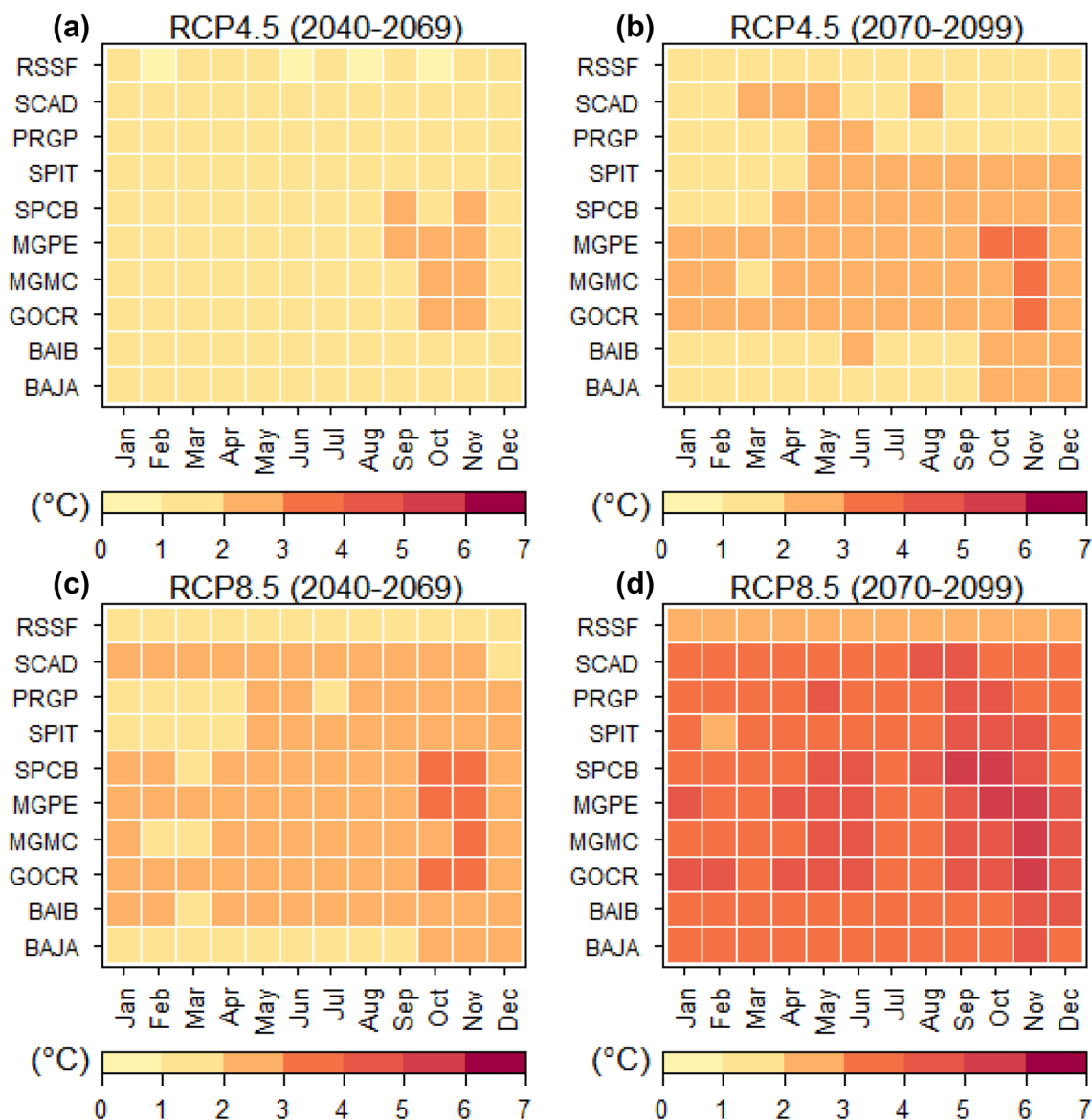
Fig. 3 Average monthly air temperature changes from baseline (1980–2009), as projected by the ensemble of five future climate classes from Coupled Model Intercomparison Project—Phase 5 (CMIP5; Taylor et al. 2012), for all assessed periods and emission scenarios: **a**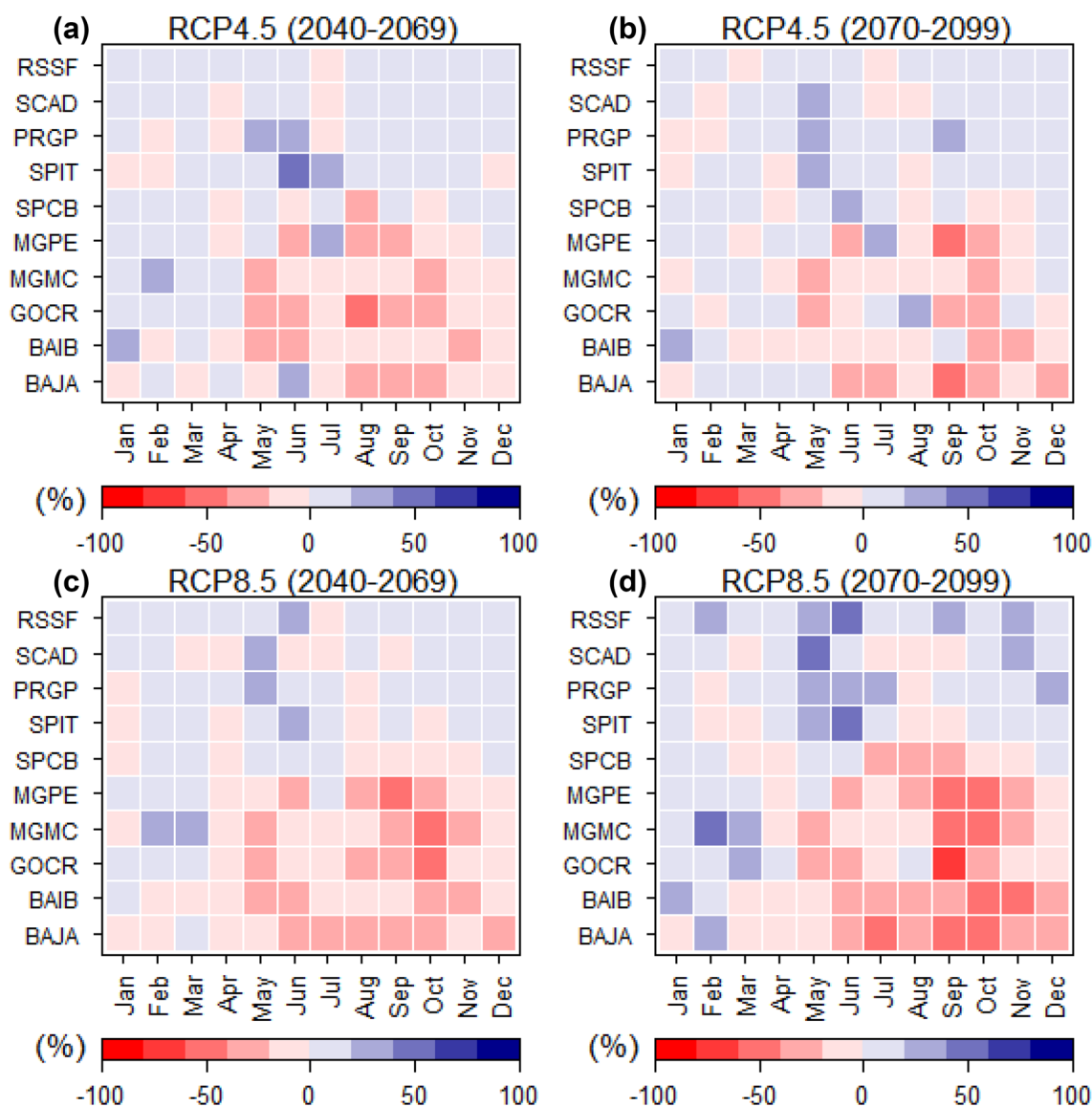 RCP4.5 (2040–2069); **b** RCP4.5 (2070–2099); **c** RCP8.5 (2040–2069); and **d** RCP8.5 (2070–2099). São Francisco de Paula, RS (RSSF); Água Doce, SC (SCAD); Guarapuava, PR (PRGP); Itapeva, SP (SPIT); Casa Branca, SP (SPCB); Perdizes, MG (MGPE); Montes Claros, MG (MGMC); Cristalina, GO (GOCR); Ibicoara, BA (BAIB); Jacobina, BA (BAJA)

and U.S.). Therefore, the calibration of the model was not required in the present study.

Climate Change Projections

Considerable variability was observed in temperature and rainfall for the future weather scenarios. Tables 2 and 3 present the projections from the five GCMs climate classes performed over ten Brazilian sites. Mean annual temperature will increase from 1.6 °C on mid-term period under

intermediate emission scenario and is expected to continue to increase over the century till 3.8 °C at worst emission scenario (Fig. 3). Higher temperatures are projected toward the end of the century, with the largest value being reached under high emission scenario (RCP8.5). Despite the great uncertainty, rainfall projections present different regional responses, with an increase in Southern Brazil and a decrease, mainly during the second half of the year, in Northeast region (Fig. 4).

Fig. 4 Average monthly rainfall changes from baseline (1980–2009), as projected by the ensemble of the five future climate classes from Coupled Model Intercomparison Project—Phase 5 (CMIP5; Taylor et al. 2012), for all assessed periods and emission scenarios: **a** RCP4.5 (2040–2069); **b** RCP4.5 (2070–2099); **c** RCP8.5 (2040–2069); and **d** RCP8.5 (2070–2099). São Francisco de Paul, RS (RSSF); Água Doce, SC (SCAD); Guarapuava, PR (PRGP); Itapeva, SP (SPIT); Casa Branca, SP (SPCB); Perdizes, MG (MGPE); Montes Claros, MG (MGMC); Cristalina, GO (GOCR); Ibicoara, BA (BAIB); Jacobina, BA (BAJA)

Climate Change Impacts on Potato Crop

Simulated potato yields for the present scenario (baseline) ranged from 22.5 to 36.6 t ha^{-1}, from 21.1 to 30.3 t ha^{-1}, and from 18.4 to 24.9 ha^{-1}, respectively for the 1st, 2nd and 3rd growing seasons (Fig. 5). These results show the great yield variability between regions and growing seasons, conditioned by differences of climate and soil conditions. Lower tuber yields are observed in the dry and winter growing seasons, where yields are mainly limited by lower temperatures, solar radiation and photoperiod. These results are very close to the national average yield, which corresponds to 27.1 t

ha^{-1}, ranging between 18.8 and 39.1 t ha^{-1} for all growing seasons (IBGE 2020).

The predicted changes in average yield from the baseline over all 1st, 2nd and 3rd growing seasons and for all climate scenarios are presented in Fig. 6 (See further details on Table S5 in the Supplementary Material). Simulated mean yield changes indicate higher potato yield losses for the 1st growing season than for the other two. On the 1st and 2nd growing seasons, the highest impacts occurred from mid-term period under intermediate emission scenario toward the end of the century at worst-case climate scenario, with yield losses ranging from 23.0 to 52.7%, and from 3.1% to
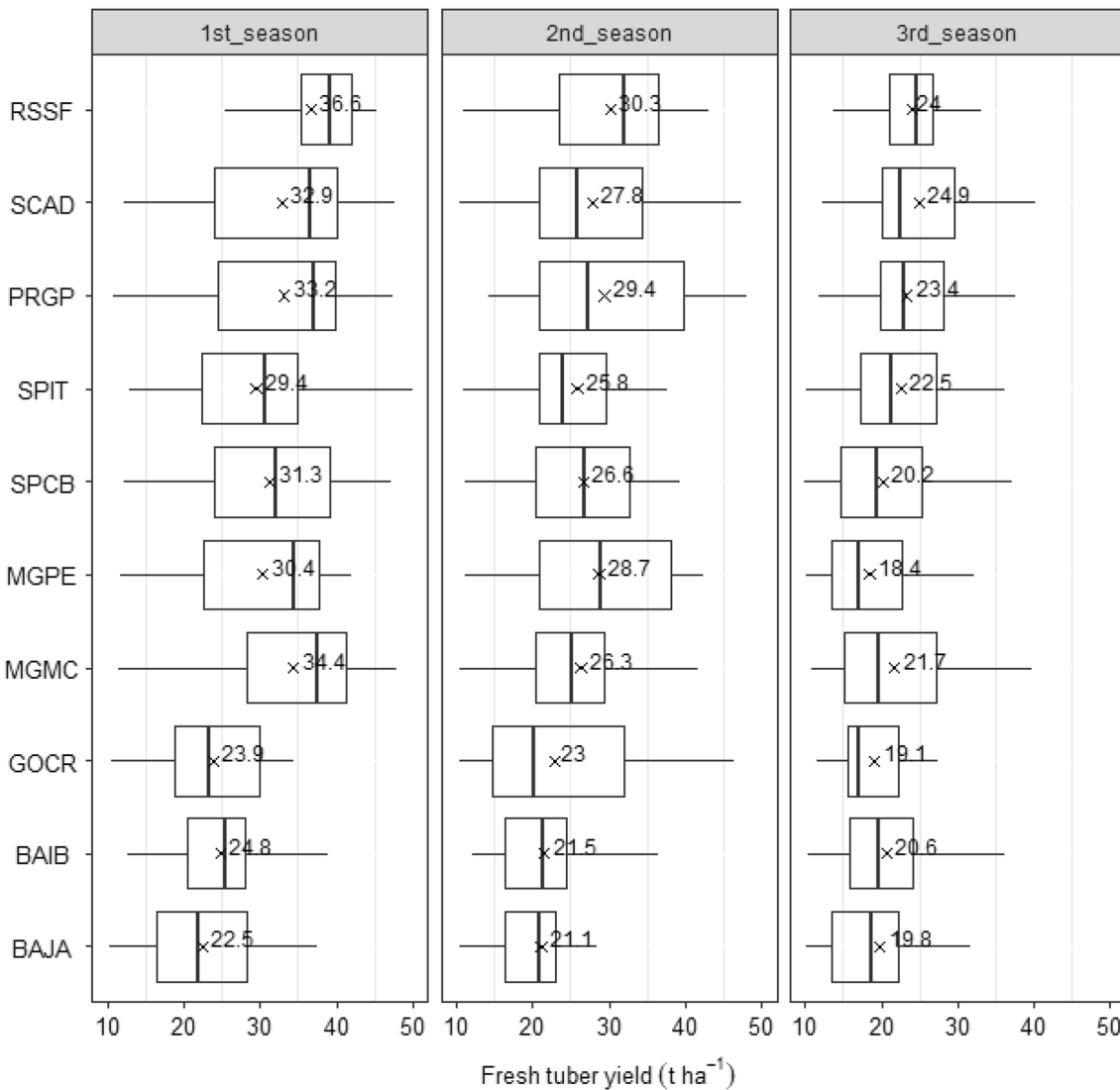
Fig. 5 Local fresh potato yield (t ha^{-1}) simulated for the baseline (1980–2009) for the 1st, 2nd and 3rd potato growing seasons, based on 30-year simulations, for ten Brazilian potato producing regions. Boxes denote the lower (25%) to upper quartile (75%) values, with median and mean yield values indicated by a line and a cross inside the box, respectively. The locations refers to: São Francisco de Paula, RS (RSSF); Água Doce, SC (SCAD); Guarapuava, PR (PRGP); Itapeva, SP (SPIT); Casa Branca, SP (SPCB); Perdizes, MG (MGPE); Montes Claros, MG (MGMC); Cristalina, GO (GOCR); Ibicoara, BA (BAIB); Jacobina, BA (BAJA)

30.6%, respectively. On the other hand, in the 3rd growing season the potato yield gains ranged from 4.8 to 5.7%, with only the most pessimistic scenario having yield reductions.

Figure 7 presents the impact of climate change on Brazilian potato yield as well as on actual crop evapotranspiration (ET) and water use efficiency (WUE), when considering distinct classes of temperature and rainfall changes. From these results, a tendency of tuber yield increase (8.0%) was observed in the more optimistic scenario, where soil water availability will be not so limiting (CW and CD). On the other hand, yield losses may occur for the pessimistic scenarios, mainly under hot and dryer conditions (HD), reaching − 48.6% (Fig. 7 and Table S6 in the Supplementary

Material). For crop ET, the simulations showed a pattern of variation different from what was observed for tuber yield. A slight increase of average water consumption by potato crop was observed for most of the future climate scenarios for RCP4.5, ranging between 0.5 and 5.7%. Only for hot and dryer future conditions actual crop ET was reduced by 2.8% for 2040–2069 period and by 3.9% for 2070–2099 period. For RCP8.5, actual crop ET was increase, in average, for CW, MI and HW future climate scenarios, whereas for driest ones (CD and HD) the crop water consumption was reduced, ranging between 2.7 and 10.2%. As a result of a predominant tuber yield reduction and variable ET changes, WUE followed the tendency of yield changes, decreasing for most of

Fig. 6 Percentage tuber yield changes from baseline for the 1st, 2nd and 3rd potato growing seasons in relation to the baseline (1980–2009), based on 30-year simulations averaged over ten sites and five future climate classes, under intermediate (RCP4.5) and high (RCP8.5) emission scenarios at mid- (2040–2069) and end-of-century (2070–2099) periods. Boxes denote the lower (25%) to upper quartile (75%) values, with median and mean yield values indicated by a line and a cross inside the box, respectively
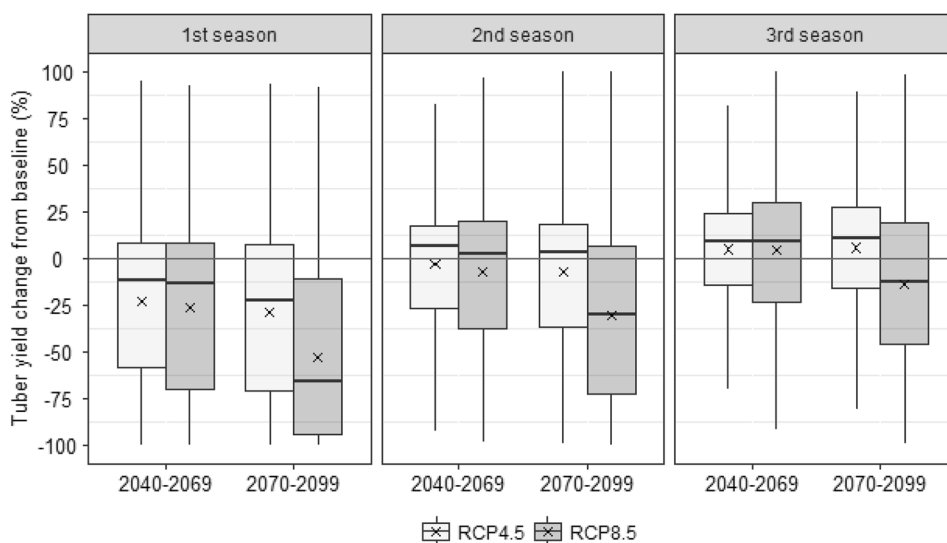
the scenarios. The only exception was for cool and dry (CD) scenario. Despite the logical pattern of these results, usually greater uncertainties are associated to them, mainly at the highest temperature scenarios due to the crop models' limitations to simulate yield under extremely high temperatures and CO_2 concentrations (Fleisher et al. 2017; Raymundo et al. 2017a).

As presented in Fig. 8, DSSAT-SUBSTOR-Potato simulations, considering all future climate classes, showed that seasonal mean potato yield changes will vary regionally (Table S7 in the Supplementary Material). In the South region, represented by RSSF and SCAD, and also in the south of the state of São Paulo (SPIT), the simulations show tendency of positive impacts on tuber yield, increasing from 1st to 3rd growing season, mainly in the more optimistic emission scenario. Only 1st and 2nd growing seasons in the pessimistic climate change scenario will present expressive yield decreases, from 1.3 to 31.0 and 4.0 to 11.4%, respectively. In the producing areas of the states of Paraná (PRGP), in average it is expected a potato yield increase only for the 2nd growing season, whereas in the states of São Paulo (SPCB) and Minas Gerais (MGPE and MGMC), it will happen mainly in the 3rd growing season. In the sites located in the northernmost part of the studied region (BAIB, BAJA and GOCR), potato yield will have an opposite impact in relation to the southern sites, with expected negative impacts on potato yield for all growing seasons, ranging from − 6.8% in the 3rd growing season to − 92.3% in the 1st. The higher impacts projected in BAJA are related to the lower soil water holding capacity of this regions in addition to its lower altitude (461 m) when compared to BAIB, which is located at 1019 m.

From all the analyses performed (Figs. 6, 7 and 8), the potato yield variability caused by different years (30),

growing seasons (3) and environments (10 sites) increased from the present scenario to the future ones. When considering only the future climate scenarios, such variability also increased from the less critical (CW and CD for RCP4.5 and 2040–2069) to the worst-case climate scenario (HW and HD for RCP8.5 and 2070–2099).

Discussions

Rising temperatures and changing rainfall patterns throughout the country presented here are consistent with previous studies (Torres and Marengo 2013; Bender and Sentelhas 2018). These changes will have regional impacts on Brazilian potato yield (Figs. 6, 7 and 8) as also estimated for other crops, such as sugarcane (Marin et al. 2013; dos Santos and Sentelhas 2014); soybean (do Rio et al. 2015; Battisti et al. 2018b); maize and beans (Costa et al. 2009) and eucalyptus (Elli et al. 2020a).

In the future climate conditions, general potato yield and WUE will be reduced, whereas actual crop ET will slightly increase for most of the scenarios, because of the increase in the atmospheric water demand imposed by higher temperatures. Similar results were also obtained by Fleisher et al. (2017), analyzing an ensemble approach on multiple locations. These authors found that under higher CO_2 concentration and temperature and with reduced rainfall, potato yield will diminish by 21–61%, with the same occurring for ET (between 3 and 35%) and WUE (between 30 and 56%). As a C3 crop, it is expected that potato will respond with higher photosynthesis rate and water use efficiency under elevated atmospheric CO_2 concentration (Kaminski et al. 2014; Asseng et al. 2015). However, higher CO_2 levels also increase air temperature and rainfall variability (IPCC 2014), which also impact ET and WUE. Our results suggest
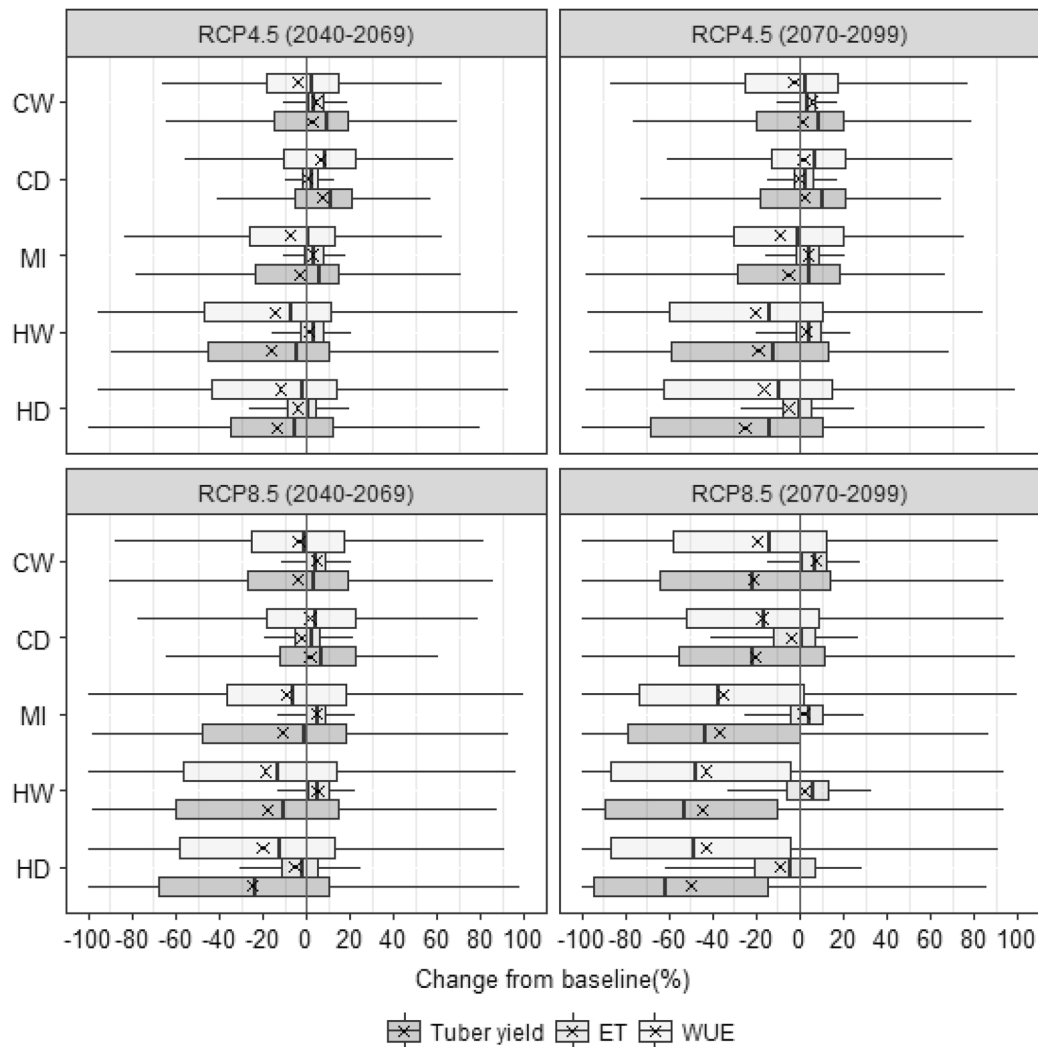
Fig. 7 Percentage of tuber yield, actual crop evapotranspiration (ET) and water use efficiency (WUE) changes in relation to the baseline (1980–2009), considering 30-year simulations averaged over ten sites and all growing seasons, for the following future climate (temperature/rainfall)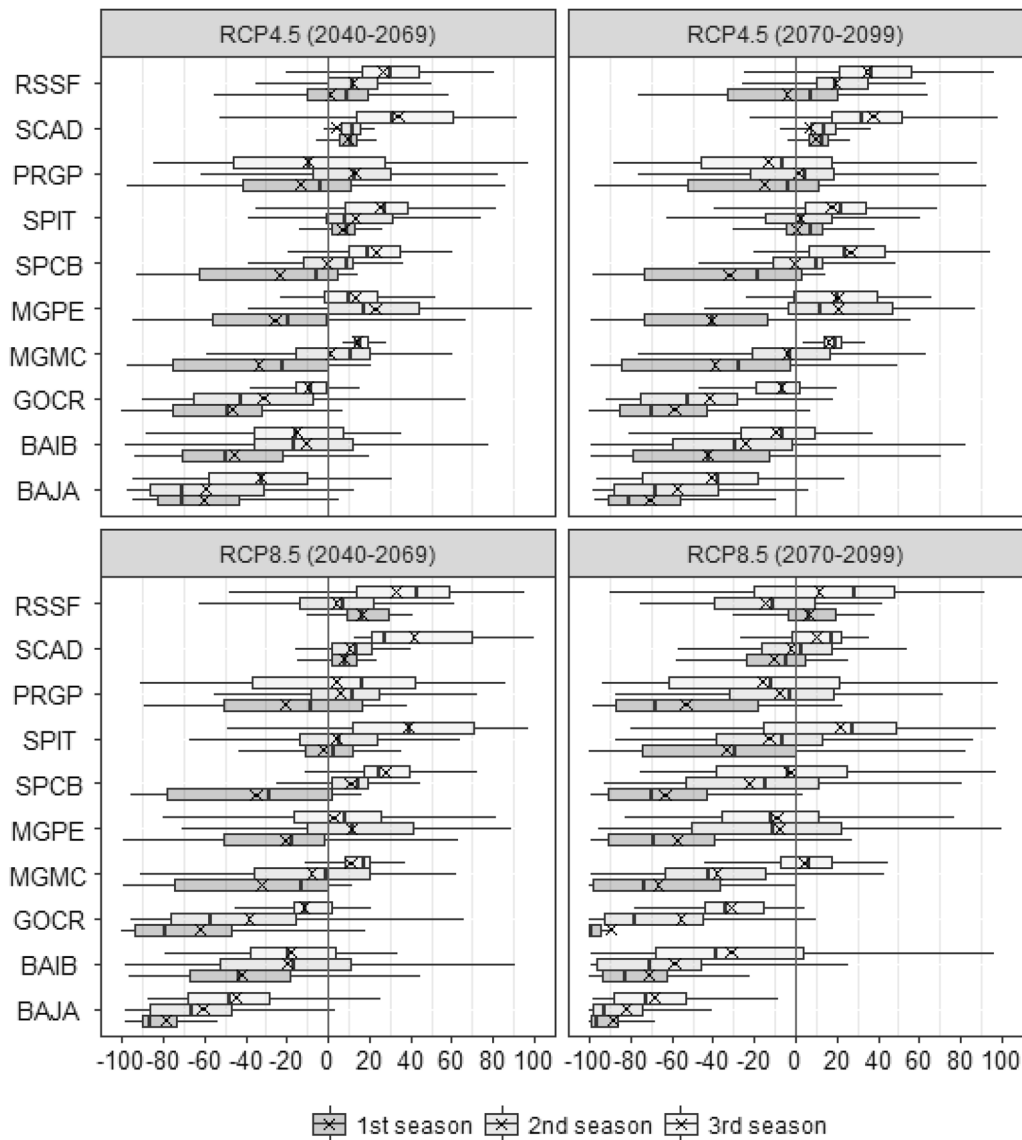 classes: cold/wet (CW), cold/dry (CD), middle (MI), hot/wet (HW) and hot/dry (HD), under intermediate (RCP4.5) and high (RCP8.5) emission scenarios at mid- (2040–2069) and end-of-century (2070–2099) periods. Boxes denote the lower (25%) to upper quartile (75%) values, with median and mean yield values indicated by a line and a cross inside the box, respectively

that Brazilian regions submitted to higher temperatures and increasing drought conditions in the future will present an offset of the expected positive effect of increased atmospheric CO_2 concentration on potato tuber yield.

The simulated potato yield changes reported in the present study refer to future expected impacts under current nitrogen management and under water limited conditions. Therefore, they do not represent the potential yield that could be obtained if nitrogen and water or irrigation were considered as unlimited. Similar results of negative impacts of climate change on potato yield were also presented for other regions around the world, with reductions of 11–31% in Iran (Adavi et al. 2018), 38.6% in Bangladesh (Rahman et al. 2018), and 50% in U.S. (Resop et al. 2016). As

reported by Adavi et al. (2018) and Rahman et al. (2018), reduced potato yields are related to temperature increase that accelerate physiological maturity, reflecting in reduced growing season length, maximum leaf area index, days to tuber initiation and days to harvest.

According to our results, the mean potato yield changes will depend on the region and growing season, which are similar to results found by Massetti et al. (2013) for other crops of Brazilian agriculture, with only the South and in some parts of Southeast regions being expected to be favored by climate change. Comparable model simulations of regional climate change impacts on potato yield have been performed at the global level by Hijmans (2003) and Raymundo et al. (2017b). By assessing these studies, changes

Fig. 8 Local percentage of tuber yield changes in relation to the base-line (1980–2009) for 1st, 2nd and 3rd potato growing seasons based on 30-year simulations averaged over five future climate classes, under intermediate (RCP4.5) and high (RCP8.5) emission scenarios at mid- (2040–2069) and end-of-century (2070–2099) periods. Boxes denote the lower (25%) to upper quartile (75%) values, with median and mean yield values indicated by a line and a cross inside the box, respectively. The locations refers to: São Francisco de Paula, RS (RSSF); Água Doce, SC (SCAD); Guarapuava, PR (PRGP); Itapeva, SP (SPIT); Casa Branca, SP (SPCB); Perdizes, MG (MGPE); Montes Claros, MG (MGMC); Cristalina, GO (GOCR); Ibicoara, BA (BAIB); Jacobina, BA (BAJA)

in potato yield in mid and high latitudes were small, or even positive, while at lower latitudes, global warming will have strong negative effects on tuber yield, as also observed in the present study. Such negative impacts over low latitude areas are mainly related to water deficit and by the heat stress, expressed by the upper critical temperature threshold for tuber initiation (TC), since temperatures above TC reduce or inhibit tuber induction.

Considering that the Brazilian potato areas that will be negatively affected by future climate scenarios, like those located in the northernmost part of the studied region, will have yields mainly affected by extremely high temperature, which will reduce crop cycle and tuber induction, and by water deficit, causing reduction in the photosynthesis rates, some strategies could be considered to mitigate such impacts. Among these strategies, crop breeding, to develop new cultivars more tolerant to higher temperatures (Adhikari et al. 2015), and irrigation will be among the major ones. Considering crop breeding, crop simulation models can also be extremely useful, since they help researcher to identify

the main crop traits that can be managed to improve yields under changing climates, as recently presented by Elli et al. (2020b). These authors, identified through a mechanistic crop model for *Eucalyptus* that some traits related to plant architecture, leaf area distribution, leaf partitioning, radiation use efficiency and cardinal temperatures for photosynthesis are among the most important ones to face climate change challenges. Even considering the huge differences between potato and *Eucalyptus*, this kind of physiological approach should also be tested for other crops, including potato, which is the purpose of new coming studies.

Conclusions

The results from five GCMs temperature and rainfall projections (CW, CD, MI, HW, and HD) for 2040–2069 and 2070–2099 periods, under RCP4.5 and RCP8.5 emission scenarios, indicates warmer conditions, with temperatures increasing from 1.6 °C, from a more optimistic scenario, to 3.8 °C, in a worst scenario. Despite the great uncertainty, rainfall will have a regional pattern of change, with an increase in Southern Brazil and a decrease in the north.

The DSSAT-SUBSTOR-Potato model showed to be suitable for simulating potato yield for Brazilian cultivars, without requiring additional calibration. By using projected future scenarios, the yield simulations indicated that climate change will affect potato yield in Brazil and it will depend on the region and growing season. Potato areas in the South region and in part of Southeast may benefit from future warmer and wetter conditions, mainly for the 3rd growing season. However, strong negative impacts on tuber yield are expected in Midwest and Northeast regions, mainly in the 1st growing season.

Smaller potato tuber yield impacts will occur in the more optimistic scenario, while largest impacts will occur under RCP8.5 in the end of the century. The regional yield responses to climate change suggest that strategies to mitigate potato yield losses will be required at local/regional level. Therefore, new studies should be conducted with this purpose, which can benefit from the results presented here, giving emphasis to the variability found between producing locations and growing seasons.

Compliance with Ethical Standards

Conflict of interest The authors declare that there is no conflict of interest regarding the publication of this article.

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