Agricultural Systems 160 (2018) 44–59

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Climate impacts on crop yields in Central Argentina. Adaptation strategies

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ABSTRACT

The Pampas is among the major agricultural regions in the world; a large proportion of Argentina crop production is originated in this region. The exportation of grain and oil crop represents more than 40% of the total national exportations.

Impact of future climate on wheat, maize and soybean yield and crop adaptation in the Pampas region (60 million hectares) are assessed using climatic inputs generated by CCSM4 climate model (National Center for Atmospheric Research, US). Projections show an increase in the seasonal means maximum and minimum temperature for both the near (2015–2039) and the far (2075–2099) future, as well as a seasonal annual precipitation increase in the near future and a significant increase in the far future with extreme emissions scenarios.

In the near future the crop model projects a reduction in wheat yield, an increase in maize yield and a significant increment in soybean yield compared to the regional baseline for moderate (RCP4.5) and extreme (RCP8.5) emissions. In the far future the projection shows a decrease in wheat yield in the RCP4.5 scenario and an increase in the RCP8.5 scenario, maize and soybean shown a yield increase in both scenarios. Adaptation strategies for the near and far future are proposed for wheat and maize that result in up to 45% yield increases. Adaptation strategies are not proposed for soybean because yield increases were predicted in all scenarios and horizons.

1. Introduction

Climate change is one of the most studied topics in the last decades due to its socio-economic, environmental and biological implications (IPCC, 2014, 2015). As yield is strongly controlled by weather and climate it is highly vulnerable to climate change. Thus, climate is one of the main risk factors involved in agricultural production. Previous studies have shown that Southeast South America (Argentina, Uruguay and southern Brazil), is one of the regions of the world where major changes in climate occurred during the last 30 years. Climate has a high rate of change in the Argentinean Pampas region where the interannual climatic variability together with the interdecadal variability explain more than 80% of the total climatic variance (the variability associated with anthropogenic climate change is around 15%). The increased rainfall recorded in the Pampas region led to yield increases of rainfed crops in the order of 38% for soybean, 18% maize, 13% wheat and 12% in sunflower (Magrin et al., 2005) and contributed to the expansion of the agricultural frontier to areas considered semi-arid (Ar-2 CN, 2006) with the consequent increase in the area planted with annual crops. Therefore, there is a need to assess and quantify the impact of climate change on the agricultural production as well as design strategies for adaptation to future climate scenarios.

2. Characterization of the study area

The study area includes the provinces of Entre Rios, Santa Fe, Cordoba, Buenos Aires and La Pampa where the biggest production of maize, wheat, sorghum, soybean and sunflower is concentrated. In the last 50 years, this region had important changes in production systems. In the 70's, agricultural land use intensified and soybean was adopted as a minor component at first, and then used as the main component in crop rotations (Viglizzo et al., 2001). Today this crop accounts more than 70% of the area under agriculture.

In the early '90s no-till and the adoption of glyphosate-tolerant

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http://dx.doi.org/10.1016/j.agsy.2017.08.007
Received 26 January 2017; Received in revised form 23 August 2017; Accepted 27 August 2017

soybean varieties marked the beginning of a system that over the years became an extensive monoculture. Since the 70's soybean planted area has gradually increased to almost 20 million hectares in the last seasons (Giancola et al., 2009).

The changes in production system were associated with changes on some climatic parameters. In the Pampas region spring and summer rains increased about 10% since the 60's and 70's. According to 3CN, mean temperature in the "Húmeda" region increased between 0.5 and 1 ºC during the period 1960 - 2010. Meanwhile in the "Central" region the mean temperature increase was less than 0.5 degrees centigrade. Coincidentally Nuñez et al. (2008) pointed out that the increase in the minimum temperature was 0.1 to 0.3 degrees centigrade per decade, while the maximum temperature increased by less than 0.1 ºC per decade (even reduced in some areas).

Alvarez et al. (2014b) showed the evolution of the major crops harvested area and yields in the Pampas region for the period 1961 to 2011. Maize planting area does not show a significant variation, with peaks of maximum area in the mid 80's and late 90's. This temporal variability coincides with wheat planting area, but with higher peaks for those decades compared to the other years. Soybeans shows a very high rate of increase in harvested area from the 80's until the early 90's (close to 900,000 ha yr^{-1}) and then a sustained growth of nearly 600,000 ha yr^{-1} up to 2014–2015 season. Associated with soybean expansion there are two major issues: a) soybean mono-culture does not allow a crop rotation that ensures system sustainability. Several reasons could explain this monoculture, for instance, the competition for land use, the lower cost of planting and the easier soybean agro management compared with maize. b) In the last crop seasons around 20% of soybean crop was planted on marginal and fragile soils, which may not withstand too long the negative balances of nitrogen that soybean produces.

3. Data and methodology

Informatics tools using simulation techniques were developed in recent decades to assess the response of growth, development, and yield to climatic factors or management system. Among these tools DSSAT suites (Decision Support System for Agro-technology Transfer) (Jones et al., 2003; Hoogenboom et al., 2015), STICS (Brisson et al., 2003) and CropSyst (Stöckle et al., 2003) stand out mainly for their acceptance and local diffusion. These models have been widely used in our region for climate risk assessment (Baethgen et al., 2009; Magrin et al., 1999; Travasso and Magrin, 1998), production assessment (Roel and Baethgen, 2007; Savin et al., 1995; Travasso and Magrin, 1998, 2001; Meira and Guevara, 1995) and assessment of impacts of climate change (Travasso et al., 2006; Baethgen and Magrin, 1995; Magrin et al., 1998, 2007, 2009).

For the evaluation of the impact of climate change on crops of major economic importance, simulation models included in DSSAT like CERES-Wheat (Ritchie and Otter, 1985), CERES-Maize (Jones and Kiniry, 1986) and CROPGRO (Boote et al., 1998) were used for wheat, maize and soybean respectively. DSSAT is one of 31 recommended tools in United Nations Framework Convention on Climate Change (UNF„CCC, 2005) to assess impacts, vulnerability and adaptation to climate change.

Crop models for wheat, maize, soybean were calibrated and validated during 1991 to 1994 farming seasons, in eight environments (Fig. 1), without water or nutritional limitation (Calibration) and under different management conditions (Validation) like initial conditions of water and nitrogen, nitrogen fertilization, rainfed and under different condition of irrigation sheets, dates of planting, among others.

Fig. 1a and 1b shows the comparison between simulated and observed values on experimental plots for wheat (1a) with an NRMSE of 8%, as well as adjustments for different crops from experimental data in Uruguay, Brazil and Argentina (1b).

Fig. 1c and 1d shows the adjustment between simulated and observed values on farm fields, showing NRMSE values of 10% and 10.9% for wheat and soybean respectively (1c), while for the maize crop was 7.8% (1d).

Finally, considering "the higher the signal / noise ratio, more reliable the climate projection" and admitting a degree of uncertainty in the near future regarding rainfall predictions, it is important to design some strategies that allow reducing the negative impact of climate change on crops, or at least reduce the impact in the near future.

3.1. Climate

The simulation of growth, development, and yield of wheat, maize and soybean was made for the present time (1980–2010) and for climate projections for two periods, one in near future (2015–2039) and another in a far future (2075–2099). Two Representative Concentration Pathways (RCP) as emission scenarios of greenhouse gases were used, a moderate emissions scenario (RCP4.5) and a higher emissions scenario (RCP8.5).

The climate inputs were generated from the CCSM4 (Community Climate System Model 4) climate model of National Centre for Atmospheric Research (NCAR, USA), because it was regarded as the best model among 24 climate models from CMIP5 (Coupled Model Intercomparison Project 5) and CLARIS-LPB (A Europe-South America Network for Climate Change Issues and Impacts Assessment – La Plata Basin Project), assessed for the present time in the region after a quantile-mapping bias correction using CRU (Climate Research Unit) observations. A comprehensive evaluation index has been defined by averaging temperature and precipitation indices in each of the regions studied during the Argentina National Communication of Climate Change (3CN, 2014). This index is the single index model validation (IUVM), which varies between 0 and 1, where values close to 0 are indicators of poor performance, while the greater the ability of the model to represent the observed climate, IUVM approaches 1. The Table 1 represents the values of the IUVM for each studied region and each model analyzed in the 3CN. As shown in Table 1 the weighted IUVM for "Centro" and "Húmeda" region (our area of interest) is the highest for CCSM4.

The climate database at Centro de Investigaciones del Mar y la Atmosfera (CIMA) (http://3cn.cima.fcen.uba.ar) was used. Data corresponding to the CCSM4 model for the historical (1980–2010), near future (2015–2039) and far future (2075–2099) for the two scenarios (RCP4.5, RCP8.5) in the study area was arranged to be used with the computational platform CASANDRA (Rolla et al., 2016). Table 2, shows the prediction space of the 8 top models at Table 1. The values are monthly mean changes of maximum and minimum temperature and precipitation in the growing period of crops (spring-summer). It is possible to observe that the model CCSM4 is in the middle of the models prediction space.

3.2. Computational platform (CASANDRA)

Calibrated and validated crop models are normally used to estimate yield, among other important variables such as phenology, dry matter, LAI (Leaf Area Index), soil water content, soil and water management, as well as to evaluate different climate or management scenarios at a particular site. In our case, the geospatial web platform CASANDRA was used to simplify the computations and solve the spatial scale problem using the site specific crop models with climate scenarios, crop management and initial conditions at regional level. In this way it was possible to visualize maps of impacts at both spatial and temporal level, and also to evaluate different regional adaptation strategies.

3.3. Regions

The sub-regions for these simulations correspond to the current Delegations of the Ministry of Agriculture and Livestock of Argentina

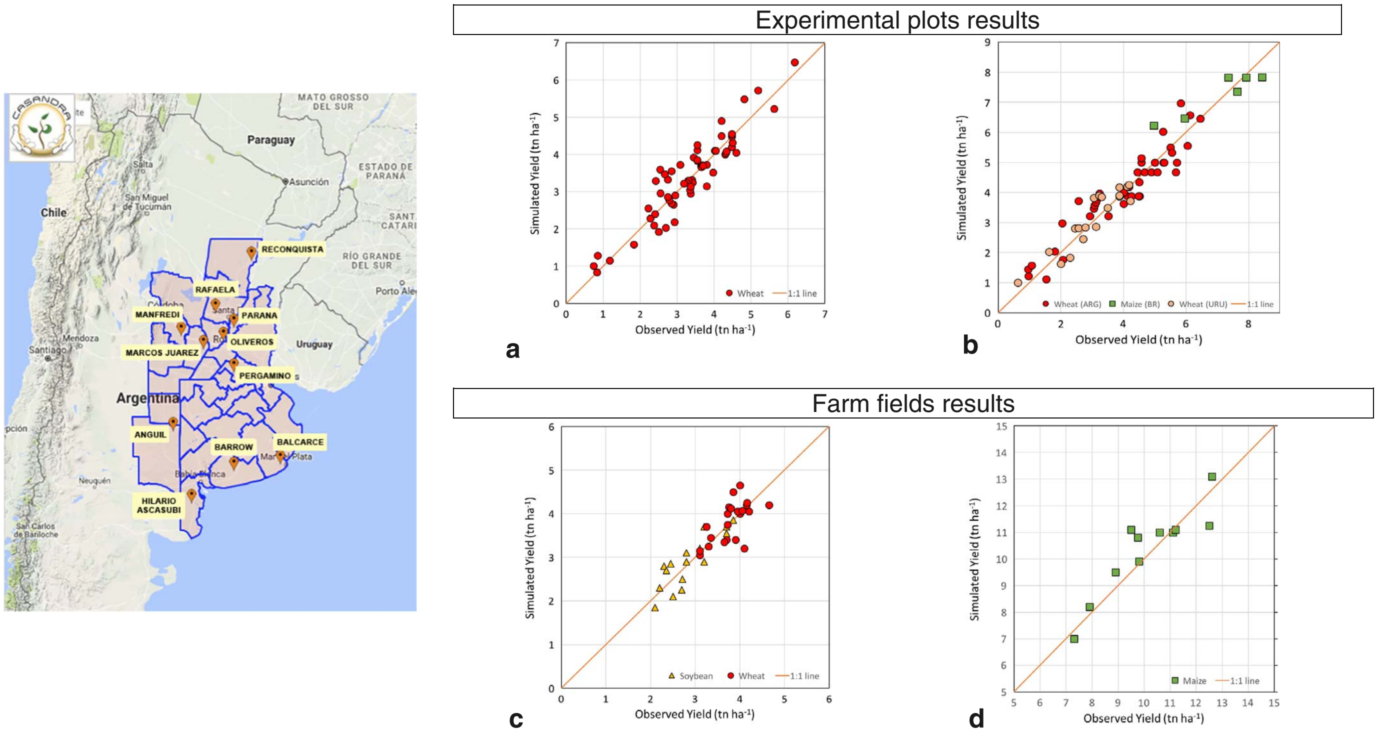

Fig. 1. Region and locations where crop models for wheat, maize and soybean were calibrated and validated.

(MINAGRI) (Fig. 2). The choice of this zoning is based on the criteria of homogeneity of agro-climatic, logistics and crop management.

3.4. Soil

The soil data belong to the Argentine scale 1:500000 soil map, provided by Argentina National Institute of Agricultural Technology (INTA). Each soil series has been differentiated into five production levels from the "0" level indicating the inability for agricultural production, up to level "4" indicating the probable maximum production according to this environmental-productive factor.

Production rates were originated from the classification in terms of potential capability and limitation of soil productivity closely related with climate variability; they contribute to characterize the variability

Table 1
Single index model validation (IUVM). Classified descendent by IUVM weighted.

Models	Regions				IUVM mean	IUVM stddev	IUVM weighted	Ranking
	Patagonia	Andes	Centro	Húmeda				
CCSM4	0.36	0.51	0.56	0.91	0.59	0.23	0.81	1
MRI/JMA	0.48	0.54	0.57	0.88	0.62	0.18	0.79	2
NorESM1-M	0.45	0.51	0.56	0.62	0.54	0.07	0.60	3
CNRM-CM5	0.35	0.15	0.9	0.47	0.47	0.32	0.60	4
MPI-ESM-LR	0.31	0.52	0.6	0.55	0.5	0.13	0.57	5
MRI-CGCM3	0.51	0.51	0.7	0.49	0.55	0.10	0.55	6
IPSL-CM5A-MR	0.22	0.93	0.48	0.53	0.54	0.29	0.52	7
HadGEM2-CC	0.43	0.47	0.36	0.57	0.46	0.09	0.51	8
RegCM3-HadCM3	0.14	0.21	0.48	0.48	0.33	0.18	0.48	9
CSIRO-Mk3-6-0	0.52	0.46	0.71	0.38	0.52	0.14	0.48	10
LMDZ-IPSL	0.15	0.19	0.66	0.34	0.34	0.23	0.44	11
LMDZ-ECHAM5	0.28	0.5	0.42	0.42	0.41	0.09	0.42	12
GFDL-ESM2G	0.52	0.3	0.63	0.31	0.44	0.16	0.41	13
RCA-ECHAM5-3	0.48	0.17	0.4	0.4	0.36	0.13	0.40	14
RCA-ECHAM5-2	0.47	0.17	0.4	0.4	0.36	0.13	0.40	15
HadGEM2-ES	0.44	0.43	0.49	0.32	0.42	0.07	0.37	16
MRI/JMA	0.24	0.37	0.23	0.43	0.32	0.10	0.37	17
RCA-ECHAM5-1	0.3	0.14	0.36	0.34	0.29	0.10	0.35	18
REMO_ECHAM5	0.66	0.4	0.36	0.3	0.43	0.16	0.32	19
RegCM3-ECHAM5	0.19	0.37	0.26	0.25	0.27	0.07	0.25	20
PROMES-HadCM3	0.51	0.47	0.34	0.16	0.37	0.16	0.21	21
INMCM4	0.37	0.37	0.23	0.14	0.28	0.11	0.17	22
MIROC5	0.35	0.2	0.3	0.11	0.24	0.11	0.17	23
MM5-HadCM3	0.58	0.31	0.12	0.12	0.28	0.22	0.12	24

Table 2
Prediction space of climate models used, for monthly means changes in spring-summer period.

Models	Minimum temperature (°C)				Maximum temperature (°C)				Precipitation (%)			
	Near future		Far future		Near future		Far future		Near future		Far future	
	rcp4.5	rcp8.5	rcp4.5	rcp8.5	rcp4.5	rcp8.5	rcp4.5	rcp8.5	rcp4.5	rcp8.5	rcp4.5	rcp8.5
CCSM4	0.6	0.8	1.3	2.8	0.7	0.8	1.5	3.1	8	10	8	18
CNRM-CM5	0.7	0.9	2.0	3.4	0.3	0.4	1.9	2.9	10	18	7	18
CSIRO-Mk3-6-0	0.8	0.7	2.0	3.4	0.7	0.7	1.9	3.1	2	0	15	10
GFDL-ESM2G	0.6	0.4	0.3	1.8	0.9	0.6	1.0	2.5	0	10	10	9
IPSL-CM5A-MR	1.0	1.1	2.1	4.7	0.8	0.7	2.1	4.0	8	0	0	− 10
MPI-ESM-LR	0.6	0.8	1.8	3.3	0.5	0.7	1.9	3.0	7	0	− 5	10
MRI-CGCM3	0.4	0.5	1.0	4.0	0.2	0.2	0.5	0.0	15	2	18	19
NorESM1-M	0.5	0.4	1.0	2.3	0.7	0.5	1.0	2.5	1	3	10	10

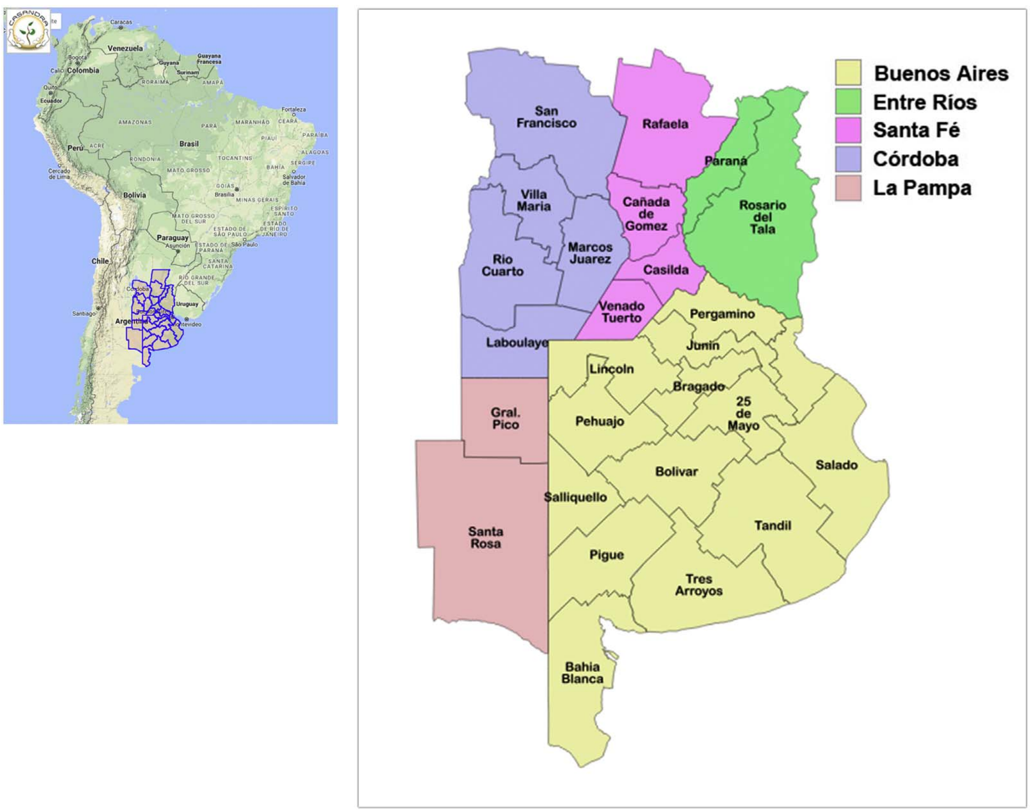

Fig. 2. Delegations of the Ministry of Agriculture and Livestock of Argentina (MINAGRI). Provinces are in colors.

in the regions studied and the interaction with crops, their genetic and management. Fig. 3 shows the soil types and the characterization of their productivity index.

3.5. Cultivars

The varieties and hybrids that were used for simulations of wheat, soybeans and maize, represent widely available genetic materials in high percentages of the planted areas. They were also considered according to their production capacity, plasticity, environmental adaptation and their stability demonstrated across different growing seasons in the last decade. In the case of soybeans, the selection of different varieties, corresponds to the response of cultivars of different Maturity Group associated with an approximate strip from north to south with changes in day length and in the extreme and average temperatures.

3.6. Management

Management variables considered are related to each Delegations of MINAGRI Table 3, 4 and 5 shows for wheat, maize and soybean current management and initial conditions per district.

3.6.1. Initial available water and nitrogen

Most likely values for this variable at planting date, based on climate history of soil water availability were taken. In the case of nitrogen, the most probable values were obtained through surveys of values available from different regional laboratories with samples taken in several trials which represented the spatial and temporal variability.

3.6.2. Planting date

The most common date for each crop in the study regions was selected. Following a criterion of intermediate values within the more likely planting date window for each delegation or group of delegations of MINAGRI according to matching of latitudinal strips (soybean) or to differential management according to initial water availability and probability of escape of the most common seasonal drought (maize), considering the variability of planting windows in the case of intermediate-long or intermediate cultivars (wheat).

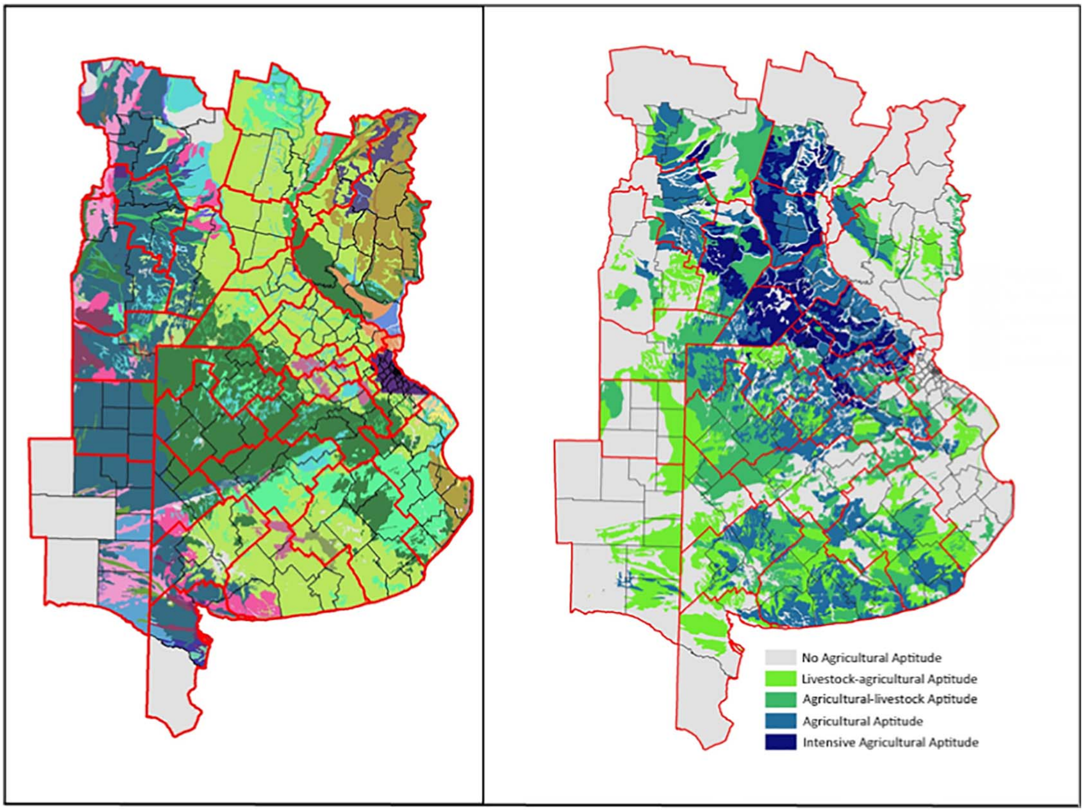

Fig. 3. Areas with different soil types (left) and characterization of its productivity index (right).

Table 3
Wheat, current management practices and initial condition.

District	Wheat							
	Planting date (DOY)	Initial water content (%)	Initial Nitrogen (ppm)	Plant density (pl m^{-2})	Row space (m)	Nitrogen applied (kg ha^{-1})	Date applied (DOY)	Water management
Rafaela	160	75	8.6	300	0.18	70	160	Rainfed
San Francisco	160	75	7.7	300	0.18	70	160	Rainfed
Rosario del Tala	166	90	7.3	300	0.18	55	166	Rainfed
Paraná	160	75	8.8	300	0.18	70	160	Rainfed
Villa María	150	85	7.2	300	0.18	70	150	Rainfed
Cañada de Gómez	160	75	10.2	300	0.18	70	160	Rainfed
Río Cuarto	150	85	8.2	300	0.18	70	150	Rainfed
Marcos Juárez	160	75	8.6	300	0.18	70	160	Rainfed
Casilda	160	90	8.1	300	0.18	70	160	Rainfed
Pergamino	166	90	13.7	300	0.18	55	166	Rainfed
Venado Tuerto	160	90	11.7	300	0.18	70	160	Rainfed
Laboulaye	150	85	7.2	300	0.18	70	150	Rainfed
Junín	166	90	8.2	300	0.18	55	166	Rainfed
Lincoln	150	85	7.3	300	0.18	70	150	Rainfed
Bragado	166	90	8.6	300	0.18	55	166	Rainfed
Pehuajó	150	85	7.3	300	0.18	70	150	Rainfed
25 de Mayo	166	90	7.2	300	0.18	55	166	Rainfed
General Pico	150	85	6.5	300	0.18	70	150	Rainfed
Bolívar	191	80	6.7	300	0.18	70	191	Rainfed
Saliquelló	150	85	6.5	300	0.18	70	150	Rainfed
Santa Rosa	150	85	6.1	300	0.18	70	150	Rainfed
Tandil	191	90	9.4	300	0.18	55	191	Rainfed
Pigüé	191	80	7.5	300	0.18	60	191	Rainfed
Tres Arroyos	150	85	6.8	300	0.18	70	150	Rainfed
Bahía Blanca	191	80	5.0	300	0.18	60	191	Rainfed
Salado	191	90	9.4	300	0.18	55	191	Rainfed

Table 4
Maize, current management practices and initial condition.

District	Maize							
	Planting date (DOY)	Initial water content (%)	Initial Nitrogen (ppm)	Plant density (pl m^{-2})	Row space (m)	Nitrogen applied (kg ha^{-1})	Date applied (DOY)	Water management
Rafaela	263	70	12	7.5	0.52	122	263	Rainfed
San Francisco	263	60	11	7.5	0.52	122	263	Rainfed
Rosario del Tala	273	70	11	7.5	0.52	122	273	Rainfed
Paraná	263	80	13	7.5	0.52	122	263	Rainfed
Villa María	273	70	10	7.5	0.52	112	273	Rainfed
Cañada de Gómez	273	80	15	7.5	0.52	122	273	Rainfed
Río Cuarto	273	70	12	7.5	0.52	112	273	Rainfed
Marcos Juárez	273	80	12	7.5	0.52	152	273	Rainfed
Casilda	283	70	12	7.5	0.52	112	283	Rainfed
Pergamino	283	80	20	7.5	0.52	92	283	Rainfed
Venado Tuerto	283	80	17	7.5	0.52	92	283	Rainfed
Laboulaye	283	60	10	7.5	0.52	92	283	Rainfed
Junín	288	90	12	7.5	0.52	112	288	Rainfed
Lincoln	288	90	11	7.5	0.52	112	288	Rainfed
Bragado	283	70	12	7.5	0.52	112	283	Rainfed
Pehuajó	288	60	11	7.5	0.52	92	288	Rainfed
25 de Mayo	288	60	10	7.5	0.52	112	288	Rainfed
General Pico	288	60	9	7.5	0.52	92	288	Rainfed
Bolívar	298	60	10	7.5	0.52	92	298	Rainfed
Saliquelló	298	60	9	7.5	0.52	92	298	Rainfed
Santa Rosa	298	60	9	7.5	0.52	92	298	Rainfed
Tandil	303	70	14	7.5	0.52	112	303	Rainfed
Pigüé	303	60	11	7.5	0.52	92	303	Rainfed
Tres Arroyos	303	60	10	7.5	0.52	92	303	Rainfed
Bahía Blanca	303	50	7	7.5	0.52	72	303	Rainfed
Salado	303	70	14	7.5	0.52	112	303	Rainfed

Table 5
Soybean, current management practices and initial conditions.

District	Soybean						
	Planting date (DOY)	Initial water content (%)	Initial Nitrogen (ppm)	Plant density (pl m^{-2})	Row space (m)	Nitrogen applied (kg ha^{-1})	Water management
Rafaela	288	70	12.3	30	0.52	0	Rainfed
San Francisco	288	60	11	30	0.52	0	Rainfed
Rosario del Tala	288	70	10.5	30	0.52	0	Rainfed
Paraná	288	80	12.5	30	0.52	0	Rainfed
Villa María	288	70	10.3	30	0.52	0	Rainfed
Cañada de Gómez	288	80	14.6	30	0.52	0	Rainfed
Río Cuarto	298	70	11.7	30	0.52	0	Rainfed
Marcos Juárez	298	80	12.3	30	0.52	0	Rainfed
Casilda	298	70	11.5	30	0.52	0	Rainfed
Pergamino	298	80	16.7	30	0.52	0	Rainfed
Venado Tuerto	298	80	16.7	30	0.52	0	Rainfed
Laboulaye	308	60	10.3	30	0.52	0	Rainfed
Junín	308	70	11.7	30	0.52	0	Rainfed
Lincoln	308	60	10.5	30	0.52	0	Rainfed
Bragado	318	70	12.3	30	0.52	0	Rainfed
Pehuajó	318	60	10.5	30	0.52	0	Rainfed
25 de Mayo	318	60	10.3	30	0.52	0	Rainfed
General Pico	318	60	9.3	30	0.52	0	Rainfed
Bolívar	328	60	9.5	30	0.52	0	Rainfed
Saliquelló	328	60	9.3	30	0.52	0	Rainfed
Santa Rosa	343	60	8.7	30	0.52	0	Rainfed
Tandil	343	70	13.5	30	0.52	0	Rainfed
Pigüé	343	60	10.7	30	0.52	0	Rainfed
Tres Arroyos	343	60	9.7	30	0.52	0	Rainfed
Bahía Blanca	343	50	7.1	30	0.52	0	Rainfed
Salado	343	70	13.5	30	0.52	0	Rainfed

3.6.3. Plant population

The most frequent value of plant density per unit area was used.

3.6.4. Fertilization

We consider the fertilization date and rate as well as the possibility of splitting the rate in more than one time during the cycle, and complementing fertilization at planting date. Rates were adjusted according to the maximum expected productivity in each area, or production subregion, as well as according to the probability of occurrence of rainfall during the cycle, and emphasizing the crop conditions, which are more

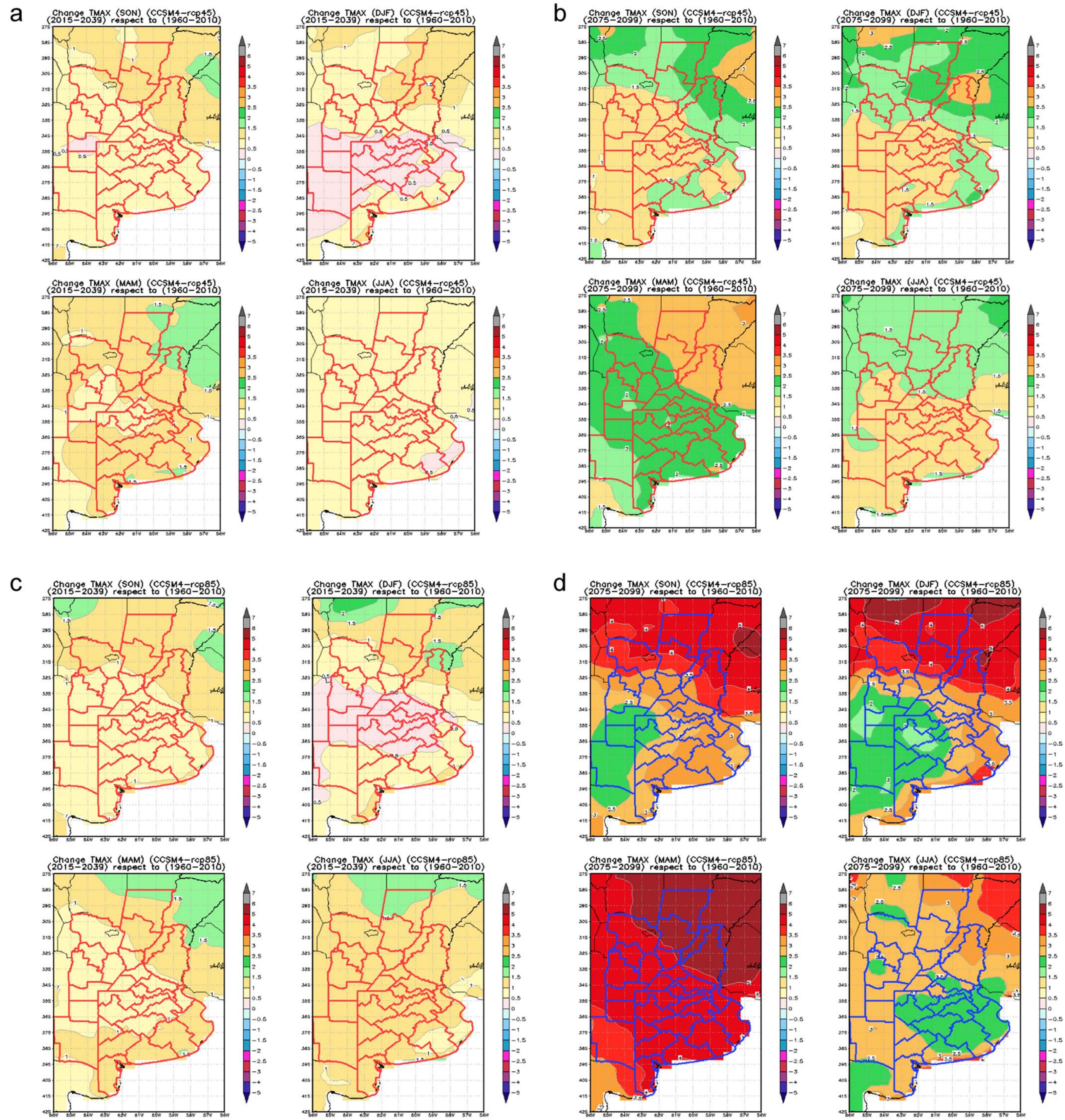

Fig. 4. a. Expected changes in mean seasonal maximum temperature, RCP 4.5. Near future. b. Expected changes in mean seasonal maximum temperature, RCP 4.5. Far future. c. Expected changes in mean seasonal maximum temperature, RCP 8.5. Near future. d. Expected changes in mean seasonal maximum temperature, RCP 8.5. Far future.

sensitive to a water deficit. In the case of soybeans, no nitrogen applications were made, although the process of symbiosis, described within the CROPGRO model was considered.

3.6.5. Irrigation

Simulations for present, near and far future periods, with different emission levels, have been done in rainfed conditions, without irrigation.

4. Results and discussion

4.1. Changes in mean climate

Changes in the 25-year seasonal mean climate are analyzed in this section, Seasonal mean and not annual mean is analyzed because of the importance of seasonal climate values for crops.

4.1.1. Seasonal mean maximum temperatures

Fig. 4a to 4d show the expected changes in the seasonal mean maximum temperature in the region of study for the near future (2015–2039) and far future (2075–2099) and for two scenarios, one scenario of moderate emissions (RCP4.5) and one of higher emissions (RCP8.5). For each scenario changes in temperatures are estimated for spring (SON), summer (DJF), fall (MAM) and winter (JJA). Fig. 4a and b corresponds to the lower emissions scenario (RCP4.5), for the near future and far future, respectively. The major changes in the near future and moderate emissions scenario are observed during spring and fall in the north of the region, varying between 0.5 °C and 1.5 °C. However, the changes are not significant throughout the four seasons (varying between 0.5 °C and 1.5 °C). For the far future and lower emissions (Fig. 4b) the major changes are expected during the fall with increases of 2.0 °C to 2.5 °C in most of the region.

Data for spring, summer, fall and winter for the higher emission scenario (RCP8.5) future are shown in Fig. 4c (near future) and 4d (far future). The major changes for the near future in the higher-emission scenario are observed in winter, in the north of the region, varying between 1.0 °C and 1.5 °C. These changes are not significant throughout the four seasons, varying between 0.5 °C and 2.0 °C in the North of the region. Minor changes are observed during summer, with values lower than 0.5 °C in the Core Zone (an area with higher crop yield). In the near future the increased seasonal average maximum temperature is not dependent on the emission scenario.

Strong changes in the four seasons are expected in the far future with the higher emission scenario. Fig. 4d shows changes in the seasonal maximum mean temperature exceeding 6.0 °C towards the northeast of the study area during the fall. Minor changes are projected for winter, while for summer and spring the projected changes are higher than 2.5 °C.

4.1.2. Seasonal mean minimum temperatures

Projected changes in the seasonal mean minimum temperature in the region of study are shown in Fig. 5a to 5d for the near future (2015–2039) and far future (2075–2099) and for two scenarios, one scenario of moderate emissions (RCP4 0.5) and other of higher emissions (RCP8.5). For each scenario changes in temperatures are estimated for spring (SON), summer (DJF), fall (MAM) and winter (JJA). Fig. 5a and 5b corresponds to the lower emissions scenario (RCP4.5), for the near and far future, respectively.

The major changes for the near future in the moderate emission scenario (Fig. 5a) are observed in fall, in the north of the region, varying between 0.5 °C and 1.5°. It is important to note that the minimum temperature are predicted to decrease in winter, almost throughout the study region with decreases up to − 0.5 °C. This is also observed for the far future scenario - higher emissions, with temperature decreases up to − 1.5 °C in winter. In this scenario the major variations of the minimum temperature are projected in fall, with increases up to 2.5 °C toward the northeast of the study region.

Data for the higher emission scenario of (RCP8.5) for spring, summer, fall and winter are shown in Fig. 5c for the near future and in Fig. 5d for the far future. The minimum temperatures decrease during winter in both the near (Fig. 5c) and the far future (Fig. 5d). The projected changes are up to − 2.5 °C toward the Northeast of the study region. The major changes for the far future and higher-emissions scenario are expected during fall, with values up to 4.5 °C towards the northeast of the study region.

4.1.3. Seasonal mean precipitation

Fig. 6a to 6d show the projected changes in seasonal mean precipitation for the near future (2015–2039) and far future (2075–2099) and for two scenarios, one with moderate emissions (RCP4.5) and another with higher emissions (RCP8.5). For each scenario changes in the precipitation for spring (SON), summer (DJF), autumn (MAM) and winter (JJA) are estimated.

Fig. 6a and 6b show the projected changes in precipitation for the lower emission scenario (RCP4.5) in the near and far future, respectively. The major changes for the near future and lower emissions are projected during summer and winter, with up to 40% increase in precipitation in summer and up to 30% decrease precipitation in winter on the west of the study region.

The decrease in winter precipitation is consistent with the decrease in the minimum temperature (Fig. 5a and 5b), which is associated with less cloud cover and loss of terrestrial energy. It is important to note that the lower minimum temperatures are not a result of a radiation loss due to lack of cloud cover only, but also it can be related to mechanisms such as cold air advection like polar air masses. Results for the far future (Fig. 6b) are like those of the near future but with higher values. The precipitation decrease in winter is lower than in the near future, meanwhile during summer the changes in precipitation are up to 60% higher, in the middle of the study region. A marked decrease in summer rainfall in the center of the study area is projected for the near and the far future, being more noticeable in the near future.

Again, the major changes in the near and far future for the higher emission scenario occur in summer and winter. In the near future, up to a 50% increase in summer precipitation and up to a 30% decrease in winter are projected towards the West of the study region (Fig. 6c and 6d). In the near future there is a projected decrease in rainfall (up 20%) during fall, while changes in precipitation in both the near and the far future are notably positive (up 60%) during summer in the higher emissions scenario. In the far future decreases in precipitation are projected only over the north of the study area.

4.2. Impacts on crop yields

4.2.1. Baseline (present time)

Wheat, maize and soybeans yield are expressed as grain weight in kg dry matter ha^{-1}.

Wheat yields range from 500 kg ha^{-1} to 5000 kg ha^{-1}, with a regional average of 2617 kg ha^{-1}, reaching the lowest values in a western corridor stretching from Cordoba province to the south of La Pampa province, and the highest in the central grain belt – (North of Buenos Aires and Santa Fe, South and Southeast of Buenos Aires province (Fig. 7.1). The productivity values exceeding 2900 kg ha^{-1} (National average yield of the last 10 years), represent 66% of the total area of the wheat region, and are located mainly in Buenos Aires province and Southern Santa Fe province. This variability follows the productive capacity of soils, in interaction with water availability and seasonal variability.

The average regional maize yield for the 1980–2010 period is 6594 kg ha^{-1}, with the minimum yields (less than 4000 kg ha^{-1}) occur in the southwest of Buenos Aires and south of La Pampa provinces. Yields above the national historic average of the past 10 years (7600 kg ha^{-1}) are found in the core area (southeast of Buenos Aires and south-central Santa Fe province and some environments in the Center-East of Cordoba province) (Fig. 8.1) and represent about 40% of the planted area with maximum values higher than 11,000 kg ha^{-1}.

Soybean shows an average yield for the 1980–2010 series of 1849 kg ha^{-1}, with a minimum value of 500 kg ha^{-1} in the south of Cordoba, east of La Pampa and southwest of Buenos Aires provinces. Yields above 3000 kg ha^{-1} are found in the core area (center-east of Cordoba, center Santa Fe and north center Buenos Aires). The remaining area of Buenos Aires shows yields ranging between 1500 kg ha^{-1} and 2500 kg ha^{-1} (Fig. 9.1). Parana district in the north central area shows a productivity like the core zone.

The spatial and time variability of productivity is a highlight for all three crops, and is associated with the variability of the environmental

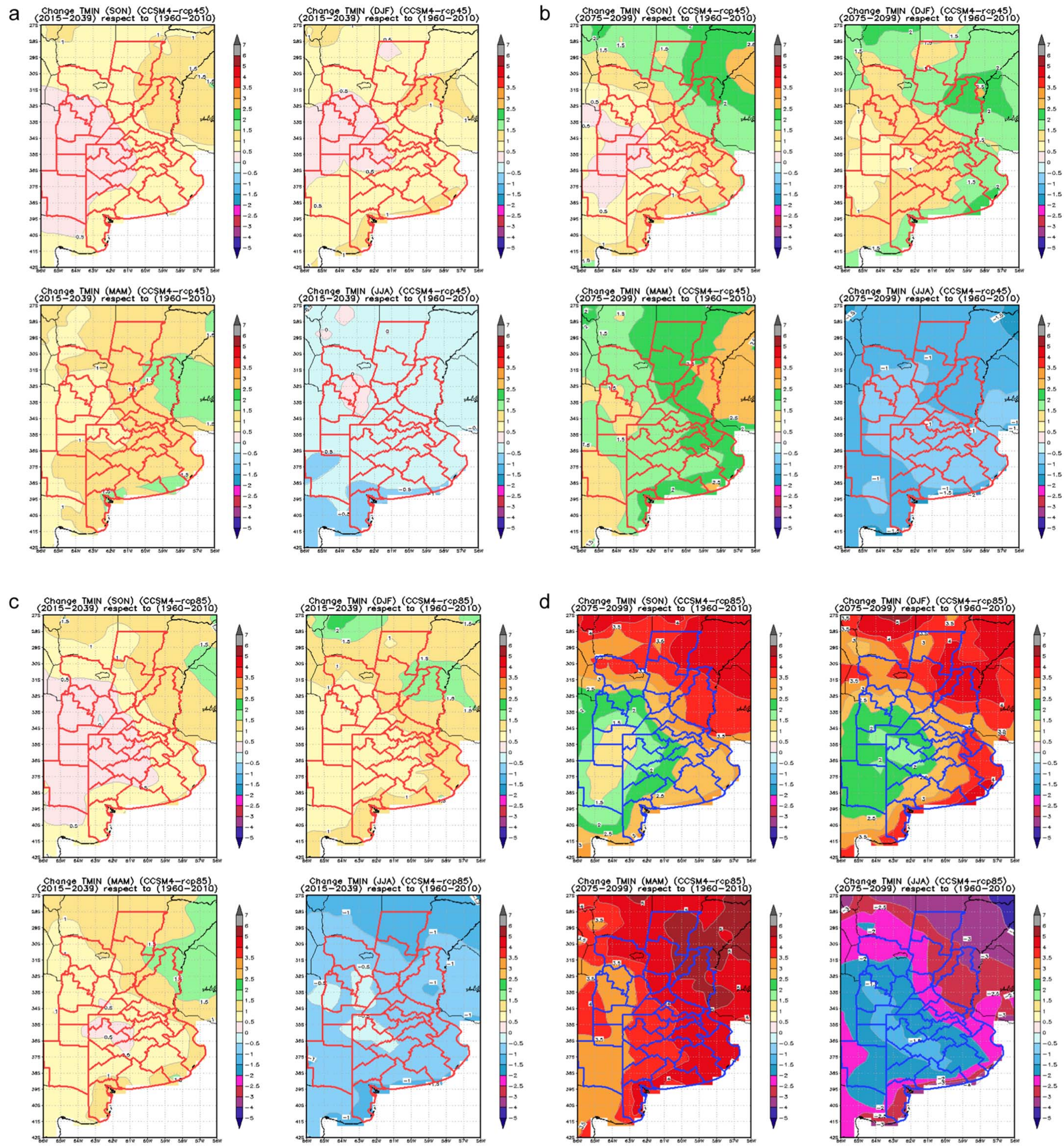

Fig. 5. a. Expected changes in mean seasonal minimum temperature, RCP 4.5. Near future. b. Expected changes in mean seasonal minimum temperature, RCP 4.5. Far future. c. Expected changes in mean seasonal minimum temperature, RCP 8.5. Near future. d. Expected changes in mean seasonal minimum temperature, RCP 8.5. Far future.

resources and the interannual climate variability. The climate parameter showing the highest spatial variability is the rainfall frequency and distribution. When the rainfall frequency and distribution is coincident with specific crop critical periods, could impact crop growth with different degrees of severity, according to the level of water stress.

4.2.2. Near future (2015–2039)

Calculating an overall yield average for the entire region, wheat decreased 12.7% and 13.3% for RCP4.5 and RCP8.5 respectively. Fig. 7.2 and 7.4 shows the percentage difference in yields in both scenarios of emissions. The largest decreases, with yield reductions up to 49%, were found in Santa Fe and Cordoba provinces, mainly for the RCP8.5 scenario in the East and North of Cordoba.

This decrease in crop yield is associated with the rainfall decrease and its spatial distribution during October (Fig. 6.1) which is coincident with the critical period (near flowering).

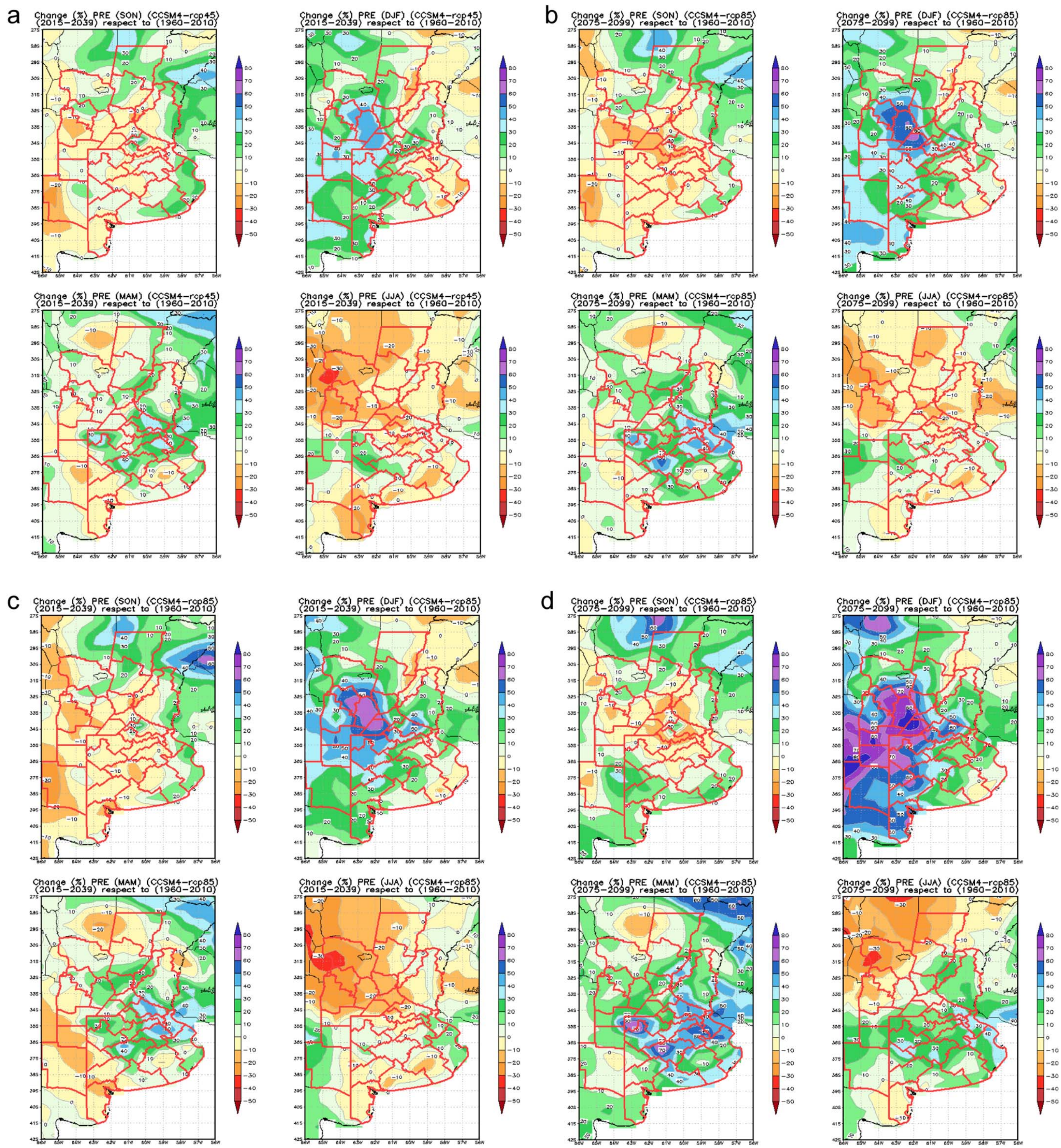

Fig. 6. a. Expected changes in mean seasonal precipitation, RCP 4.5. Near future. b. Expected changes in mean seasonal precipitation, RCP 4.5. Far future. c. Expected changes in mean seasonal precipitation, RCP 8.5. Near future. 6. d. Expected changes in mean seasonal precipitation, RCP 8.5. Far future.

For the RCP8.5 scenario, the decrease in rainfall is more widespread spatially than in the RCP4.5.

Yield increase is found in the South-East of Buenos Aires, with an up to 20% that could be partly explained by the up to 40% increase in rainfall. The increase in mean temperature during the critical period was less than 1 °C for both RCPs, and did not significantly modify the duration of the Emergence-Flowering period, with no impact on the number of grains per unit area.

The average maize yield (Fig. 8.2 and 8.4) for the region showed 8.4% and 11.9% increases for RCP4.5 and RCP8.5 scenarios, respectively. A 10% average increment occurs in most of the region following a north-south gradient, except in the southeast of Buenos Aires where decreases are observed. Spatial differences in maize yields are associated with an increase or decrease in seasonal rainfall. A decrease between 10 to 20% in some areas for the RCP4.5 scenario was associated with rainfall decrease during the growing season. For the RCP8.5

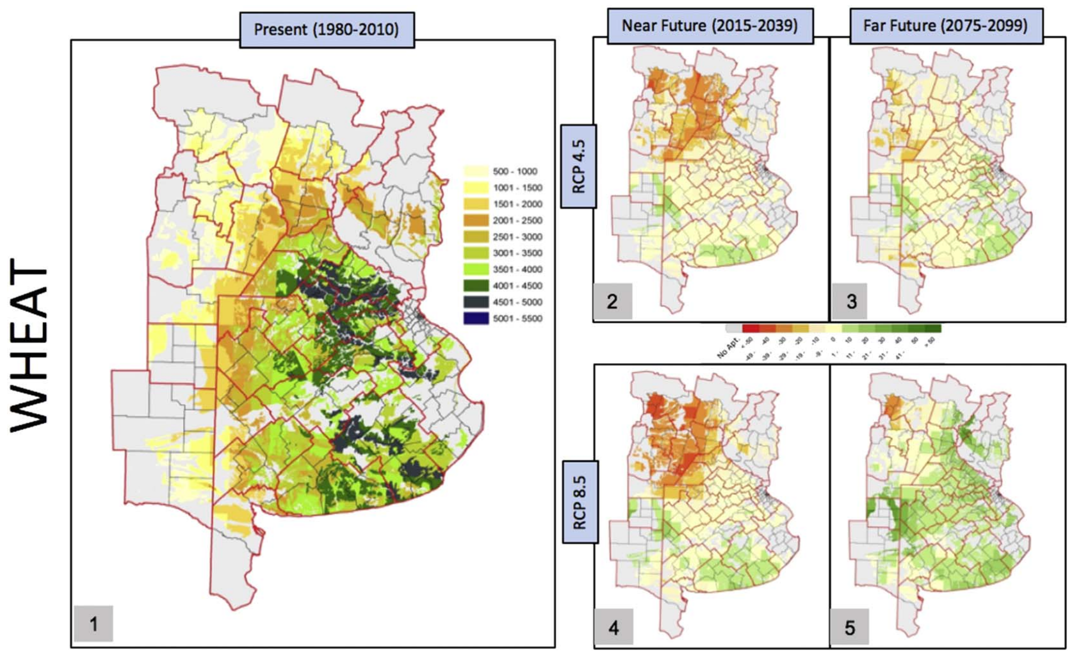

Fig. 7. Wheat. (1) Present time (1980–2010) mean crop yield (kg/ha); (2) RCP 4.5 Near future (2015–2039) crop yield percentage change; (3) RCP 4.5 Far future (2075–2099) crop yield percentage change; (4) RCP 8.5 Near future (2015–2039) crop yield percentage change; (5) RCP 8.5 Far future (2075–2099) crop yield percentage change.

scenario the rainfall increases up to 120 mm. These values resulted in a higher spatial yield for Southeast and Central of Buenos Aires and Southeast of Santa Fe.

For maize, the temperature increased by less than 1 °C for both scenarios (RCP4.5 and RCP8.5) during December and January. Nevertheless, a slightly higher increase in December did not modified the duration of flowering.

Soybean shows yield increases of 32.5% and 42.5% for both emission scenarios, exceeding in some cases a 50% (Fig. 9.2 and 9.4). The differences between the two scenarios are due to the increase of rainfall from December to February in the highest emission scenario. For both scenarios, the spatial rainfall distribution showed a positive increment towards the west of the core area, which resulted in crop evapotranspiration levels exceeding 100 mm compared to present time. In the RCP8.5 scenario these values are found in a larger area. The temperature increase is less than 1 °C for both scenarios (RCP4.5 and RCP8.5) during December and January. Variability in the length of the grain filling period was observed for the Southeast districts of Cordoba and Southern Santa Fe.

4.2.3. Far future (2075–2099)

Regionally, wheat showed a different response to each emission scenario (Fig. 7.3 and 7.5). The RCP4.5 scenario shown a decrease average of 7.9% in crop yield whereas the RCP8.5 scenario shown an

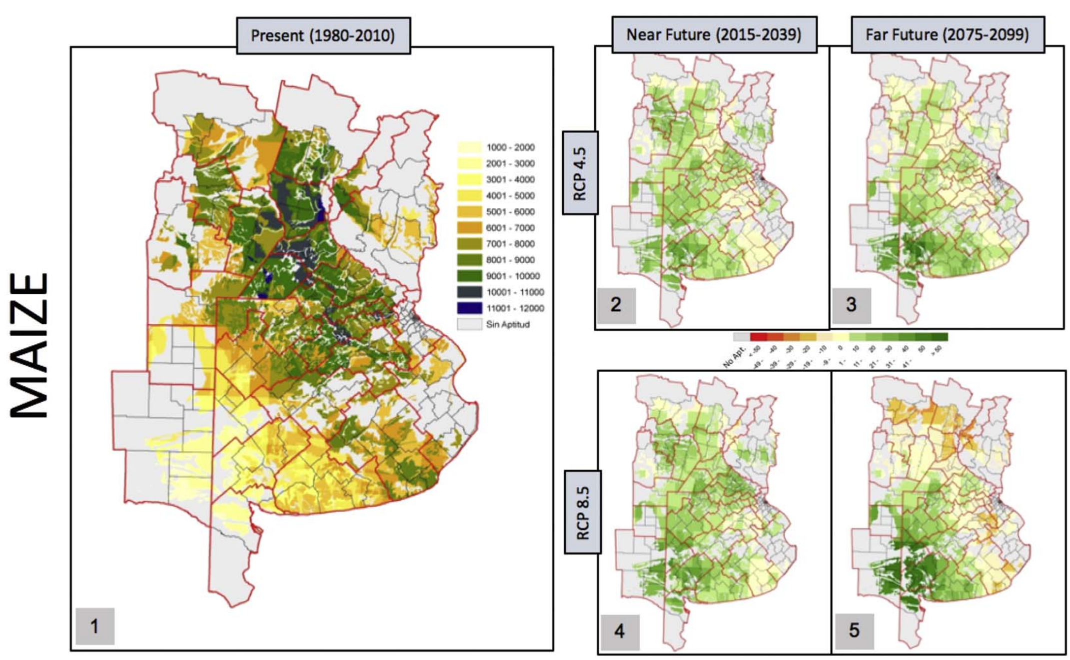

Fig. 8. Maize. (1) Present time (1980–2010) mean crop yield (kg/ha); (2) RCP 4.5 Near future (2015–2039) crop yield percentage change; (3) RCP 4.5 Far future (2075–2099) crop yield percentage change; (4) RCP 8.5 Near future (2015–2039) crop yield percentage change; (5) RCP 8.5 Far future (2075–2099) crop yield percentage change.

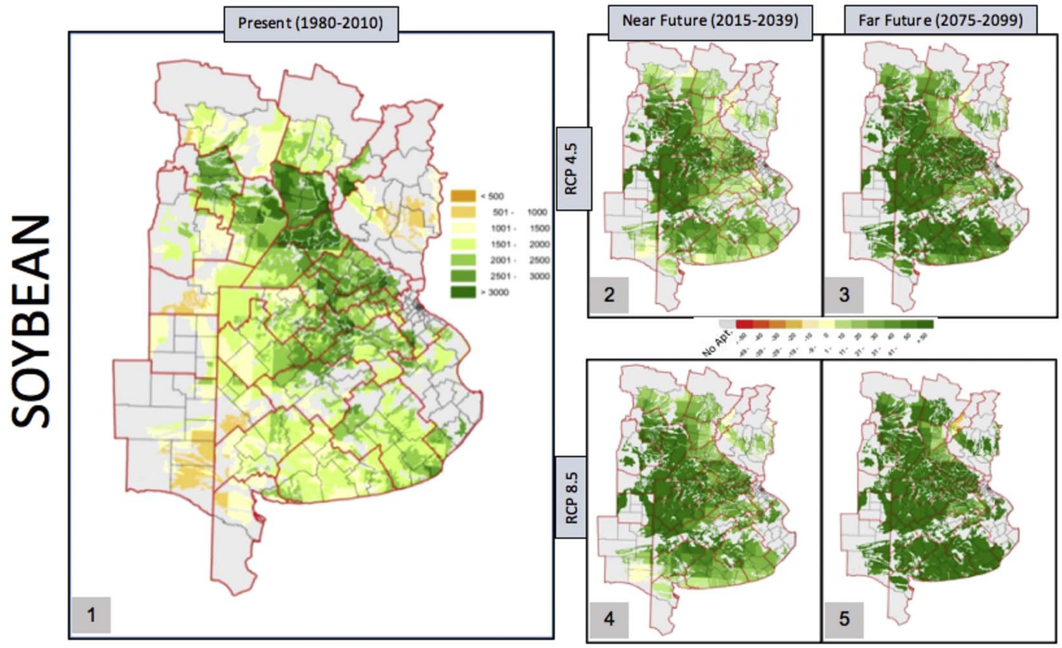

Fig. 9. Soybean. (1) Present time (1980–2010) mean crop yield (kg/ha); (2) RCP 4.5 Near future (2015–2039) crop yield percentage change; (3) RCP 4.5 Far future (2075–2099) crop yield percentage change; (4) RCP 8.5 Near future (2015–2039) crop yield percentage change; (5) RCP 8.5 Far future (2075–2099) crop yield percentage change.

increase in the average productivity of 4.1%, compared to baseline (present time).

The RCP4.5 scenario shows a 20% yield reduction in most of the region, except in the Southeast of Buenos Aires, and in a narrow strip between West Buenos Aires and East La Pampa, where yield increases up to 10%.

The RCP8.5 scenario shows 10% to 30% increases in yield across the region, except in Córdoba and a strip west of Santa Fe with a 10% decrease. There would be three possible causes: a) a 10% to 50% rainfall decrease during September–October for RCP4.5, and rainfall ranging from − 40% to + 30% for RCP8.5, except for Southeast of Buenos Aires that shows increases of rainfall up to 40% during October. b) Temperature increases of 4 °C for RCP8.5 and 2 °C for RCP4.5. c) The well known positive effect of CO2 increase on the crops (Kimball et al., 2003).

For maize, the regional average percentage differences in simulated yield for RCP4.5 and RCP8.5 scenarios were 7.7% and 5.5%, respectively. In the first scenario, the yield increment has a spatial distribution ranging between 10% and 30% from North to South of the Pampas region (Fig. 8.3 and 8.5). Yield increases are higher for the Center-Southwest of Buenos Aires Province in a range of 20% to 40% in the RCP8.5 scenario. The largest decreases in productivity were found in Cordoba Province, with values ranging from 40% to 10%. Also, a 20% to 10% decrease, was found in almost all Santa Fe province. The same impact was found on the districts of Entre Rios and in Southeast Buenos Aires. Cordoba and Santa Fe showed a 3.5 °C increment in average temperature, which impacts the emergence - flowering period in 9 to 12 days, with extremes in Southeast Buenos Aires exceeding 13 days shortening. The consequent effect is the reduction of the number of potential grains in the ear, associated with a likely water stress. The rainfall increase is not enough to compensate the water demand due to the higher temperatures. In Southeast Buenos Aires the impact of temperature range decrease adds another factor that could impact the loss of productivity.

Soybean yield increases by more than 50% for both scenarios (Fig. 9.3 and 9.5), being higher for the RCP8.5. These high yield increases are due to the high water availability for February, with 50% to 70% increase, coinciding with the period of maximum crop requirements. The rising temperatures in the higher emission, results in a shortening of emergence - flowering period, as this occurs in marginal areas (extreme north of Santa Fe and Cordoba provinces). Nevertheless, there are no impacts on the average productivity of the Pampas region.

4.3. Adaptation

In this section, we address a discussion about simple planting date adaptation strategies which do not require important investments. Tables 6 and 7 show reference simulated yield values by districts at present time and the better planting date adaptation strategies in future scenarios. Irrigation and genetic have not been considered as adaptation strategies because these could require important investments. Additionally, irrigation was not considered as a possible adaptation strategy because water will be a scarce resource in the future. Actual irrigated regions in the study area show no likelihood of increasing or even maintaining the current areas under irrigation.

4.3.1. Wheat

One of the strategies that we evaluated is the modification of the planting date to avoid the rainfall deficits projected for the near future in both emission scenarios. Different planting date patterns were used, following the trends of decreases and increases of the spatial distribution of rainfall in the different environments because the rainfall spatial variability is the most significant variable. In RCP4.5 scenario in the near future, the northern districts of the region under study, planting 40 days earlier increases productivity between 15% and 33%; while 20 day earlier planting date in the northern districts of Buenos Aires, Entre Rios and South of Santa Fe provinces reduces the negative impact up to −8% values. In the southern districts of Buenos Aires very slight increases of up to 2% were found. The central districts of Buenos Aires, south of Cordoba and La Pampa show mostly a productivity increase from 1% to 15% with a 20 days planting date delay (Fig. 10). For RCP8.5 scenario in the far future, the effect of rainfall in September–-October has a lower impact on the crop yield. Instead, temperatures begin to play a more important role. The strategy of 40 days earlier planting date in three districts of the Northwest Region shows an increase of 3.5% to 14% of productivity, while the San Francisco district has reduced the negative impact up to − 2.2%. The approach of a 20 day earlier planting date in 13 districts (about 60% of the regional

Table 6
Wheat: Reference average grain yield by districts at present time and the better planting date adaptation strategies in future scenarios. PD: Planting date at present time expressed in day of year (DOY), + 40, + 20, NC, − 20, − 40 number of day before and after PD. NC: No change in planting day.

District	Wheat grain yield (Dry matter grain) Present time (kg ha^{-1})	Near future RCP 4.5		Near future RCP 8.5		Far future RCP 4.5		Far future RCP 8.5	
		Change in planting date (days)	Change "up to" (%)	Change in planting date (days)	Change "up to" (%)	Change in planting date (days)	Change "up to" (%)	Change in planting date (days)	Change "up to" (%)
Rafaela	1377	PD − 40	14.8	PD − 40	5.4	PD − 40	28.6	PD − 40	11.9
San Francisco	897	PD − 40	15.2	PD − 40	3.7	PD − 40	18.2	PD − 40	-2.5
Rosario del Tala	2658	PD − 20	− 7.9	PD − 40	− 3.9	PD − 40	− 4.7	NC	12.3
Paraná	1699	PD − 40	10.5	PD − 40	18.1	PD − 40	33.7	NC	28.3
Villa María	1088	PD − 40	33.5	PD − 40	10.1	PD − 40	21.5	PD − 40	13.5
Cañada de Gómez	2003	PD − 40	− 1.6	PD − 40	− 4.5	PD − 40	12	NC	4.8
Río Cuarto	995	PD − 40	19.2	PD − 40	− 4.9	PD − 40	− 3.4	PD − 40	3.5
Marcos Juárez	1660	PD − 20	0.6	PD − 40	− 14.3	PD + 20	5.7	NC	− 8.7
Casilda	3100	PD − 20	− 7.7	PD − 40	− 12.6	PD + 20	− 4.9	NC	7.7
Pergamino	4120	PD − 20	− 7.7	PD + 20	− 5.2	PD + 20	− 2.1	NC	11.3
Venado Tuerto	3099	PD − 20	− 6.9	PD + 20	− 15.7	PD + 20	1.1	NC	− 2.3
Laboulaye	1504	PD + 20	5.5	PD + 20	− 7.1	PD + 20	− 1.9	PD − 20	1.3
Junín	4029	PD + 20	− 0.9	PD + 20	− 1.5	PD + 20	1.7	PD − 20	6.7
Lincoln	2935	PD + 20	5.7	PD + 20	− 3.7	PD + 20	1	PD − 20	10.2
Bragado	3741	PD + 20	− 1.1	PD + 20	− 1.2	PD + 20	0.9	PD − 20	8.1
Pehuajó	2877	PD + 20	7.7	PD + 20	0.8	PD + 20	1	PD − 20	14.4
25 de Mayo	3829	PD + 20	0.5	PD + 20	0.5	PD + 20	1.8	PD − 20	7.1
General Pico	1373	PD + 20	15.5	PD + 20	17.8	PD + 20	6.6	PD − 20	19.9
Bolívar	3676	PD − 20	1.4	PD − 20	− 1.4	PD + 20	− 3.3	PD − 20	5.5
Saliquelló	2302	PD + 20	11.1	PD + 20	12.5	PD + 20	6.9	PD − 20	22.6
Santa Rosa	1513	PD + 20	11.5	PD + 20	9.6	PD + 20	− 5.4	PD − 20	21.7
Tandil	3951	PD − 20	1.4	NC	1.6	PD − 20	2.4	PD − 20	7.3
Pigüé	2866	PD + 20	2.2	PD + 20	3.5	PD − 20	− 2.7	PD − 20	10.5
Tres Arroyos	3469	PD − 20	2.0	NC	4.2	PD − 20	4.2	PD − 20	7.4
Bahía Blanca	1899	PD − 20	− 1.9	PD + 20	− 4.5	PD − 20	12.1	PD − 20	− 2.5
Salado	3751	PD − 20	− 0.3	NC	− 2.3	NC	1.4	NC	9.4

Table 7
Maize: Reference average grain yield by districts at present time and the better planting date adaptation strategies in future scenarios. PD: Planting date at present time expressed in day of year (DOY), + 40, + 20, NC, − 20, − 40 number of day before and after PD. NC: No change in planting day.

District	Maize grain yield (Dry matter grain) Present time (kg ha^{-1})	Near future RCP 4.5		Near future RCP 8.5		Far future RCP 4.5		Far future RCP 8.5	
		Change in planting date (days)	Change "up to" (%)	Change in planting date (days)	Change "up to" (%)	Change in planting date (days)	Change "up to" (%)	Change in planting date (days)	Change "up to" (%)
Rafaela	8367	PD-20	5.7	PD-20	7.2	PD-40	1.4	PD-20	− 17.6
San Francisco	6688	NC	4.7	PD-40	1.8	PD-40	− 3	PD-40	− 18.1
Rosario del Tala	6252	PD-20	12.4	PD-20	10.9	PD-20	5.7	PD-20	− 3.4
Paraná	7961	PD-20	− 4.5	PD-20	-2.9	PD-20	− 7.2	PD-20	− 22.5
Villa María	7630	NC	20.5	NC	19.4	NC	1.8	PD-20	− 6.1
Cañada de Gómez	9259	NC	4.2	NC	6.5	PD-20	− 0.7	PD-20	− 11.4
Río Cuarto	6836	NC	5.4	NC	9.1	NC	− 4.6	PD-40	− 5.8
Marcos Juárez	8480	NC	11.5	NC	12.7	NC	3.3	PD-20	− 0.9
Casilda	8794	PD-20	7.5	NC	9.5	PD-20	0.8	PD-20	-2.5
Pergamino	8413	PD-20	18.0	PD-20	20.6	PD-20	12.4	PD-20	13.3
Venado Tuerto	8855	NC	9.7	NC	15.2	NC	5.3	NC	5.5
Laboulaye	6777	NC	8.0	NC	9.9	NC	3.2	NC	5.9
Junín	8457	PD-20	5.4	NC	10.4	NC	1.6	PD-20	1.2
Lincoln	7598	NC	10.0	NC	13.4	NC	4.9	NC	12.1
Bragado	8455	PD-20	3.0	NC	8.0	NC	− 4.1	PD-20	-2.1
Pehuajó	6795	NC	11.2	NC	14.6	NC	7.4	NC	17.7
25 de Mayo	7797	PD-20	2.1	PD-20	3.6	PD-20	− 5.9	PD-20	− 5.4
General Pico	4853	PD-20	13.8	NC	14.9	NC	13.1	NC	25.5
Bolívar	6818	PD-20	9.0	NC	10.8	NC	7.4	PD-20	12.3
Saliquelló	3933	PD-20	36.9	PD-20	31.0	PD-20	34.6	NC	52.9
Santa Rosa	2911	PD-20	18.0	NC	22.9	PD-20	28.2	NC	29.2
Tandil	6931	PD-20	6.0	PD-20	6.5	PD-20	5.8	PD-20	5.9
Pigüé	4356	PD-20	44.4	PD-20	37.4	PD-20	44.8	PD-20	63.1
Tres Arroyos	5160	PD-20	18.0	PD-20	14.0	PD-20	17.2	PD-20	25.6
Bahía Blanca	2765	NC	18.7	NC	16.9	NC	27	NC	43.5
Salado	6740	PD-20	6.5	PD-20	6.7	PD-20	4	PD-20	0.2

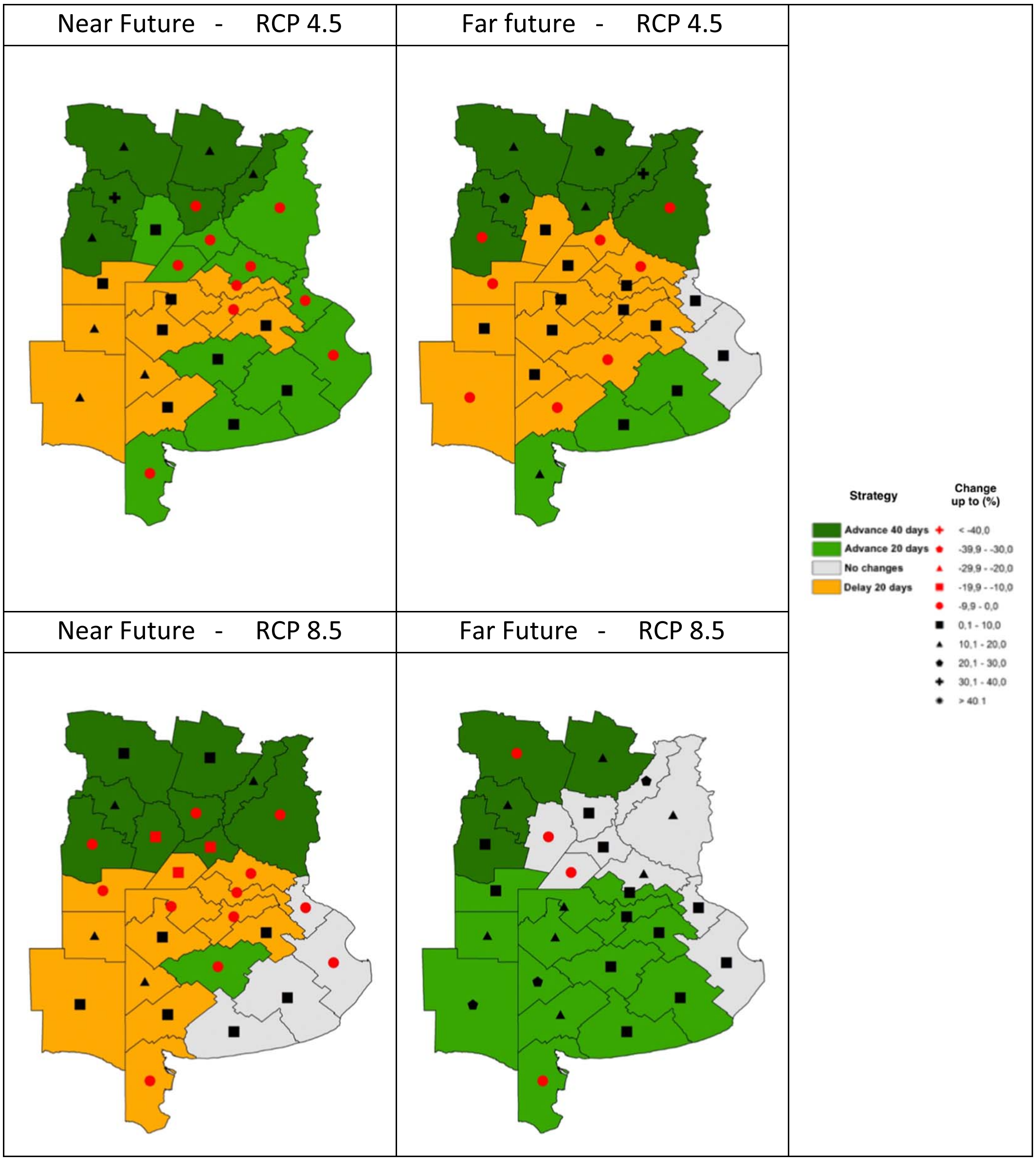

Fig. 10. Wheat. Adaptation to climate change shifting the planting dates for the near future (1015–2039) and far future (2075–2099) and scenarios RCP 4.5 and 8.5.

area), results in yield increments of 1.3% to 22%. The remaining seven districts show no change in sensitivity to planting date with yield increases between 5% and 28%, and decrease the negative impact in two districts up to − 2% in Venado Tuerto and − 9% in Marcos Juárez (Fig. 10). We emphasize that these approaches resulted in a set of adaptations with a significant degree of variability, depending on the environment interacting with the emission scenarios and horizons chosen. Moreover, the importance of strategies of delay in planting date comes from a temporal and spatial interaction with rainfall deficit, which makes it necessary to adapt the critical period to avoid water stress.

4.3.2. Maize

For maize, the same approach used in wheat in terms of planting date was used. Only early planting dates were selected because the projections for future climate showed a low probability of coincidence between water deficit and critical crop period. Then the evaluation of these approaches involves the interaction of rainfall and temperature variables associated with its intensity and spatial distribution. For RCP4.5 scenario in the near future, most districts of the region, in a distribution from North spanning two districts of Santa Fe Province, Entre Rios Province, throughout the province of Buenos Aires, except Lincoln and Pehuajó, and the province of La Pampa, showed increases in yields with high spatial variability, between 2% and 45%, using a planting date of 20 days earlier. The rest of the districts located in Santa Fe and Cordoba, were not sensitive to a change of planting date compared to those used in the present time, although the results shown yield increment ranging from 4% to 21% (Fig. 11). In RCP8.5 scenario near future, only San Francisco district shows sensitivity to the 40 days in advance planting date, with just a 1.8% yield increase. With the 20 days earlier planting date strategy, Avellaneda district, Entre Rios province, East–Southeast and Southwest Buenos Aires increase yield in a range of 3% to 31%, showing a high spatial variability. The remaining Santa Fe and Buenos Aires districts, La Pampa and all the rest of Cordoba province (except San Francisco) show productivity increases between 1% and 23%.For the far future, in both scenarios planting 40 days earlier appears to be slightly better, although still dominant the approach of earlier planting date in 20 days (Fig. 11). In RCP4.5 scenario San Francisco and Rafaela districts, in the North of the region, react to the earlier planting date, but with different responses. San

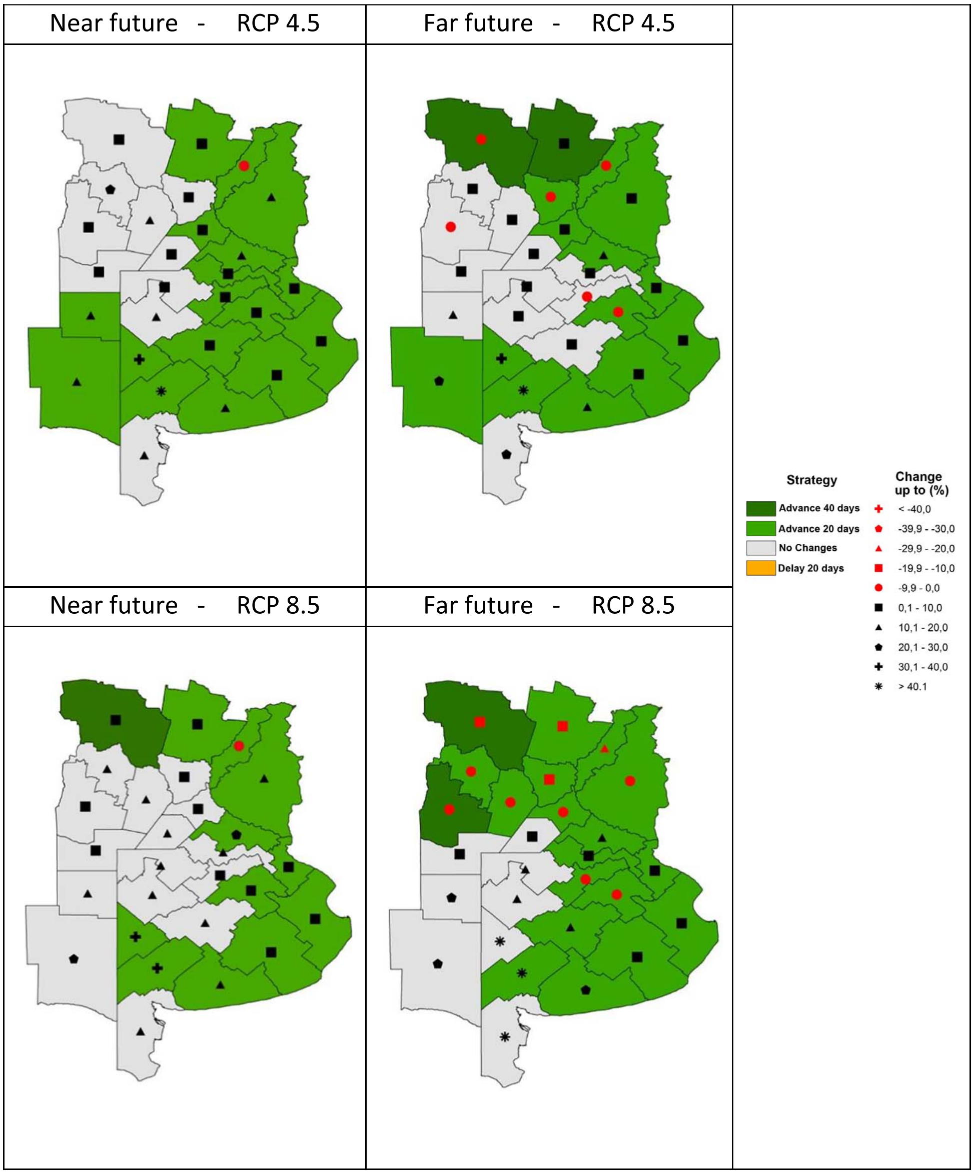

Fig. 11. Maize. Adaptation to climate change shifting the planting dates for the near future (1015–2039) and far future (2075–2099) and scenarios RCP 4.5 and 8.5.

Francisco shows a decrease of the negative impact reaching a value of − 4.6%, while Rafaela shows a slight increase of 1.4%. The approach of a 20 day earlier planting date shows increases in a range of 3.3% and 34.6%, these extremes correspond Rosario del Tala and Saliqueló districts, respectively (including the rest of the districts of East Southeast and Southwest of Buenos Aires province). There is a decrease in yield impact in Parana, 25 de Mayo and Cañada de Gómez districts, with values reaching a very slight decrease of − 0.7% to − 7.2%.The rest of Buenos Aires, Cordoba and northern La Pampa showed no variations to changes in planting dates compared to present time with an increase in performance in a range of 1.6% to 7.4%. In RCP8.5 scenario and for most of the region, the situation improved using 20 days in advance. For this scenario and horizon two responses are observed: a) increased productivity in Buenos Aires Districts except Bragado and 25 de Mayo, b) decrease of negative climate impact in Santa Fe, Entre Rios and Cordoba provinces. The ranges of increased yield are 1.2% (Junín) to 63.1% (Pigüé). The decrease of a negative climate impact ranges from -0.9% (Marcos Juárez) to − 22.5% (Paraná). It is generally observed that, although the scenario shows good water availability from the point of view of rainfall distribution, the rainfall does not satisfy water demand due to the high increase in average temperatures (approximately 3.5ºC), generating a water deficit that limits crop evapotranspiration. In the case of Bragado and 25 de Mayo a rainfall deficit in a critical moment (January) may partly explain a slight yield decrease. West Buenos Aires, and La Pampa province, along with Laboulaye district, showed no sensitivity to the change in planting date with yield increases between 5.9% (Laboulaye) and 52.9% (Saliqueló). Finally, the strategy of planting 40 days earlier partially compensated the negative impact on yield in Córdoba districts San Francisco and Rio Cuarto, reaching values of − 18.1% and − 5.8, respectively.

4.3.3. Soybean

In both horizons and scenarios, soybean yield always increase, exceeding in some environments more than 50% of productivity compared to present time. For this reason, it was not necessary to design an adaptative strategy for future climate scenarios.

5. Conclusion

The productivity models considered (CERES-Wheat, CERES-Maize and CROPGRO) indicate that on average for the near future (2015–2039) and far future (2075–2099) considering the effect of CO_2, soybean yield would increase considerably and maize yield would increase moderately, while wheat would suffer slight reductions in productivity. These behaviors are associated with the projected increase in summer rainfalls (December to February), mainly favoring soybean and maize. The reduced winter-spring rains, together with the lengthening of the winter dry season would impact wheat productivity in the central area of the country (Córdoba, Santa Fe and north of Buenos Aires provinces). On average, the south and west of Buenos Aires province area and the productive area of La Pampa would benefit. Finally, we showed that changing the planting date would be an effective adaptation strategy to climate change. This strategy will not affect the common sequence of cropping system, wheat – soybean – maize – soybean, in the region.

References

3CN: Secretaría de Ambiente y Desarrollo Sustentable de la Nación, 2014. Tercera Comunicación Nacional sobre Cambio Climático. In: "Cambio Climático en Argentina; Tendencias y Proyecciones" (Centro de Investigaciones del Mar y la Atmósfera). Buenos Aires, Argentina. . http://ambiente.gob.ar/tercera-comunicacion-nacional/.

Alvarez, R., De Paepe, J., Steinbach, H.S., Fernandez, P.L., Alvarez, C.R., 2014b. Cambios en los niveles de Carbono y Nitrógeno de los suelos pampeanos producidos por el uso. In: Medina, C.P., Zubillaga, M.M., Taboada, M.A. (Eds.), Suelos, producción agropecuaria y cambio climático. Avances en la Argentina (ISBN 978-987-1873-25-8).

Ar-2CN, 2006. Segunda Comunicación Nacional de Cambio Climático. http://unfccc.int/resource/docs/natc/argnc2s.pdf.

Baethgen, W.E., Magrin, G.O., 1995. Assessing the impacts of climate change on winter crop production in Uruguay and Argentina using crop simulation models. In: Rosenzweig, C. (Ed.), Climate Change and Agriculture: Analysis of Potential International Impacts. 59. American Society of Agronomy Special Publication, Madison WI, pp. 207–228.

Baethgen, W.E., Carriquiry, M., Ropelewski, C., 2009. Tilting the odds in maize yields: how climate information can help manage risks. Bull. Am. Met. Soc. 90 (2), 179–183.

Boote, K.J., Jones, J.W., Hoogenboom, G., Pickering, N.B., 1998. The CROPGRO model for grain legumes. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), Understanding Options for Agricultural Production. Kluwer Academic Publishers, Dordrecht, pp. 99–128.

Brisson, N., Gary, C., Justes, E., Roche, R., Mary, B., Ripoche, D., Zimmer, D., Sierra, J., Bertuzzi, P., Burger, P., Bussière, F., Cabidoche, Y.M., Cellier, P., Debaeke, P., Gaudillère, J.P., Hénault, C., Maraux, F., Seguin, B., Sinoquet, H., 2003. An overview of the crop model STICS. Eur. J. Agron. 18, 309–332.

Giancola, S.I., Salvador, M.L., Vovacevich, M.Y., Iturrioz, G., 2009. Analisis de la cadena de soja en la Argentina. Estudios socioeconómicos de los sistemas agroalimentarios y agroindustriales. Area Estrategica de Economia y Sociologia. INTA (ISSN: 1852-4605).

Hoogenboom, G., Jones, J.W., Wilkens, P.W., Porter, C.H., Boote, K.J., Hunt, L.A., Singh, U., Lizaso, J.I., White, J.W., Uryasev, O., Ogoshi, R., Koo, J., Shelia, V., Tsuji, G.Y., 2015. Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.6 (http://dssat.net). DSSAT Foundation, Prosser, Washington.

IPCC, 2014. Climate Change 2014: Synthesis Report. In: Core Writing Team, Pachauri, R.K., Meyer, L.A. (Eds.), Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland (151pp.).

Jones, C.A., Kiniry, J.R., 1986. CERES-Maize: A Simulation Model of Maize. Growth and Development. Texas A & M University Press, College Station, Texas.

Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J., Ritchie, J.T., 2003. DSSAT cropping system model. Eur. J. Agron. 18, 235–265.

Kimball, B.A., Kobayasi, K., Bindi, M., 2003. Response CO_2 enrichment. Adv. Agron. 77, 293–368.

Magrin, G.O., Díaz, R.A., Travasso, M.I., Rodriguez, G., Boullón, D., Nuñez, M., Solman, S., 1998. Vulnerabilidad y Mitigación relacionada con el Impacto del Cambio Global sobre la Producción Agrícola. In: Barros, V., Hoffmann, J.A., Vargas, W.M. (Eds.), En Proyecto de Estudio sobre el Cambio Climático en Argentina, proyecto ARG/95/G/31-PNUD-SECYT, 290 p. (In Spanish). http://www2.medioambiente.gov.ar/documentos/acuerdos/convenciones/unfccc/Agricultura.pdf.

Magrin, G.O., Grondona, M.O., Travasso, M.I., Boullón, D.R., Rodríguez, G.R. and Messina, C.D., 1999. ENSO impacts on crop production in the Argentina's Pampas Region. Proc. 10th Symposium on Global Change Studies, 10–15 Jan. 1999, Dallas, TX, by the AMS, Boston, MA. pp. 65–66.

Magrin, G.O., Travasso, M.I., Rodríguez, G.R., 2005. Changes in climate and crop production during the 20th century in Argentina. Clim. Chang. 72, 229–249.

Magrin, G.O., Travasso, M.I., López, G.M., Rodríguez, G.R., Lloveras, A.R., 2007. Vulnerabilidad de la Producción Agrícola en la Región Pampeana Argentina. In: Componente B3 de la Segunda Comunicación Nacional de Cambio Climático, (86pp.). http://climayagua.inta.gob.ar/impactos_del_cambio_climatico_en_la_produccion_agricola_de_la_region_pampeana.

Magrin, G.O., Travasso, M.I., Rodríguez, G.R., Solman, S., Nuñez, M., 2009. Global warming and wheat production in Argentina. Int. J. Global Warming 1, 214–226.

Meira, S., Guevara, E., 1995. Application of SOYGRO model in Argentina. In: Second International Symposium on Systems Approaches for Agricultural Development (SAAD2). Los Baños - IRRI, Filipinas.

Nuñez, M.N., Ciappesoni, H.H., Rolla, A., Kalnay, E., Ming Cai, 2008. Impact of land-use and precipitation changes on surface temperature trends in Argentina. J. Geophys. Res. 113, D06111. http://dx.doi.org/10.1029/2007JD008638.

Ritchie, J.T., Otter, S., 1985. Description and performance of CERES-Wheat: a user-oriented wheat yield model. In: ARS Wheat Yield Project. ARS-38. Natl Tech. Info. Serv., Springfield, Missouri, pp. 159–175.

Roel, A., Baethgen, W.E., 2007. Towards the Development of a Spatial Decision Support System (SDSS) for the application of climate forecasts in Uruguayan rice production sector. In: Sivakumar, M., Hansen, J. (Eds.), Climate Prediction and Agriculture Advances and Challenges. Springer, Berlin Heidelberg, pp. 89–97.

Rolla, A., Guevara, E., Meira, S., 2016. CASANDRA: web based platform to assess impacts and define adaption strategies to climate change. http://www.agmip.org/6th-agmip-global-workshop/.

Savin, R., Satorre, E.H., Hall, A.J., Slafer, G.A., 1995. Assessing strategies for wheat cropping in the monsoonal climate of the Pampas using the CERES-Wheat simulation-model. Field Crops Res. 42 (2–3), 81–91.

Stöckle, C.O., Donatelli, M., Nelson, R., 2003. CropSyst, a cropping systems simulation model. Eur. J. Agronomy 18, 289–307.

Travasso, M.I., Magrin, G.O., 1998. Utility of CERES-Barley under Argentine conditions. Field Crops Res. 57 (3), 325–329.

Travasso, M.I., Magrin, G.O., 2001. Testing crop models at the field level in Argentina. In: Proc. 2nd International Symposium "Modelling Cropping Systems". July 16–18 2001. Florence, Italy, pp. 89–90.

Travasso, M.I., Magrin, G.O., Baethgen, W.E., Castaño, J.P., Rodriguez, G.R., Pires, J.L., Gimenez, A., Cunha, G., Fernandes, M., 2006. Adaptation Measures for Maize and Soybean in Southeastern South America. AIACC Working Paper No. 28.

UNF„CCC Secretariat, 2005. Compendium on methods and tools to evaluate impacts of, and vulnerability and adaptation to, climate change.

Viglizzo, E.F., Létora, F., Pordomingo, A.J., Bernardos, J.N., Roberto, Z.E., Del Valle, H., 2001. Ecological lessons and applications from one Century of low external-input farming in the pampas of Argentina. Agric. Ecosys. Environ. 83, 64–81.