American Journal of Climate Change, **2013, 2, 237-253**
Published Online December 2013 (http://www.scirp.org/journal/ajcc)
http://dx.doi.org/10.4236/ajcc.2013.24024

Scientific Research

Mean and Interannual Variability of Maize and Soybean in Brazil under Global Warming Conditions

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Received August 9, 2013; revised September 11, 2013; accepted October 8, 2013

ABSTRACT

Brazil is responsible for 27% of the world production of soybeans and 7% of maize. Mato Grosso and Para states in Brazil are among the largest producer. The viability to the cultivation of maize (*Zea mays*) and soybeans (*Glycine max*), for future climate scenarios (2070-2100, GHG) is evaluated based on crop modeling (DSSAT) forced by observational data and regional climate simulations (HadRM3). The results demonstrated that a substantial reduction in the yield in particular for maize may be expected for the end of the 21st century. Distinct results are found for soybeans. By applying the A2 climate changes scenario, soybean yield rises by up top 60% assuming optimum soil treatment and no water stress. However, by analyzing the inter-annual variability of crop yields for both maize and soybean, could be demonstrated larger year-to-year fluctuations under greenhouse warming conditions as compared to current conditions, leading to very low productivity by the end of the 21st century. Therefore, these Brazilian states do not appear to be economically suitable for a future cultivation of maize and soybeans. Improved adaptation measures and soil management may however partially alleviate the negative climate change effect.

Keywords: Climate Changes; Soybeans; Maize

1. Introduction

The last century has been characterized by a substantial increase in world population, and consequently has brought food supply at the forefront of global issues. In general, to increase the food production, one may enlarge the planted area, maximize the crop productivity to reach values close to the potential productivity, or to develop new crop varieties [1,2]. The necessity for the enlargement of the crop-livestock area has increased the pressure on primary forests, in particular in the tropical region [3,4]. For instance, the Amazon basin, in particular Mato Grosso and Para States, has been experiencing high rates of deforestation for many years [5], and this may be affecting the ecological integrity of the forests, as discussed by [6].

The soybean and pasture expansion in the Amazon basin states (Amazonas, Acre, Roraima, Rondônia, Mato Grosso, Pará e Amapá), including Maranhão and Tocantins states expanded at the rate of 14.1% per year from 1990 to 2005 [7]. The crop expansion, in particular soybeans and pastures associated with the cattle ranching have lead to a leveling of 560,000 km^2 of the Brazilian Amazonia [8]. It is important to mention, however, that most of the soybean expansion has been occurring on the borders of the Amazon basin where the vegetation (cerrado) is not quite the same as present in the Amazonas and Para states.

The Amazon basin is among the major drivers of the global climate system due to the substantial amount of water vapor released by the rainforest, which plays a crucial role in maintaining the Hadley circulation and the regional tropical and global circulation. Several Modeling studies have proposed that the extent of the Amazon basin rainforest may be strongly affected by induced climate changes through human emissions of greenhouse gases (see discussion in [9,10]).

While future changes of the Amazon basin and environment have been extensively investigated [11-14], the viability of the region to a potential implementation, in the future, of an agricultural system has not received the necessary attention. Similarly, studies focusing on the effect of greenhouse warming conditions in the current crop production in the Amazon basin are still scarce. Reference [15] puts forward and analyzes on the impact of future human driven changed precipitation and temperatures on the Brazilian crop system, in which they found that in exception of sugarcane, most of crops cultivated in Brazil may experience drop in productivity.

The climate in the Amazon region has been affected by extremes in weather, such as the drought of 2005 [16-18], the floods of 2009 [19]. It might be noted that a considerable number of farmers and indigenous peoples in the Mato Grosso and Pará States rely on local agricultural production.

Therefore, the proposed climate-crop evaluation is crucial because the crop phenological cycle and the crop yield are tightly linked to meteorological conditions [20]. There exists, moreover, a lively debate on the role of future atmospheric CO_2 concentration as a forcing agent to crop yields. Present day CO_2 concentration limits performance of many agricultural crops through photosynthesis, a process by which leaves absorb CO_2 from the air to make compounds required for plant growth. Field experiments and modeling studies have demonstrated positive effects of increasing atmospheric CO_2 concentrations on crop photosynthetic efficiency and water use [e.g. 21].

C3 species, such as soybeans are more photosynthetically-limited by available atmospheric carbon dioxide than C4 species with relatively efficient pathways (e.g. maize). Exposure of plants belonging to the C3 group to elevated CO_2 generally results in stimulated photosynthesis and enhanced growth [22]. C4 species, on the other hand, are efficient enough at utilizing carbon that they are not currently limited significantly by available atmospheric carbon. As proposed by [23], in theory, at 25˚C, an increase in atmospheric CO_2 concentration from the present-day value of 380 ppm to that of 550 ppm, projected for the year 2050, would increase C3 photosynthesis by 38%. Reference [24] argued that by 2055, one may expect a 10% reduction in maize production in Africa and Latin America which can increase the food insecurity. For most country the climate impact from 1980-2008 has negatively affected the soybeans yield which may be intensified under future climate change conditions.

As proposed by [25], a 10% reduction of soybean in the (2003-2008) period would have decreased deforestation by as much as 40%. In this sense, to check the viability to crop extension practices in Pará and Mato Grosso states may shed some light on the economic risks when considering investments on agricultural expansion in this region. The purpose of this paper is to quantify the joint impact of climate change on the yield of soybean and maize in the Pará and Mato Grosso states, under present day climate condition and climate scenarios with extreme emission assumptions.

However, the investigation conducted in this paper may be very useful to evaluate the potential impact posed by increased crop areas linked to indirect land use change (ILUC), by increased mechanized agriculture. It should be noted that the EMBRAPA, the Brazilian Agricultural Research Corporation, has demonstrated that a viable solution for this region, which may avoid deforestation is to associate the pastures and crops system with the forest.

2. Database and the Design of the Numerical Experiments

Present Day and Greenhouse Warming Climates

To evaluate the climate impact on maize and soybeans daily data of minimum and maximum temperatures, precipitation, wind and solar radiation have been utilized. **Figure 1** shows the spatial distribution of grid points used in the study. Two model simulations were performed with the HadRM3P Regional Climate Model from the UK Met Office for present day (1961-1990) and future (2071-2100) conditions [11]. These experiments were conducted with horizontal resolution of approximately 50 km, surface and lateral boundary conditions are taken from the HadAM3P climatology for the respective epoch.

The HadRM3P regional model was developed at the UK-Met Office Hadley Centre and is part of the PRECIS (Providing Regional Climate for Impacts Studies) regional climate modeling system [see 26], which also includes a detailed description of HadRM3P). HadRM3P has 19 vertical levels and a choice of two horizontal resolutions, 50 km as used in this study (and the standard resolution for larger areas) and 25 km for smaller areas and when higher resolution is particularly important.

Lateral boundary conditions for HadRM3P are available from a range of model and observationally based sources and in this study are obtained from the HadAM3P. The model formulation is the same as HadAM3P, an experimental setup that promotes consistency of high resolution climate change projections from the RCM, with those from the global model.

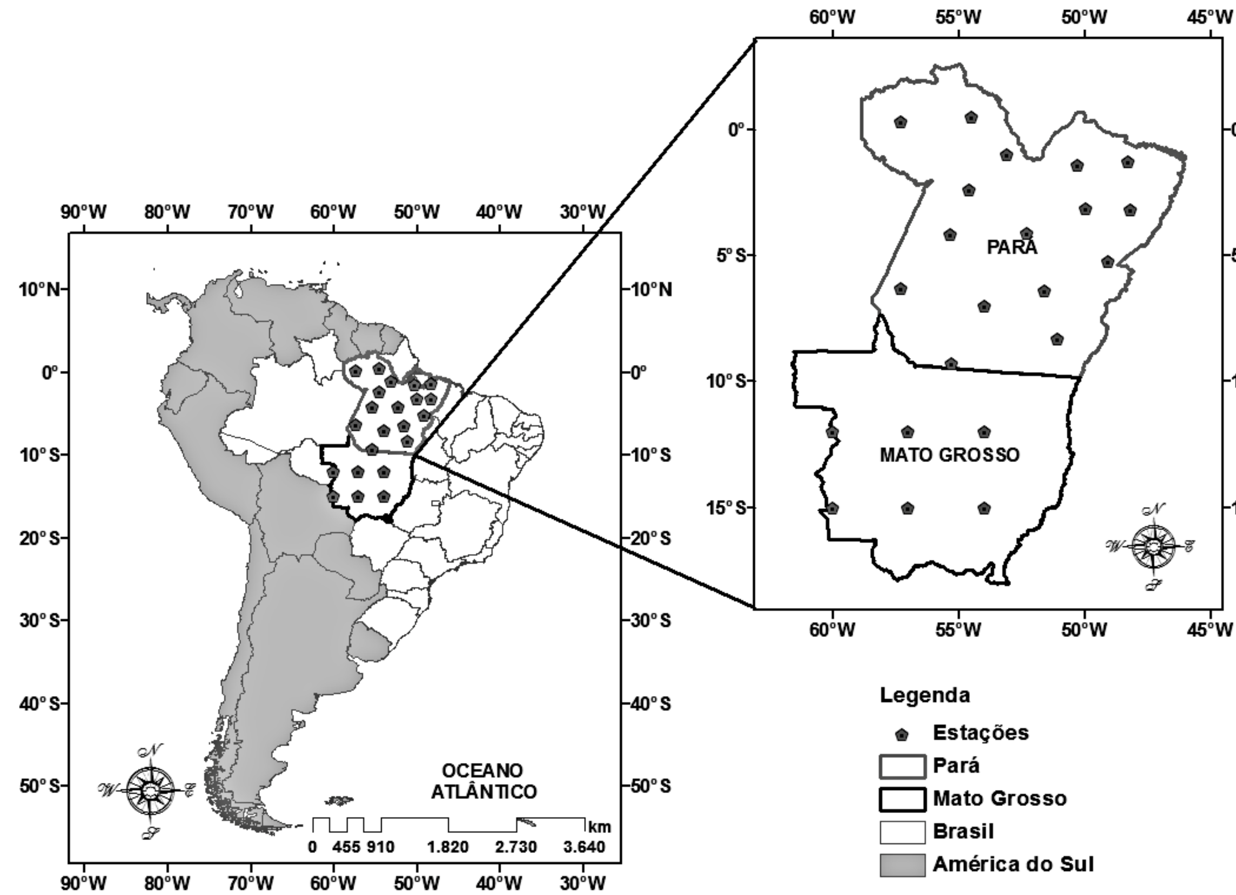

Figure 1. Pará and Mato Grosso states and the spatial distribution of grid points used in the present study.

Matching the sea surface temperature (SST) forcing the HadAM3P and HadRM3P simulations for the present climate incorporated observed Greenhouse Gas (GHG) concentrations and CO_2 emissions, and for the future incorporated GHG concentrations and CO_2 emissions taken from two contrasting emission scenarios [11,27].

These future climate projections were based on two extreme emission scenarios from IPCC-SRES, namely B2 and A2. These scenarios project an atmospheric CO_2 concentration by the end of the 21st Century of approximately 550 ppm and 770 ppm, respectively. The Amazon's climate under present day conditions is primarily influenced by the position of the Inter-Tropical Convergence Zone (ITCZ), the South Atlantic Convergence Zone (SACZ) the Andes mountains, the eastern Pacific and tropical Atlantic Oceans, as well as by vegetation and soil moisture interactions [e.g. 9]. As discussed by [11, 27], the present day regional model simulation presented here reproduces qualitatively well the precipitation and temperature as compared to observation. Moreover, the semi-annual cycle of precipitation, and temperature is well captured over the Amazon basin as demonstrated by harmonic analysis calculation (not shown).

Under present day conditions, the amount of precipitation and the range of temperature in the Pará and Mato Grosso states do not create severe constraints for crop growth and yields. One should have in mind that other factors such as soil characteristics and the occurrence of dry spells can reduce the viability of crop cultivation [28].

However, from climate modeling projections [e.g. 18, 27], the strengthening of GHG forcing leads to reduction in precipitation in the central and eastern Amazonia, as well as the increase of rainfall in the west coast of Peru and Ecuador resembles a rainfall anomaly pattern similar to El Niño. The link between the ENSO and Amazon basin has been observed under present day conditions [e.g. 11,29,30], where there is a tendency for dry conditions in Amazonia during El Niño, even though intense drought events (as in 1964 and 2005) were not related to El Niño but to anomalously warm surface waters in the tropical North Atlantic.

The precipitation regime in the southern and western part of the Amazon basin is connected with a thermal low over 20˚ - 30˚S, over the Chaco-Northern Argentina region, and in phase with the active period of the SACZ. An increase in the intensity of this thermal low may be responsible for acceleration of the moisture transport from northern to southern Amazonia, and this may induce more rainfall in the later region. As should be anticipated, the climate response to the inclusion of the A2 scenario leads to stronger changes as compared to those delivered by the B2 scenario. The T_{min} (T_{max}) increase by up to 6˚C (8˚C) under A2 conditions (figures now shown).

The analyzes are based on a specific climate model output, thus the findings are subjected to at least uncertainties/limitations associated with the model dynamics and projected climate changes anomalies. Nevertheless, several models outputs project a future drier and warmer climate for the Amazon basin by the end of 21st century, as reproduced here (see e.g. [9] and references therein).

3. Results and Discussion

3.1. Crop Modeling Approach

The analysis presented here extends the discussion and consequences of climate changes for the productivity of soybeans (*Glycine max* L) in the Pará and Mato Grosso states. To simulate crop yields, the Decision Support System for Agrotechnology Transfer has been used (DSSAT) [26]. Additionally, our simulations include variations in the atmospheric CO_2 concentration as proposed by the A2 (770 ppm) and B2 (550 ppm) scenarios.

The calibration of the model CROPGRO-Soybean and Ceres-Maize, which are part of the DSSAT cropping system model, are obtained from experimental conditions by adjusting the model genetic coefficients which characterize primary aspects of the crop, according to [26]. The DSSAT is characterized by one soil module, a crop template module, a weather module and a module for simulating the interchange among the soil, plants, and atmosphere in regarding to light and water. For details see [26].

The field experiment for soybeans (maize), with a continuous extension of 200 (23) ha, was conducted in Paragominas (02˚59S, 47˚21W, **Figure 1**) located in the northeastern part of Para state in the east part of the Amazon basin [31]. In Paragominas, large landholders are changing their economic activities from ranching to production of soybeans which may increase the pressure on the Amazon basin forest.

For the calibration of the genetic coefficients of the CROPGRO-Soybean, data from a intermediate maturity cultivar (BRS Tracaja), sown in 28/02/2007 and 08/02/2008, with spacing of 0.50 m between rows, and 200 thousand plants/ha on tillage system have been utilized [31]. In order to calibrate the crop simulation the first experiment initiated in 28/02/2007 has been used. The second experimental campaign (08/02/2008) has been applied to validate the modeling results. The soil is predominantly Xanthic Hapludox (claly yellow latosol, 71% of clay), with volumetric water content at the field capacity of 0.43 m^3/m^3 and 0.19 m^3/m^3 at the wilting point. Weather data of maximum and minimum temperatures, solar radiation, precipitation, relative humidity and wind were collected at 3 m height in the experimental area during 2007-2008. The genetic coefficients used in the CROPGRO-Soybean module are presented in **Table 1**.

3.2. Evaluation of the Phenological Calibration

The calibration has been evaluated by comparing the growth and accumulated biomass between the experimental and simulated data sets. The parameters used to check the validity of the simulation are number of days from the sowing to maturation; grain filling and biophysical aspects of physiological maturation and flourishing.

Specifically, attention has been paid to anthesis, physiological maturity, unit weight at maturity, LAI, tops weight at maturity and yield. **Table 2** shows the inter-comparison between the models results and experimental data in the years 2007 (calibration) and 2008 (validation).

Table 1. Genetic coefficient for soybeans.

Cultivar BRS Tracaja	Coefficient
CSDL	12.07
PPSEN	0.33
EM-FL	36.0
FL-SH	10.0
FL-SD	16.0
SD-PM	38.0
FL-LF	18.0
FLMAX	1.030
SLAVAR	355
SIZLF	180
XFRT	1.00
WTPSD	0.18
SFDUR	18.0
SDPDV	2.05
PODUR	10.0

CSDL: critical day length, above which the reproductive development process is not affected (h); PPSEN: response inclination regarding development for the photo phase with time (1 h^{-1}); EM-FL: period between plant emergence and the appearance of the first flower (R1) (photothermal days); FL-SH: period between the appearance of the first flower and the first pod (R3) (photothermal days); FL-SD: period between the appearance of the first flower and the start of seed formation (R5) (photothermal days); SD-PM: period between the start of seed formation and physiological maturity (R7) (photothermal days); FL-LF: period between the appearance of the first flower (R1) and the end of leaf expansion; LFMAX: maximum leaf photosynthesis rate at an optimal temperature rate of 30 C; SLAVARN: specific leaf area under standard growth conditions (cm^2); SIZLF: maximum size of completely expanded leaf (cm^2); XFRT: maximum fraction of the daily growth that is partitioned between the seed plots the pod; WTPSD: maximum weight per seed (g); SFDUR: duration of the grain swelling period in the pods, under standard growth conditions (photothermal days); SDPDV: mean seeds per pod, under standard growth conditions (photothermal days); PODUR: time necessary for the cultivar to reach ideal pod conditions (photothermal days).

It may be demonstrated that the model does a reasonable job in simulating the crop characteristics as delivered by the field campaign, in particular for anthesis, the physiological maturity and the crop yield. The largest differences between observation and the modeled data are identified for tops weight at maturity.

Evaluation of the Crop Growth

Model evaluation has also been carried out for the dry mass of above-ground (DM) and leaf area index (LAI, **Figure 2**) in the years 2007 and 2008. It may be noted that the model accurately simulated the DM in the calibration experiment (2007) as compared to the experimental values, but slightly underestimates the DM along the soybean cycle in the validation year (2008) (**Figure 2(b)**). Some discrepancies between observed and simulated BM were found by [32] predicting on-farm soybean yields in the pampas biome.

Turning to LAI results, it is clear that the model simulation matches closely the field observations during most of the life cycle of the soybean (**Figure 2(c)**). For instance, the peak of the LAI is 4.1 m^2/m^2 based on observations and 4.6 m^2/m^2 in the COPGRO-Soybean simulation. In 2008 (validation) the predicted pace of leaf area expansion was low throughout the soybean growing season. The reason for this discrepancy between measured and modeled data may be due to lower minimum and maximum temperatures in 2008 in particular in the first 30 days after planting.

Reference [33] also found disagreement between meas-

Table 2. Observed and simulated soybean phenological data.

Parameters	Calibration			Validation		
	Obs	*Sim*	*Diff*	*Obs*	*Sim*	*Diff*
Anthesis (days)	44	44	0	41	45	4
Physiological maturity (days)	105	105	0	113	113	0
Unit weight at maturity (g)	0.138	0.145	0.008	0.144	0.192	0.049
Leaf area index, maximum ($m^2 \cdot m^{-2}$)	4.1	4.6	0.5	6.49	4.3	2.19
Weight at maturity ($kg \cdot ha^{-1}$)	7.648	5.717	1.931	8.412	7.246	1.166
Yield ($kg \cdot ha^{-1}$)	3.273	3.154	119	3.479	3.484	5

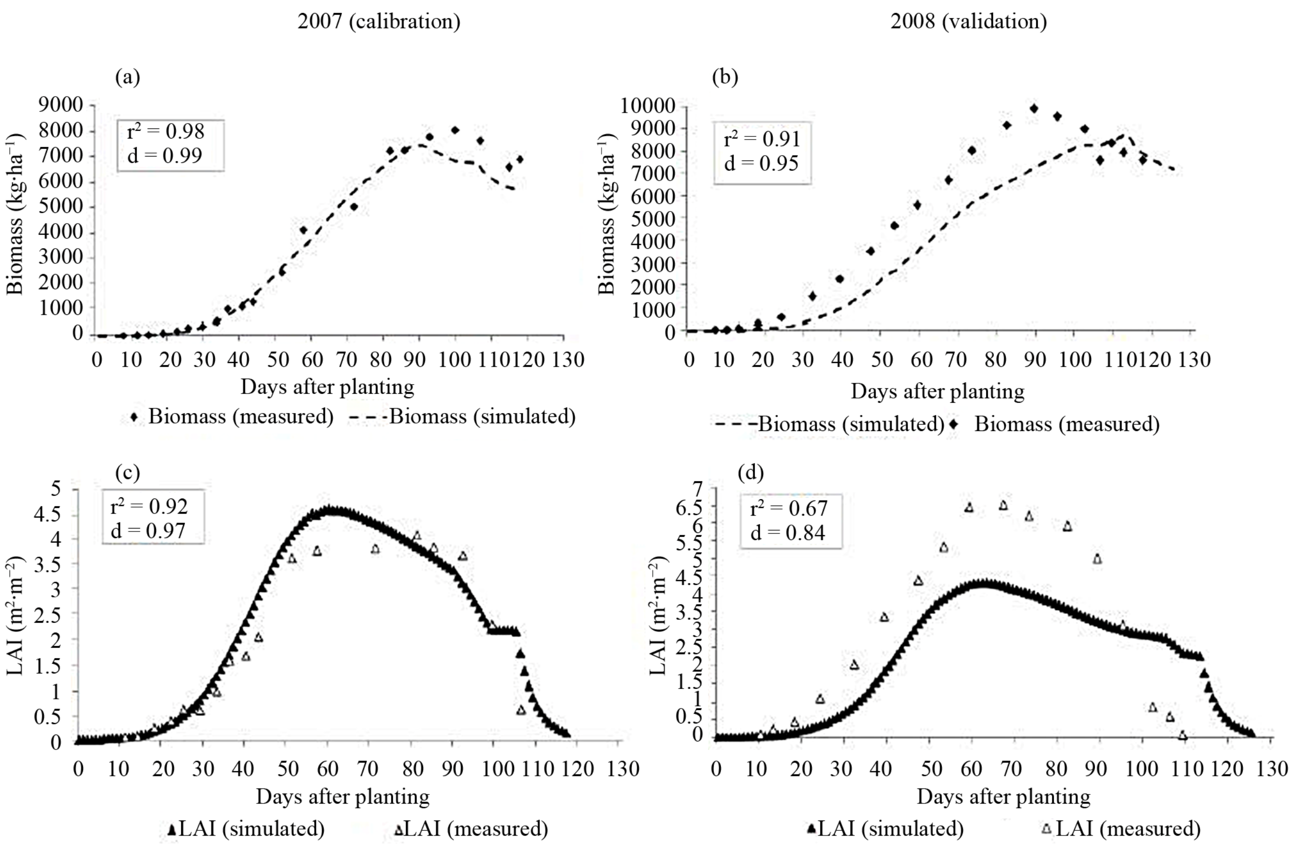

Figure 2. Time evolution of the simulated and observed above ground biomass for the calibration experiment (a) and for the validation experiment (b), (c) and (d) are the same but for LAI.

ured and predicted soybean leaf area index which has been attributed to water deficit. It should be noted that in the case presented here there were no substantial changes in precipitation and water stress in 2008 as compared to 2007.

Turning to the maize field experiment, we have used a short maturity variety, CD308, because it is most cultivated in the intra-season. The maize has been sown on 28/01/2007 and 28/01/2008 with spacing of 0.80 m between plants/rows. This accounts for 52,000 plants/ha. Similarly we have done for soybeans, the first experiment has been used to calibrate DSSAT, and the second one has been taken for model validation. It might be noted that for maize only anthesis, physiological maturity and yield are used to calibrate/validate the model results. The genetic coefficients used in the CERES-Maize module are presented in **Table 3**.

The model evaluation for maize demonstrates that the model simulates values very similar to those observed for the flowering date (anthesis), physiological maturity and yields. However, there exists difference of 100 kg/ha between the observed value (6832 kg/ha) and the simulated (6932 kg/ha) in the year 2007. Analyzes of the phenological validation for the year 2008, demonstrates that model overestimated the maize yield with difference of 606 kg/ha between the observed (5606 kg/ha) and the simulated value (6000 kg/ha) (**Table 4**).

Table 3. Genetic coefficient for maize.

Cultivar AG7000	P1	P2	P5	G2	G3	*PHINT*
	319	0.5	880	695	5.2	42.3

P1: Thermal time from seedling emergence to the end of the juvenile phase (expressed in degree days, ˚C/day, above a base temperature of 8˚C) during which the plant is not responsive to changes in photoperiod. P2: Extent to which development (expressed as days) is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate (which is considered to be 12.5 h). P5: Thermal time from silking to physiological maturity (expressed in degree days above a base temperature of 8˚C). G2: Maximum possible number of kernels per plant. G3: Kernel filling rate during the linear grain filling stage and under optimum conditions (mg·day^{-1}). PHINT: Phyllochron interval; the interval in thermal time (degree days) between successive leaf tip appearances [34].

3.3. Crop Response to Climate and CO_2

Differences in productivity between the current and future scenarios, as investigated in the present study, are dependent only of weather parameters and atmospheric CO_2 concentration. It might be stressed that the DSSAT models does not include interactions between temperature and CO_2 concentration however by changing the CO_2 concentration, modifications are imposed to the crop physiology by the fertilization effect. Several investigations have been conducted to evaluate the impact of anomalous climate conditions on crop yields [e.g. 1,21, 35-38]. Based upon these studies is concluded that warming conditions would lead to reductions in the potential productivity. This is associated with the shortening of the phenological stage changing the growing degrees days requirements. In fact, higher air temperatures accelerate plant phenology. Other effects not less important are related to physiological responses of photosynthesis, water stress, and grain filling rates.

Four modeling experiments have been conducted to quantify the individual effect of climate for both epochs present day (CLI-P and CLI-W) and future (GHG-P and GHG-W). The CLI-P and GHG-P experiments stand for simulations with no water stresses and optimum soil managements. The CLI-W and GHG-W experiments, however, take into account the effect of daily variations of precipitation in the crop phenology. These experiments, therefore, explores the effects of extremes events such as dry spells and torrential rains in the crop yields. The difference between PS and AS simulations may be assumed as the modeled "yield gap" for both current and future time slices. Specifically: the CLI-P (GHG-P) simulates productivity assuming that water and nutritional conditions do not limit the growth and development of the crop; 2. CLI-W (GHG-W) simulates productivity assuming that water does limit the growth and development of the crop. The simulations are not conducted with crop rotations system that in some parts of Brazil is the current practice.

All experiments assume optimum soil management. This treatment is needed because the soil in most of the

Table 4. Observed and simulated maize phenological data.

Parameters	Calibration			Validation		
	Obs	*Sim*	*Diff*	*Obs*	*Sim*	*Diff*
Anthesis (days)	52	52	0	56	55	1
Physiological maturity (days)	105	107	2	104	107	3
Yield (kg·ha^{-1})	6832	6932	100	5606	6000	406
Leaf area index, maximum (m^2·m^{-2})	4.1	4.6	0.5	6.49	4.3	2.19
Weight at maturity (kg·ha^{-1})	7.648	5.717	1.931	8.412	7.246	1.166
Yield (kg·ha^{-1})	3.273	3.154	119	3.479	3.484	5

Pará and Mato Grosso states is extremely poor of nutriaents. The top two inches of the acidic soil contains 99% of the nutrients. However, there exists regions, known as black earth, characterized by the presence of low-temperature charcoal in high concentrations; of high quantities of pottery sherds; of organic matter such as plant residues, animal feces, fish and animal bones and other material; and of nutrients such as nitrogen (N), phosphorus (P), calcium (Ca), zinc (Zn) and manganese (Mn) [39]. Black earth zones are generally surrounded by poor soil, or "common soil". These are infertile soils, mainly acrisols, but also ferralsols and arenosols [40].

The third set of simulations aims to investigate the influence of soil conditions on crop yields. This is done by comparing experiments conducted with minimum soil treatment with experiments previously discussed for present day (CLI-W) and the future (GHG-W) intervals. Experiments that do not include soil managements, such as practices and treatments used to protect soil and enhance its performance are hereafter referred to CLI-PN and CLI-AN for current conditions, and GHG-PN and GHG-AN for GHG conditions.

The method used for spatial interpolation of the model grid was the Kriging method, which is a statistical method similar to interpolation by weighted moving average. However, the Kriging weights given to each point are determined from a spatial pre-analysis using experimental semivariogramas. Thus, this method has the advantage of optimize the variable interpolated and has been used widely to spatial interpolation of grid points. These climatic variables were georeferenced in function of latitude and longitude, with the use a geographic information system (GIS) software ArcGIS version 9.3.

We disregarded the limitations on yield due to attack of pests and diseases as well as we have not applied shifting cultivation. This is a clear limitation of the study because it rather well established that climate change can affect the pest-plant dynamics. However, there do not exist a general consensus on literature how to treat/model this issue. For instance, [41] based on soybean free air concentration enrichment (SoyFACE) demonstrated that responses of the three pathosystems varied considerably under distinct levels of atmospheric CO_2 concentration.

Other uncertainties in our modeling approach is associated with the reliability of simulated climate for both current and future epochs. Under present day conditions our climate simulation reproduces the observed climate reasonably. The DSSAT model is driven by daily variations of weather conditions that are highly dependent on models initial and boundary conditions, and more strongly on models dynamics. Therefore, crop modeling experiments may deliver divergent results just by changing the experiment configuration. In this sense, for climate models uncertainty is an ever-present issue, as is the need to cope with it.

The modeling approach pursued here does not include also the two-ways interaction/feedback between the climate and the crop system in terms of radiative and water fluxes. Drawbacks also arise from the lack of implementation of technological advances on both crop varieties and soil managements, which may compensate the effect of climate changes.

As discussed by [1] the technological effect on productivity is tightly linked to the region and may vary locally among farmers. For instance, some areas of southern Brazil (in Minas Gerais State) experience an increase in yield by 800% from 1970 to 2000 whereas other municipalities do not show any improvement.

In this sense to include future technological advances as a forcing factor on crop yields simulation would primarily increase the uncertainties of the model outcomes, and may not necessarily represent a future crop variety. However, the application of present day varieties can help geneticists to disentangle important feedbacks, between the climate/weather and the crop system that may lead to the development of more resistant varieties to dry spells and warmer climates

3.4. Response of Crop Yields to Climate Conditions and CO_2

Figures 3(a)-(c) show the potential productivity (CLI-P) for maize under present day and greenhouse warming conditions for both B2 and A2 scenarios. Mean values of productivity simulated by DSSAT (**Figure 3(a)**) are between 2883 and 4980 kg/ha. According to the Brazilian Institute of Geography and Statistics or IBGE, the productivity of maize in the Amazon basin fluctuates between 1500 and 4500 kg/ha. In the region, the highest productivity is located in Mato Grosso (4200 kg/ha). This observed variability of yield can reveal that distinct social characteristics, soil management and technology within the region result in substantially modified productivity levels. In our simulation, these social effects are not included and changes in productivity are entirely associated to weather patterns.

Figures 3(b) and **(c)** show differences between the potential productivity of maize under present day conditions and that forced by the B2 and A2 scenarios for the interval 2070-2100. Values as low as 70% are found in response to the implementation of B2 and A2 conditions (**Figures 3(b)** and **(c)**).

This drop in the potential productivity is tightly linked to the shortening of the phenological stages. Indeed, the length of the maize phenological cycle simulated in our study is about 120 days under PD conditions. The inclusion of greenhouse forcing, however, reduces the cycle by 15% - 20% (not shown). Reduction in the maize cycle

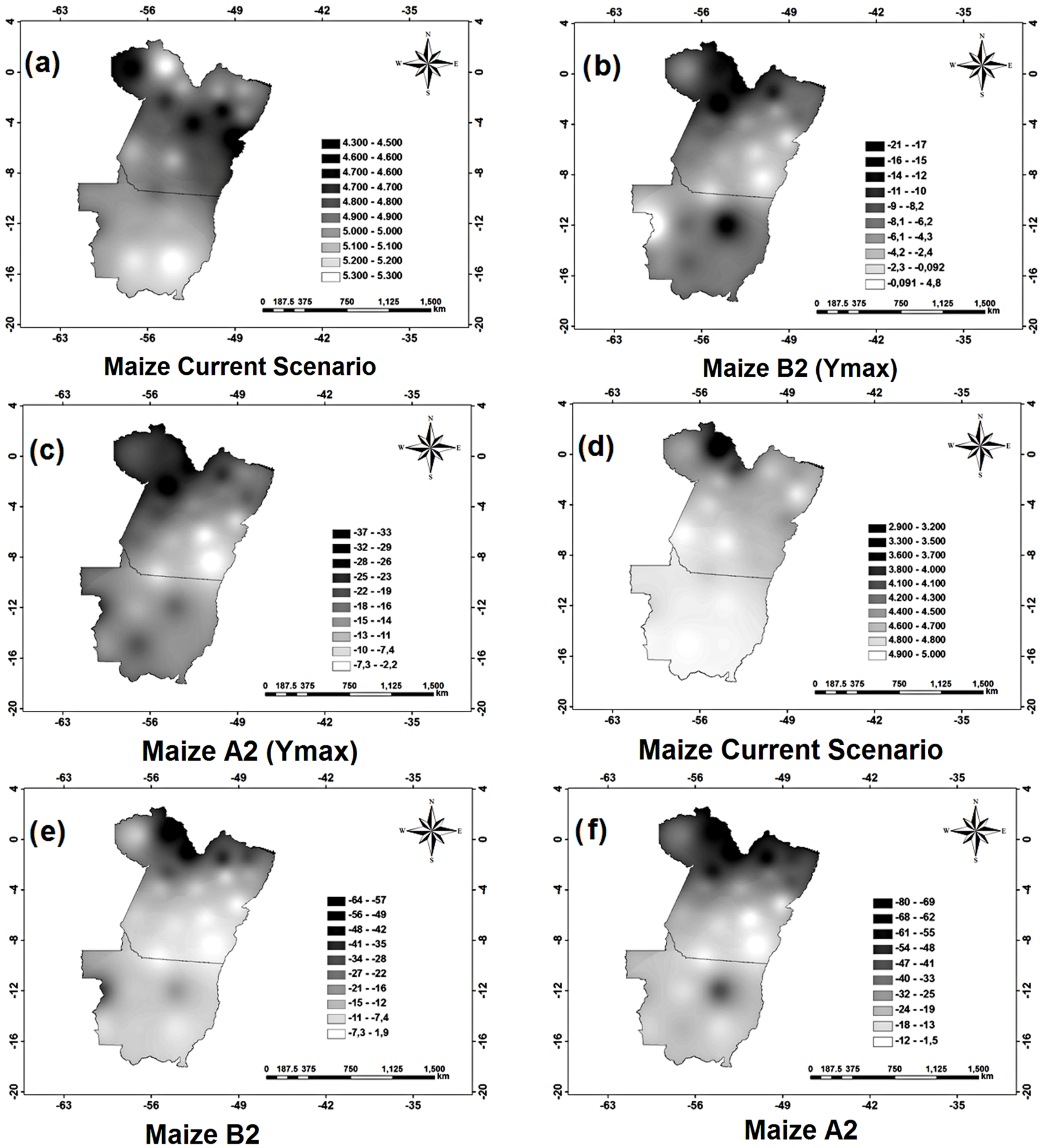

Figure 3. (a) Potential maize yield for PD conditions (kg/ha), (b) differences between the potential maize yield based on B2 scenario and PD conditions, (c) differences between the potential maize yield based on A2 scenario and PD conditions, (d), (e) and (f) are the same as (a), (b) and (c) but for the actual maize yield.

is more pronounced in northeastern/northern part of Amazon basin in close accordance with the simulated positive temperature anomalies. Based upon calculations with the CERES—Wheat model [42] demonstrated that 2˚C increase in temperature could result in a drop of productivity by up to 20%. Similar results have also been found by [1]. It should be noted that other effects, such as physiological responses of photosynthesis and grain filling rates are also important. Reference [43] argued moreover, that in well watered conditions, such as presented here, it is expected less CO_2 stimulation than in water stressed conditions, as observed in FACE enrichment experiments which may reduce maize yield.

In order to have a detailed analysis of the influence of climate change on maize yields, crop simulations have been conducted including the availability/precipitation (e.g. rainfed), which may be assumed as real projected yield or actual productivity (CLI-W, **Figures 3(d)-(f)**). By comparing **Figures 3(a)** and **(d)**, one may note that the maize productivity is not limited by precipitation for PD conditions. What is reasonable since today's precipitation is abundant in the Amazon basin. However, for increase in GHG effect, a different picture emerges in the sense that the reduction in precipitation during the phenological cycle leads to substantial productivity losses.

Figures 3(e) and **(f)** demonstrates that the inclusion of water availability as initial condition induces modifications in the crop yield due to water deficit in northern Amazon basin. Thus, the water shortage intensifies the negative effect associated with increased temperature.

Abiotic stress (precipitation + temperature) has been claimed as the most harmful factor concerning the growth and productivity of crops worldwide [44]. It is interesting to note that changes in the maize yield in the central part of Amazonia induced by climate change (precipitation) are weaker, as compared to those simulated for the potential yield (see **Figures 3(b)**, **(c)** and **(e)**, **(f)**). Despite some discussion due to scale (canopy versus leaf), it has been found that the CO_2 fertilization effect is more pronounced in water-stressed conditions leading to enhanced yield, which is primarily linked to reduced water use [36]. In this sense the CO_2 increase opposes the negative effect of reduced precipitation.

Again, these results are entirely dependent on the climate output included as initial conditions into the crop model. A brief investigation of climatic variables that more strongly affect crops during the phenological phase, demonstrated that the incorporation of initial conditions as projected by the B2 and A2 emission scenarios of climate changes, reduce total accumulated rainfall in Pará and Mato Grosso states basin with respect to PD conditions. In opposite, precipitation increases by 30% - 40% during the maize phenological cycle (**Figures 4(a)-(c)**). Based upon these analyzes we conclude that the crop yield in that region is affected by modified daily rainfall variability and therefore associated with the occurrence of dry spells. It is well known that continuous period of no precipitation during the rainy season, lasting for approximately 10 days, negatively affects crop yield.

The strengthening of GHG forcing also induces modification in the crop evapotranspiration rates (ET, **Figures 4(d)-(f)**). Theoretically, an increase in air temperature and reduction in atmospheric moisture content would be associated with an increase in the evaporative demand of the atmosphere. However, due to decrease in growing degree days and LAI (Leaf Area Index), induced by higher temperature and in transpiration due to stomatal closure, our results indicate lower ET in the GHG experiments as compared to the results carried out under today's conditions. Previous results based on experimental findings and modeling studies have indicated considerable decreases in actual ET due to stomatal closure also under elevated CO_2 concentration for maize [45,46]. As an exercise we have done simulations to evaluate the effect of soil treatment/fertilization on both crop yields. This experiment is conducted with the minimum fertilization as recommended by [47].

For maize we have used three applications of 40 kg/ha of nitrogen, 5 kg/ha of P_2O_5 and 30 kg/ha of K_2O in the seeding. This procedure is repeated 45 and 70 days after the seeding date. It is demonstrated that the actual maize yield is reduced by approximately 40%, for present day conditions, as compared to the simulation under optimum soil fertilization (**Figures 3(d)** and **(g)**). The inclusion of the B2 and A2 scenarios causes substantial changes in the yield in the sense that for appropriate soil management, climate change impact leads in general to drop in productivity by 10-30% (**Figures 3(e)** and **(f)**). On the other hand, by taking into account the soil deficiencies the reduction in maize yield may reach values as low as 50% - 60% (**Figures 3(g)** and **(h)**).

The effect of climate changes in soybeans is discussed next. This is important because the soybeans belong to C3 photosynthetic pathways and therefore elevating CO_2 concentration stimulates net photosynthesis. **Figures 5(a)-(c)** shows the potential productivity for present day as well as for climate conditions induced by the B2 and A2 emission scenarios. Currently, the simulated soybeans yield may reach values of up to 3120 and 2570 kg/ha in Pará and Mato Grosso states (**Figure 5(a)**), although mean productivity is by about 2720 kg/ha that is very close to the observed values. Under present day conditions those states provides the optimum temperature range of soybean cultivation which is between 20˚C - 30˚C and short day-length (by up to 14 hours or less).

The productivity gain is linked to higher temperature as well as higher atmospheric CO_2 concentration, for both B2 and A2 scenarios, as compared to today's conditions (**Figures 5(b)** and **(c)**). However, by applying the A2 forcing soybeans responds less efficiently in the sense that its productivity rate increases but still lower than in the B2 scenario.

Some consideration may be posed in terms of the robustness of the CO_2 fertilization effect, [48] argued that for C3 leaves, additional CO_2 results in greater photosynthesis when associated with temperatures below certain values (*i.e.* supraoptimal temperatures). Over long time scales this fertilization effect may be reduced due to photosynthetic acclimation [49]. For instance, by evaluating the response of soybean to air temperature and CO_2

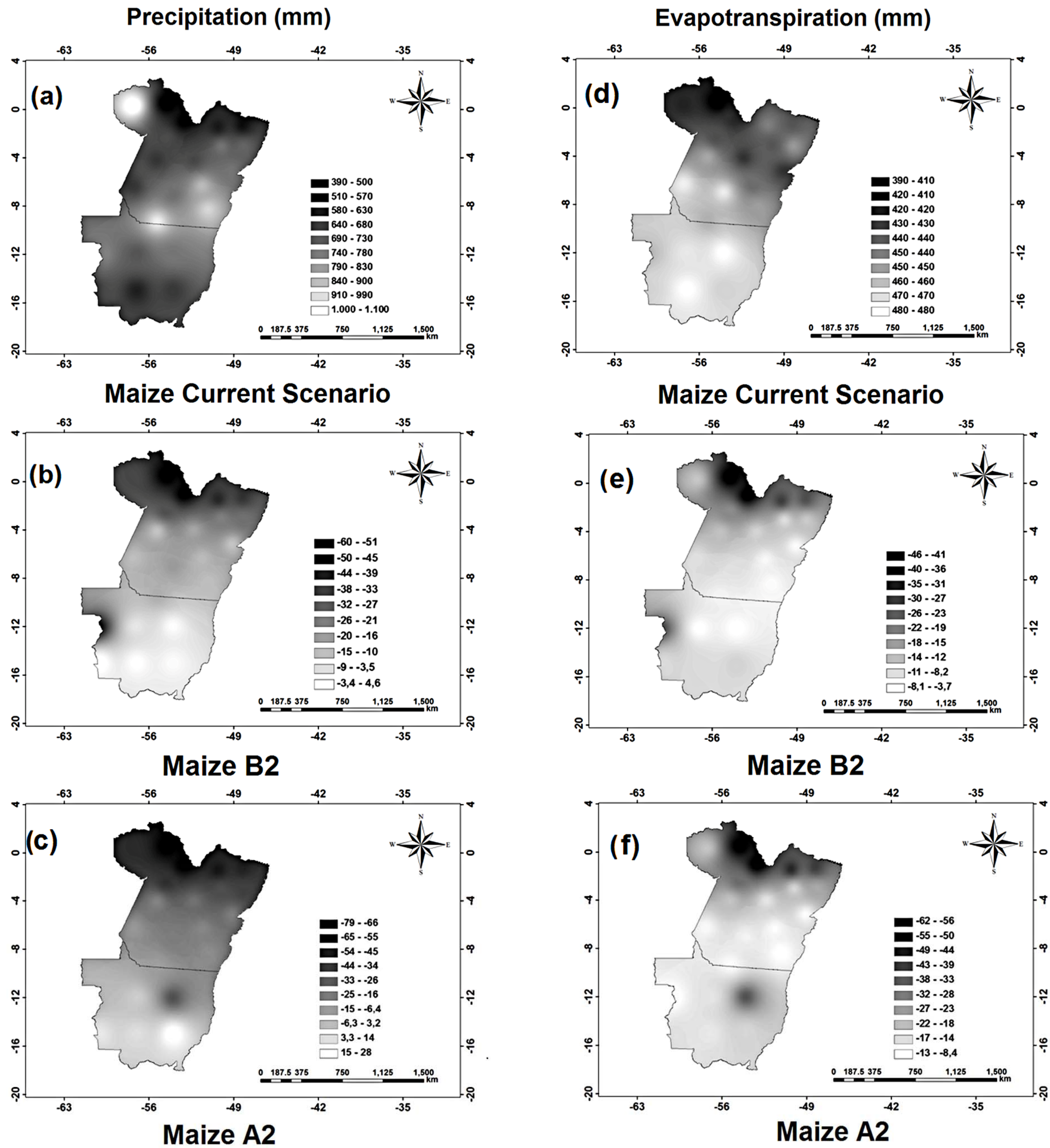

Figure 4. Total precipitation during the maize cycle: (a) present day conditions, (b) anomalies between present day and B2 simulation and (c) anomalies between present day and A2 simulation, (d), (e) and (f) are the same as (a), (b) and (c) but for evapotranspiration (mm).

concentration, [50] found that the nonlinear increase with temperature in leaf area and above ground biomass was attributed to the highest temperature treatment being near the optimum for growth and development. On the other hand, seed yield increased with CO_2 enrichment due mainly to an increase in seed number rather than weight per seed.

Figures 5(d)-(f) show the soybeans productivity under the effect of the water availability through changes in precipitation as simulated for the current and future intervals. The comparison between **Figures 5(a)** and **(d)**, demonstrated that the Pará and Mato Grosso basin ex-

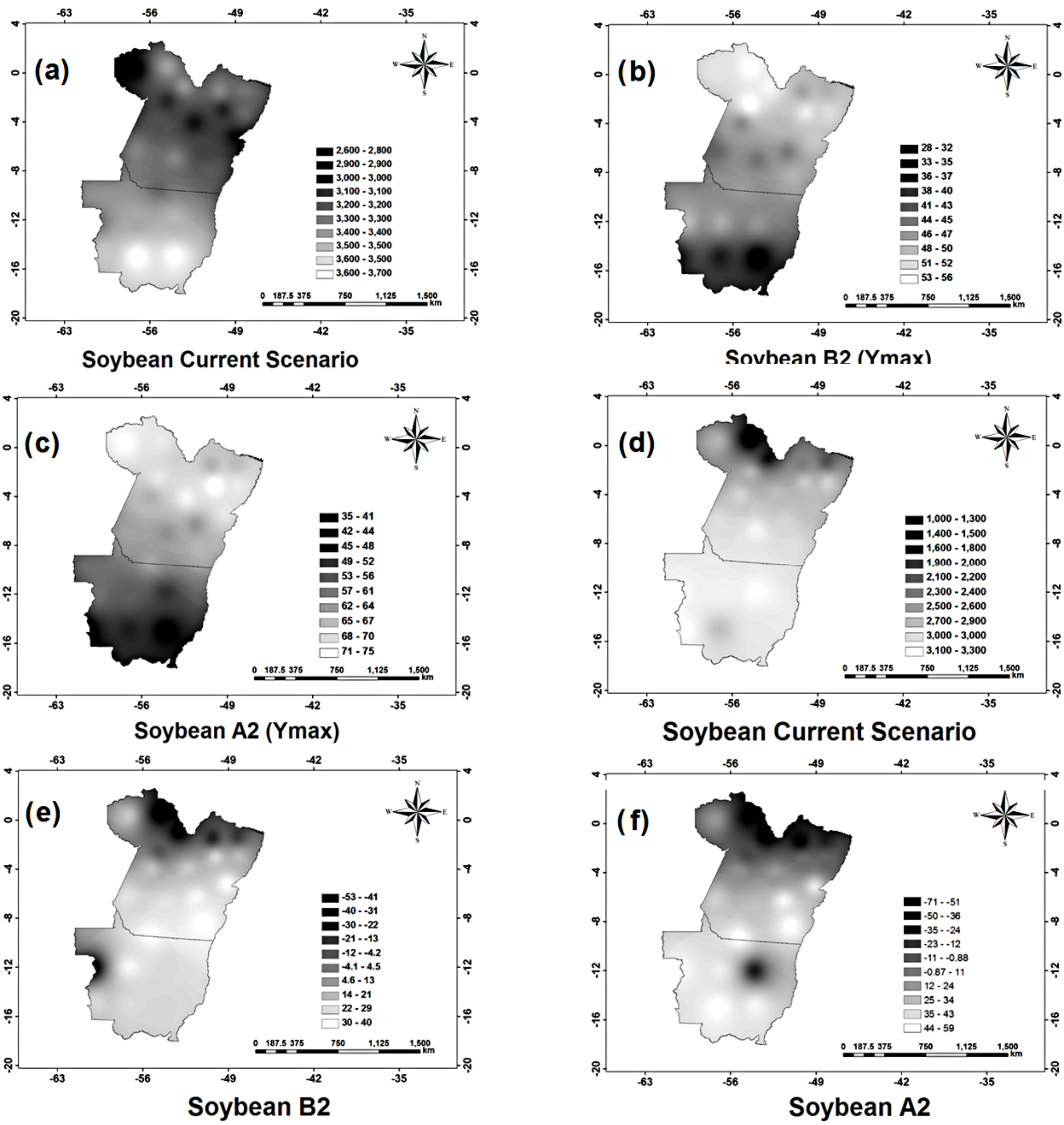

Figure 5. (a) Potential soybeans yield for PD conditions (kg/ha), (b) differences between the potential maize yield based on B2 scenario and PD conditions, (c) differences between the potential maize yield based on A2 scenario and PD conditions, (d), (e) and (f) are the same as (a), (b) and (c) but for the actual maize yield.

periences a drop in the crop yield of about 30%, by considering the influence of precipitation. Indeed, this may affect the soybeans productivity due to crop water stress. Since this experiment has been conducted with present day CO_2 concentration (380 ppm), the efficiency of the fertilization effect to increase the soybeans yield does not compensate the negative effect of the water shortage.

Turning to evaluation for the future interval, substantial changes are predicted to occur for the B2 and A2 scenario of climate change. The northern part of the Pará state are strongly affected and show reduction in soybeans productivity up to 40% - 60%, as compared to current simulated values (**Figure 5(d)**).

Despite some areas exhibit lower productivity, it should be stressed that in general the inclusion of GHG forcing flavors an enhancement in soybeans yield for most part, such as the increase in soybeans by up to 60% in the Pará and Mato Grosso states.

Similarly we have presented for maize, the importance of a reasonable minimum soil treatment has been evaluated for soybeans production. One should note that the previous discussion has been taken from simulations under optimum soil conditions (*i.e.* soil fertilization does not limit the crop development). Differently than the maize yield response to climate change, soybeans productivity increases except in the Mato Grosso. Fertilization for soybeans has been applied twice: 40 kg/ha of P_2O_5 and 30 kg/ha of K_2O in the seeding and 40 days after the seeding.

The results demonstrate as far as soybeans yield is concerned, the Pará and Mato Grosso states soil characteristics do not impose substantial limitation for the implementation of this crop for current conditions. Although, the values of the soybeans yield as delivered by this simulation are lower than those predicted by the experiments conducted with proper soil management (not shown). Nevertheless, the evaluation for future climate conditions shows that the soil fertilization may impact the crop productivity in different ways and it depends upon the amount of soil water storage, precipitation and nitrogen (N).

For instance, over regions experiencing reduction in rainfall such as northern Amazon basin (**Figure 6(a)**), inappropriate fertilization can potentially reduce even more the soybeans yield, in respect to a situation with proper soil management.

For abundant water conditions our results demonstrate that changes resulting from distinct fertilization scheme may lead to drop in 20% - 30% of soybeans yields. Biogeochemical theory demonstrates that the lack of soil nitrogen (N) may limit natural ecosystem response to enhanced CO_2 concentration, diminishing the CO_2-fertilization effect on terrestrial plant productivity in unmanaged ecosystems [51].

Figure 6 shows the total amount of precipitation and ET during the crop cycle. Under PD conditions (current scenario) soybeans received approximately 658 and 766 mm of water in Pará and Mato Grosso states. In the simulation for the B2 and A2 scenario, there do exist a substantial decrease in accumulated rainfall by up to 30%. Investigation of ET indicates that less (more) precipitation as simulated for both the B2 and A2 scenario is accompanied by reduced (increased) ET rates.

This reveals that under these climate conditions, the crop metabolism is (stimulated) decelerated until a limit that is imposed by the soil water availability. In the former case—less precipitation—the water uptake by the roots is reduced limiting the growth and crop yield. Reference [52] argued that soybean adapted to water stress by reducing transpiration through changes in stomatal conductance due to reduced rate of stem sap, which may be associated with the lower root moisture absorption efficiency.

Anomalous patterns of precipitation and ET are tightly connected with the reduction in soybeans yield as predicted to occur by the simulations forced by climate changes scenarios. This is highlighted over Pará (see **Figures 5(e)**, **(f)** and **6(b)**, **(c)**) where the substantial decrease in productivity matches closely the negative anomalies of precipitation and ET.

This crop response to climate features is more pronounced under the B2 assumption. It might be noted, therefore, the non-linear response of the crop system insofar changes in temperature, precipitation, evapotranspiration and CO_2 are concerned.

In addition to modifications in the mean climate, the introduction of greenhouse warming forcing induces a distinct temporal variability. Indeed, **Figure 7** shows the time variability of soybeans yield for PD and GHG intervals. Primarily, one may note that changes in the actual (rainfed) productivity between the PD and GHG runs are regionally dependent, water shortage is more evident in Para (**Figures 7(a)** and **(b)**).

Because the A2 scenario delivers more precipitation than the B2 scenario during the crop cycle in Mato Grosso (Figure not shown), that state is more affected in the latter scenario showing a substantial drop in the soybean yield. It should be noted that the B2 scenario delivers lower near surface temperature as compared to the A2 scenario counterpart.

Moreover, Pará exhibit large fluctuation under GHG condition (**Figures 7(a)** and **(b)**). This may be attributed to changes in the annual precipitation variability induced by the GHG forcing.

In fact, C4 plants do not benefit from increased CO_2 concentration because the CO_2 concentration in the bundle sheath cells is close to saturation [e.g. 53,54]. Differently from what has been discussed for soybean, maize is more sensitivity to water availability as may be noted in comparing actual and potential productivity. Evaluation for the GHG interval shows drop in productivity that is more evident in Pará and Mato Grosso states for both A2 and B2 scenario. By comparing projected changes of maize and soybean yields it may be demonstrated that maize productivity experiences higher inter-annual variability.

A common feature which appears in both crop simulations, is the sharp decline of yields in the end of the GHG interval associated with a severe drought throughout these states (**Figures 8(a)** and **(b)**). The highly distinct inter-annual crop response to GHG forcing, highlights the spatial heterogeneity of the predicted future climate.

On the hand, the negative values primarily result from reduction related to the yields instead of decreased ET.

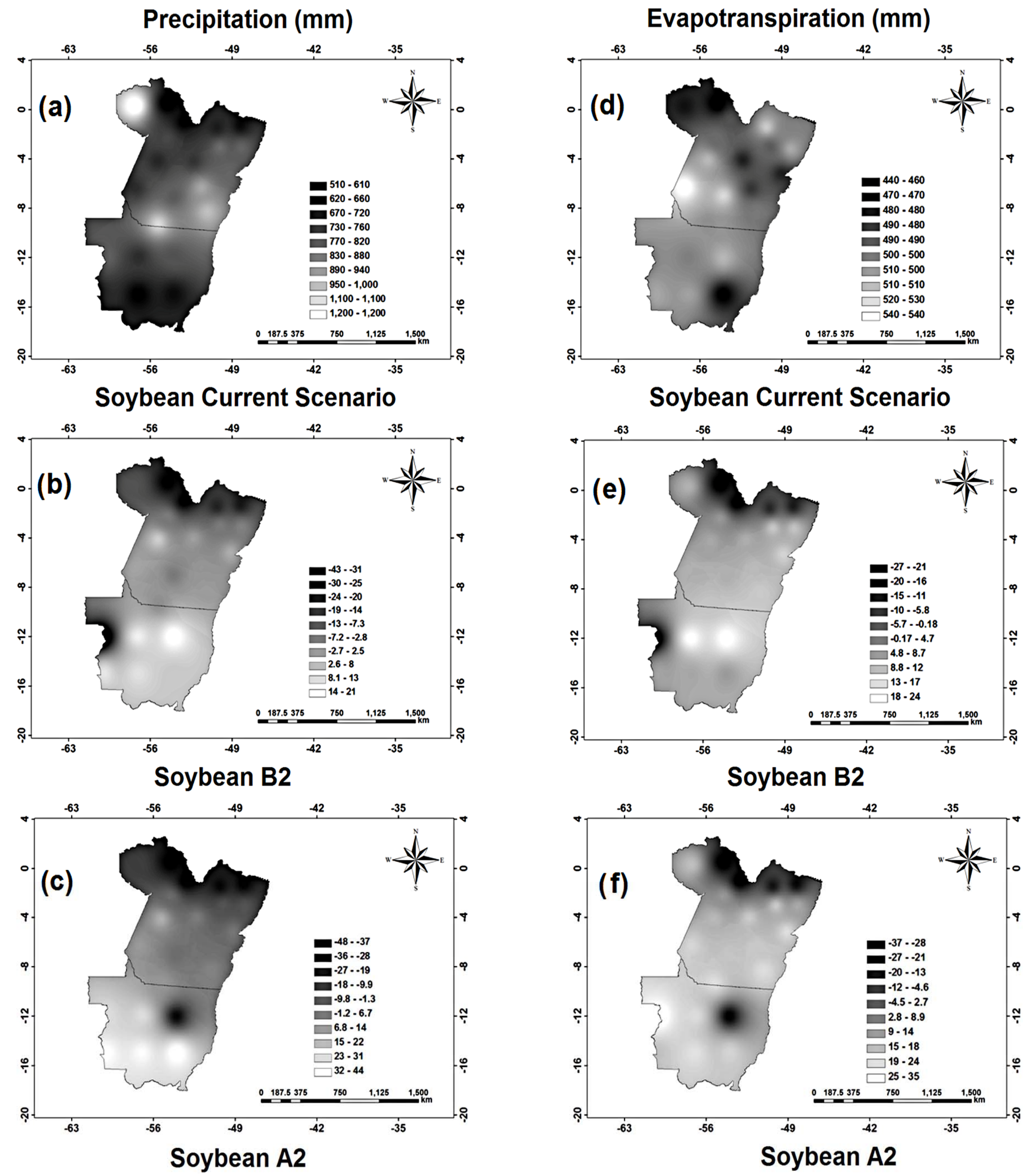

Figure 6. Same as Figure 5 but for soybeans.

Comparing the WUE response between the two crops may lead to argue that the maize (C4) experiences greater improvements in water use as compared to soybeans (C3).

These results may be compared to [53], in which the soybean dramatically reduces the WUE (69%), with the increase in temperature, because the CO_2 fertilization effect is minimized when the temperature is high than 35˚C. Reference [54] argue that both C3 and C4 species may experience an increase in WUE when submitted to higher temperatures and increased CO_2 concentration, however, the magnitude of changes is subject to water

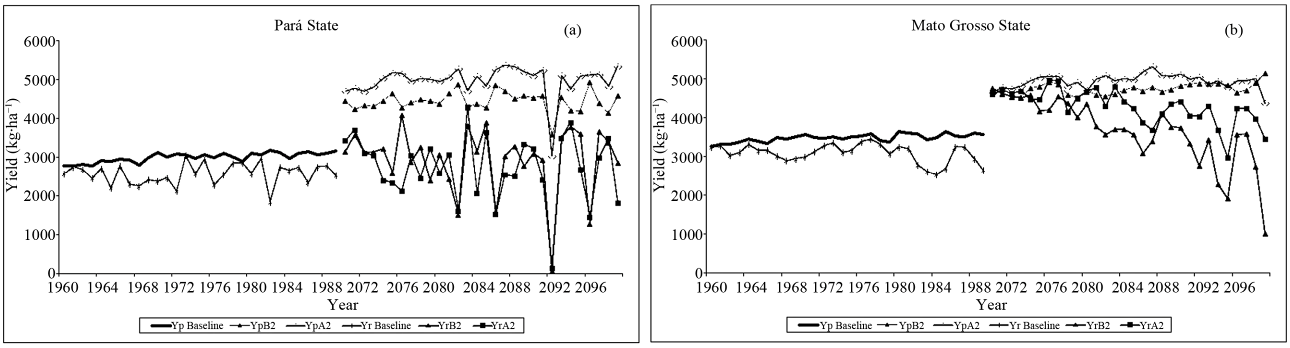

Figure 7. Temporal evolution of soybean productivity (kg/ha) in the Pará and Mato Grosso states, Yp baseline (PD potential productivity), Yr baseline (PD actual productivity (rainfed)), YpB2 (GHG potential productivity based on B2 scenario), YpA2 (GHG potential productivity based on A2 scenario), YrB2 (GHG actual productivity based on B2 scenario) and YrA2 (GHG actual productivity based on A2 scenario.

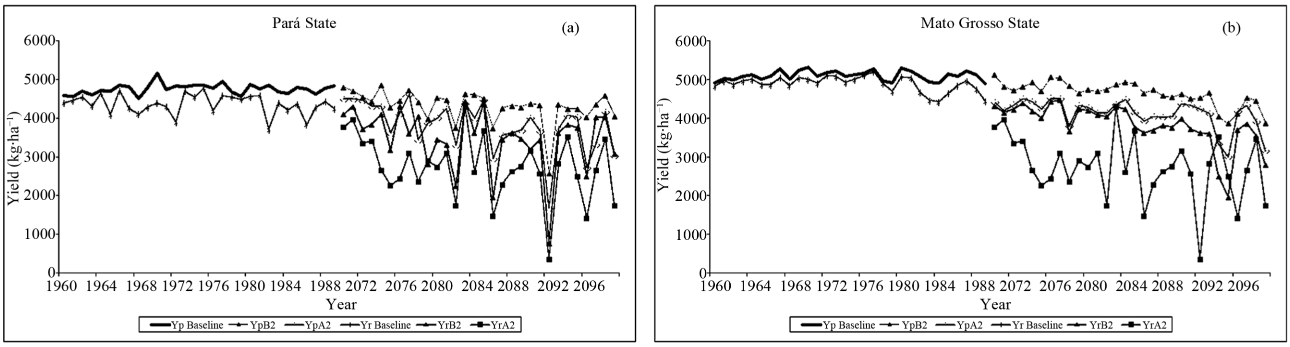

Figure 8. The same as Figure 8 but for maize.

availability, nutrients and radiation.

4. Concluding Remarks

Based on regional climate projections from the HadRM3 model for current, B2 and A2 future scenarios of climate change, further implemented as initial conditions in the DSSAT crop model, this study evaluated the feasibility of the Mato Grosso and Pará to the expansion of soybeans and maize crops. The results indicated that by taking into account future climate conditions, for the end of the 21st century, a substantial drop in maize yield is simulated despite proper soils management with optimum fertilization.

A different feature is delivered by DSSAT model for soybeans because typical C3 plant is stimulated in response to elevated atmospheric CO_2 concentration. By taking averaged conditions, soybean exhibits an enhancement in the potential yield for both scenarios B2 and A2, with values as high as 60%. The actual productivity (rainfed) also increased. It should be emphasized that future climate conditions increase the inter-annual variability of both crop leading to large fluctuation of crop yields.

These findings may point to increased pressure on the primary forests associated with the feasibility of the region to soybeans expansion and the conversion of forest to agriculture. It is important to keep in mind that the Amazonian deforestation independently of the cause; due to climate change or linked to the forest clearance will have the potential to do enormous damage for all kind of species, soil erosion and hydrology. Therefore, the results presented here may help to alert the possible problem to be faced in the future by inducing agricultural expansion.

5. Acknowledgements

This study has been sponsored by the National Institute of Science and Technology Climate Change and by the SoCoCA project funded by the Research Council of Norway (contract 190159). Moreover support has been provided by the sub-rede Agricultura do MCTI and by the INCT-Mudanças Climáticas.

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