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Increased climate risk in Brazilian double cropping agriculture systems: Implications for land use in Northern Brazil

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ABSTRACT

Brazil is currently one of the largest soybean and maize producers in the world. A dramatic increase in total production of these grains was possible due to the implementation of double cropping systems (two crops on the same land in the same agricultural calendar) in places where the wet season is sufficiently long. Although several recent studies have assessed soybean productivity change in South America after climate change, they have not considered important factors such as the decision whether or not to adopt double cropping systems and the incidence of diseases—both of which can influence planting dates. Here, we test five cultivars (expressed by total growing degree days) and 10 planting dates using two crop models and four climate models to assess soybean productivity in Brazil after climate change. Our results indicate that soybean productivity will increase in farms that choose to grow only one crop in the agricultural calendar (planting dates occur usually in November–December). However, the productivity of short-cycle cultivars planted in late September, typically sowed by farmers who chose to grow two crops in the same agricultural calendar, may dramatically decrease. While delaying planting dates of early planted cultivars can offset productivity loss, it may also compromise the possibility to plant a second crop. Furthermore, additional deforestation can lead to increased productivity loss due to further reductions in September and October rainfall. Urgent adaptation strategies are needed to maintain highly productive double cropping systems in Brazil in the advent of climate change.

1. Introduction

Brazil is the second largest soybean producer and the third largest maize producer in the world, contributing with 30% and 7%, respectively, of the global harvest of these crops in 2013. Argentina and Paraguay are also in the top six soybean producers. While global production of these commodities nearly doubled from 1993 to 2013, soybean and maize production in Brazil and Argentina increased three-fold. This enormous increase in production in the last 20 years is even greater than the increase observed in the United States, the main producer of these commodities worldwide (FAO, 2014). One of the main drivers of these dramatic increases in grain production in Brazil has been the extensive adoption of double cropping systems, in which farmers sow a second crop (mainly maize, but cotton is also common) in the same space after soybean has been harvested, optimizing the use of land and resources. Second crop production was not particularly prevalent a decade ago, but by 2014 it represented nearly 58% of the total area of harvested maize (Conab, 2015).

Double cropping systems are favored by high annual rainfall, a long wet season and a low variability of the onset of the wet season (Arvor et al., 2014). In most regions where double cropping has been adopted, the wet season is about 6–7 months long and there is very little margin for error in the timing of sowing and harvesting. For double cropping to be viable, farmers need to ensure that the soybeans are harvested in time for the second crop to mature while climatic conditions are still favorable. Considering that sowing may take as long as two to four weeks for a 10,000 ha soybean ranch in

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central-northern Brazil, farmers who aspire to use double cropping systems typically choose to sow as soon as possible: at the end of the sanitary break, when rainfall conditions are marginally favorable. The sanitary break, adopted by Brazil and Paraguay, is the 2–3 month period where soybean plants are absent from the fields as a measure to control Asian soybean rust (*Phakopsora sp*). The break typically lasts from June 15 to September 15/30 in Brazil. Sowing soybean at the end of the sanitary break carries a relatively high climate risk but a low probability of rust infection, thereby reducing the need to apply fungicides. Moreover, early harvested soybean typically fetches higher market prices.

South American, and especially Brazilian, agricultural production is projected to rise this century in order to meet part of the increasing global demand for food. The FAO estimates that Brazilian soybean and maize production may increase 37% and 13%, respectively, in the next 10 years (OECD/FAO, 2015). Similarly, the Brazilian Ministry of Agriculture, Livestock and Supply (MAPA, from the acronym in Portuguese) estimates that the production of these commodities will increase 33.9% and 26.3%, respectively. To avoid negative environmental consequences, increases in Brazilian food production should ideally not be achieved by a proportional increase in the planted area, and double cropping agriculture systems might play an important role to achieve this objective.

The long-term viability of double cropping systems in Brazil is critically dependent on future climatic conditions. However, recent long-term climate assessments indicate that the wet season in southern Amazonia is becoming shorter (Butt et al., 2011; Costa and Pires, 2010; Fu et al., 2013) due to deforestation and changes in atmospheric composition. Such changes in seasonality may be incompatible with the adoption of double cropping systems (Arvor et al., 2014).

Previous modeling studies of the impacts of climate change on crop productivity often oversimplify the complex reality of croplands (Rotter et al., 2011). For example, studies of soybean productivity in South America after climate change typically consider either fixed (Justino et al., 2013; Oliveira et al., 2013; Rosenzweig et al., 2014) or optimum planting dates (Rosenzweig et al., 2014) and the use of only a single crop in the same agricultural calendar. Critically, they have neglected the influence of plant infection, oversimplifying the representation of soybean cultivars and plantings dates that Brazilian farmers currently adopt and, by extension, their likely adaptation to climate change. Even more recent studies, while overcoming some of the previous limitations, have not incorporated the use of double cropping systems (e.g. Oliveira et al., 2013; Rosenzweig et al., 2014). A more realistic model of Brazilian agriculture needs to incorporate realistic representations of cropping systems, planting dates and cultivars, all of which are influenced by economic (e.g. profit) and biophysical (e.g. climate, disease) factors.

Here, we use two gridded crop models and four climate models to assess how regional and global climate change may affect soybean productivity until 2050 under the following realistic management options:

(i) farmers choose to plant short-cycle soybean cultivars immediately after the end of the sanitary break in order to grow two crops in the same agricultural calendar;
(ii) farmers choose to sow soybeans only under favorable climate conditions to obtain the highest productivity (one crop per agricultural calendar).

Although our focus is soybean productivity in Brazil, we also briefly discuss how the productivity of this commodity may change in Argentina and Paraguay. The results presented here can contribute to the development of effective solutions to mitigate the negative effects of climate change in soybean productivity and to maintain high levels of production in the region.

2. Methods

2.1. Gridded crop models description

We use two mechanistic gridded crop models (GCR) to evaluate the change in soybean productivity after climate change (therefore reducing the uncertainty related to model induced bias): the Light-Use Efficiency Model—LUE (Costa et al., 2009; Oliveira et al., 2013) and the Integrated Model of Land Surface Processes (INLAND, Costa et al., manuscript in preparation). Even though the phenological processes in both models are a function of temperature (accumulated growing degree-days), they differ in complexity.

The simplest GCR is the LUE model, where carbon assimilation is simulated using the concept of light-use efficiency. The intensity of radiation, limited by temperature and the availability of soil water, determines soybean daily dry matter net production. Total carbon assimilation is allocated to leaf, stem, root or grains depending on the phenological stage. Soybean productivity is estimated based on the percentage of dry matter allocated to grains. The model operates in a daily time-step, and is fully described by Oliveira et al. (2013).

The most complex crop model of our GCR ensemble is INLAND, a fifth-generation land surface model that simulates the exchanges of energy, water, carbon and momentum in the soil-vegetation-atmosphere system, canopy physiology (photosynthesis, stomatal conductance and respiration) and terrestrial carbon balance (net primary productivity, soil respiration and organic matter decomposition). Processes are organized in a hierarchical framework and operate in time-steps of 60-min. This model is an evolution of Agro-IBIS (Integrated Biosphere Simulator) (Kucharik and Twine, 2007) and has been developed as part of the Brazilian Earth System Model project, aiming to better represent Brazilian biomes (as Amazon and Cerrado) and processes (fire, flooding and agriculture). We use version 2.0, which includes the representation of four crops in addition to 12 natural plant functional types.

Both models were run for the entire South America, with a grid resolution of $1^\circ \times 1^\circ$ ($\sim$110 km $\times$ 110 km).

2.2. Experiment design

2.2.1. Planting dates and cultivars

In each individual simulation in this work (sets of simulations are described in Section 2.2.2) we simulated 10 planting dates (09/15, 09/25, 10/05, 10/15, 10/25, 11/05, 11/15, 11/25, 12/05 and 12/15) and 5 cultivars, that vary according to the accumulation of growing degree-days (GDD) needed to achieve physiological maturity – from the earliest to the latest cultivar: 1500, 1600, 1700, 1800 and 1900 GDD (base temperature 10 °C), with typical total cycle duration from 100 to 130 days. Therefore, for every model/scenario we have 50 possible configurations of planting dates and cultivars for each pixel. We then focus our analysis on two specific cases:

- **ESOY**: Short-cycle soybean cultivar (average cycle duration of 100 days) planted early right after the sanitary break (September 25th), to represent farmers who choose to harvest soybean in time to plant a second crop in the same agricultural calendar;
- **HSOY**: Highly productive soybeans, representing farmers who choose to plant only one crop in the same agricultural calendar, and therefore can sow soybean under the most favorable climate conditions. In this case, planting dates and cultivars at each pixel are the ones that lead to highest yields among all of the 50 simulated configurations.

2.2.2. Land use and climate change scenarios

We conducted two sets of simulations, from 2011 to 2050, to estimate the change in soybean productivity after climate change, as follows.

2.2.2.1. Effects of land-use change and change in atmospheric composition on climate as in CMIP5 (RCP8.5). This group of simulations accounts for the effects of land-use change and the change in atmospheric composition on climate with both land use and atmospheric composition according to the CMIP5 (Coupled Model Intercomparison Project Phase 5) experiment. We assess the RCP 8.5 $W m^{-2}$ scenario (RCP8.5, Riahi et al., 2011) which assumes that climate change leads to a radiative forcing of about 8.5 $W m^{-2}$ in 2100, and CO_2 concentrations increase from 387 to 541 ppmv from 2011 to 2050. This is considered a high emission scenario and, although it is the most pessimistic among all four IPCC AR5 scenarios, it is also the one that best represents the 2005–2014 emissions (Fuss et al., 2014).

We run simulations for RCP8.5 with climate data from four climate models: the Hadley Centre Global Environmental Model, version 2 (HadGEM2-ES), the Model for Interdisciplinary Research on Climate (MIROC-ESM), the Meteorological Research Institute Coupled Atmosphere–Ocean General Circulation Model, version 3 (MRI-CGCM3) and the Norwegian Earth System Model, version 1 (NorESM1-M). Models ability to correctly simulate the onset and the cessation of the wet season in soybean productive regions is assessed in Appendix A. Although the models capture the spatial patterns of precipitation compared to the Terrestrial Hydrology Research Group (THRG) database (Sheffield et al., 2006), there are tendencies to underestimate rainfall amounts and delays in model wet season onset that ranges from 6 to 24 days, in the cropping location studied. (see Appendix A). The following variables were used as inputs for these simulations: mean, maximum and minimum temperature (°C), precipitation (mm/day), incoming solar radiation ($W m^{-2}$), wind speed (m/s) and specific humidity (kg_{H_2O}/kg_{air}). These simulations also consider the physiological effects of elevated CO_2 concentration on carbon assimilation by soybeans. We run simulations with input of all climate models, using both crop models.

RCP8.5 provides a very comprehensive description of land use change until the end of the 21st century, including the representation of transition from primary land to cropland, pasture, urban areas and also the shift from all of these previous uses to the others. However, regardless of the completeness of the transitions depicted, each Earth System Model (ESM) implements land-use differently, following the structure of their land surface models.

We examined land use data used in HadGEM2-ES and MIROC-ESM (the main ESMs used in this study). In these models, the amount of Amazonia and Cerrado deforested until the middle of the century seems to be low: until 2050, total deforested area in these biomes is smaller than 20% and 60%, respectively (Fig. 1), and these levels of deforestation were already achieved in reality in the early 2010's. Such deficiency in land surface could also impact the climate model data, including the time of onset of the wet seasons used to drive the crop model simulations. Although Amazon deforestation rates have dramatically decreased from 2005 to 2012 (Hansen et al., 2013), in 2013 the decreasing trends reversed and started to increase again until 2015, according to PRODES (Projeto de Monitoramento da Floresta Amazônica Brasileira por Satélite). Even though deforestation has slowed down, currently there is little evidence that agriculture expansion is coming to a halt in Cerrado and Amazonia (Bowman et al., 2012; Lapola et al., 2014; Soares-Filho et al., 2014; Dias et al., 2016). Therefore, we believe a second evaluation with strong deforestation scenarios is needed to assess the risk of land-use change its effects on climate. For this reason, we run additional simulations to account for the biogeophysical effects of a more severe land-use change in Amazonia and Cerrado until the middle of the century, as described below.

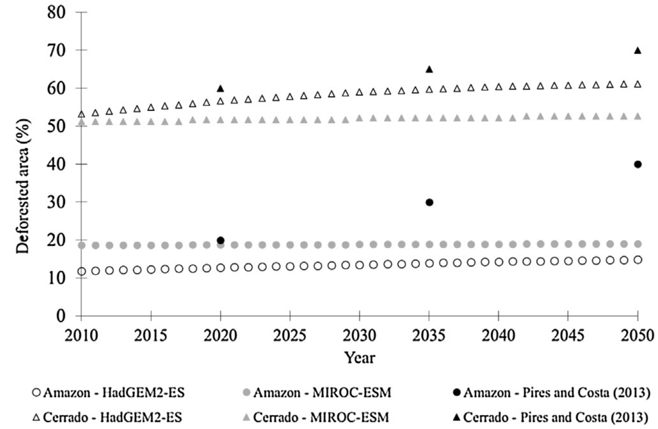

Fig. 1. Scenarios of total Amazon and Cerrado deforested area according to RCP8.5 as implemented in models HadGEM2-ES and MIROC-ESM and in Pires and Costa (2013).

2.2.2.2. Effects of land-use change as in Pires and Costa (2013) and change in atmospheric composition as in CMIP5 on climate (LUCID + PC13). In a pioneer modeling study, Oliveira et al. (2013) concluded that the isolated effects of a regional climate change induced by intense land-use change in Amazonia could negatively affect soybean productivity in a magnitude comparable to the global climate change induced by a change in atmospheric composition. Therefore, considering that CMIP5's land use change scenarios appear to be modest for central-northern South America until 2050 (which could lead to underestimating the effects of climate change on soybean productivity), we chose to conduct a more conservative analysis and assess a second group of simulations with more intense land use trajectories.

In this set of simulations we use deforestation scenarios used in Pires and Costa (2013), hereafter referred to as PC13, and CO_2 trajectories according to CMIP5 experiment (RCP8.5 scenario). According to a pessimistic perspective as RCP8.5, until 2050 deforestation could reach ~40% in Amazonia and ~70% in Cerrado. We assessed only four out of the 20 scenarios published by Pires and Costa (2013): those that assume that deforestation in Pan-Amazonia will reach 10%, 20%, 30% and 40% by 2050, combined with Cerrado deforestation, ranging from 60 to 70%. The Amazon deforestation scenarios are based on Soares-Filho et al. (2006) scenarios. The $A_{10}C_{60}$ (10% of Amazon deforestation and 60% of Cerrado deforestation) scenario is the control run, as it represents the average situation in the period 1970–2000. Starting from an average 20% of Amazon deforestation and 60% of Cerrado deforestation ($A_{20}C_{60}$) in 2011–2020 period, we assume that by 2035, 30% of the Amazon and 65% of Cerrado will be deforested ($A_{30}C_{65}$), and by 2050, 40% of Amazonia and 70% of Cerrado will be deforested ($A_{40}C_{70}$).

Instead of using original CMIP5 simulations where the biogeophysical effects of land-use change are simulated (but underestimated), we use CMIP5 simulations where land-use is fixed so that climatic anomalies related to PC13 deforestation scenarios could be added. Simulations with emissions according to RCP8.5 and fixed land-use were previously run as a part of the LUCID project (*Land-Use and Climate, Identification of Robust Impacts*) (Brovkin et al., 2013), in the L2A85 experiment (atmospheric composition of RCP8.5 $W m^{-2}$, but land-use fixed as in 2005). We use outputs for two models, HadGEM2-ES and MIROC-ESM. To combine RCP8.5 and PC13, we adjusted LUCID climate outputs (precipitation, temperature, wind speed, specific humidity and solar radiation) to PC13 climate anomalies, as described in

Appendix B, creating a new climate input—hereafter referred to as LUCID + PC13. Even though adding the climate anomalies of two different types of simulations (regional climate change and global climate change) may miss interactions, second order processes or feedbacks, it allows the representation of the most relevant processes. Indeed, Costa and Foley (2000), who conducted a full climate experiment to assess the effects caused by these different types of climate change, concluded that the interaction between the two processes is less than 10% of the sum of the individual processes.

Inputs for these simulations were also mean, maximum and minimum temperature (°C), precipitation (mm/day), incoming solar radiation ($W\,m^{-2}$), wind speed (m/s) and specific humidity (kg_{H20}/kg_{air}) and the elevated CO_2 concentration (which also directly affects soybean carbon assimilation). The changes of each climate parameter in LUCID + PC13 as compared to RCP8.5 are shown in Supplementary materia (Tables S1–S6). We run five ensembles for each climate model (HadGEM2-ES and MIROC-ESM) and for each GCR.

2.2.3. Significance tests

For each group of simulations described in Section 2.2.2, we averaged the outputs of simulations of all ensembles (each individual simulation of crop model forced by each climate model is considered a member of the ensemble) and created an average time-series (from 2011 to 2050) of soybean productivity, thereby reducing uncertainty and model-related bias. We then tested the hypothesis that the average soybean productivity changes from the first to the last decade in the 2011–2050 period due to climate change. In other words, we test the hypothesis that soy productivity in 2041–2050 ($Y_{2041–2050}$) is different than the average soybean productivity in 2011–2020 ($Y_{2011–2020}$), being that difference related to the climate change that occurred between these periods. We used the Student's *t*-test, with a 5% level of significance and n = 10 years to test this hypothesis, in the two groups of simulations described in Section 2.2.2. We focus our discussion in statistically significant changes in soybean productivity until the middle of the century.

2.3. Productive regions

We individually evaluated the results of soybean productivity change in the main productive regions in South America (Table 1), identified by the following acronyms: Mato Grosso (MT); MATOPIBA, which aggregates results for Maranhão, Tocantins, Piauí and Bahia states; Central Brazil (CB), with results from Mato Grosso do Sul, Goiás, Minas Gerais and São Paulo states; and Southern Brazil (SB), for Paraná, Santa Catarina and Rio Grande do Sul. Even though our focus is Brazil, we also briefly assess the changes in soybean productivity for Argentina (AR) and Paraguay (PY). Together, these regions accounted for about 95% of the soybean produced in South America (Table 1) and 45% of the soybean produced worldwide.

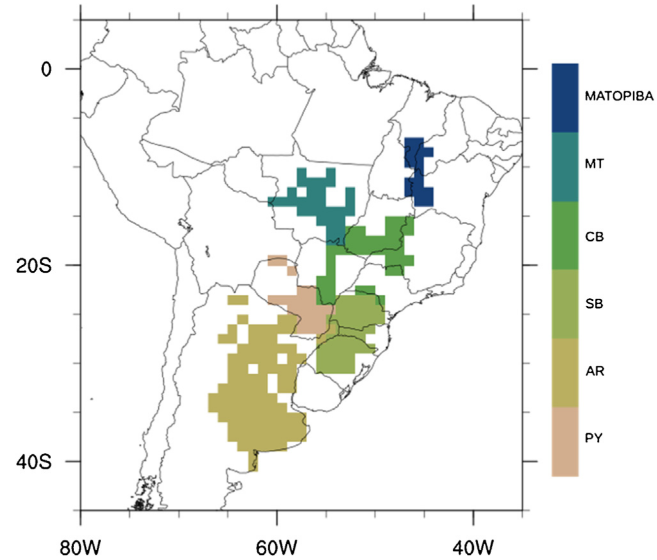

Fig. 2. Analyzed productive regions. Each 1° × 1° pixel in Brazil shown here had at least 5% of its area planted with soybean in 2012. For Argentina and Paraguay, soybean planted area in 2000 is shown.

For Brazilian productive regions, we use the soybean planted area from Dias et al. (2016), to filter pixels that have at least 5% of area planted with soybeans in 2012 (Fig. 2). For Argentina and Paraguay, we used the soybean planted area in 2000, from Monfreda et al. (2008).

3. Results

3.1. Effects of climate change in ESOY and HSOY productivity

The results of both the RCP8.5 and LUCID + PC13 simulations indicate that the magnitude and direction of change in soybean yield (Y) in South America varies spatially and in relation to planting date (Fig. 3).

For short-cycle cultivars planted in rainfed conditions after the end of the sanitary break (ESOY), Y is projected to decrease in Central-Northern Brazilian regions until 2050 (Table 2 and Fig. 3a and c). In these cases, according to both RCP8.5 and LUCID + PC13, the physiological effects of an increased CO_2 atmospheric concentration is not sufficient to offset a dramatic decrease in Y in response to a more severe climate. This drop in ESOY productivity is induced by a sharp decrease in precipitation during the transition from dry to wet season when large-scale land-ocean interactions are less influential (Lawrence and Vandecar, 2015). Costa and Pires (2010)

Table 1
Main soybean productive regions in South America and their total production. Data for Brazilian states are from IBGE (2015). Argentina and Paraguay data are from FAO (2014). Total South America and global production in 2012 was ~1.16×10^8 and 2.41×10^8 ton, respectively (FAO, 2014).

Region	Acronym	Production in 2012 (ton)	% from total South America production in 2012	% from total Global production in 2012
Maranhão, Tocantins, Piauí and Bahia	MATOPIBA	7.74×10^6	6.69	3.21
Mato Grosso	MT	21.8×10^6	18.90	9.06
Central Brazil	CB	17.6×10^6	15.26	7.32
Southern Brazil	SB	18.0×10^6	15.54	7.45
Argentina	AR	40.1×10^6	34.70	16.64
Paraguay	PY	4.34×10^6	3.76	1.80
Total		1.10×10^8	94.85	45.49

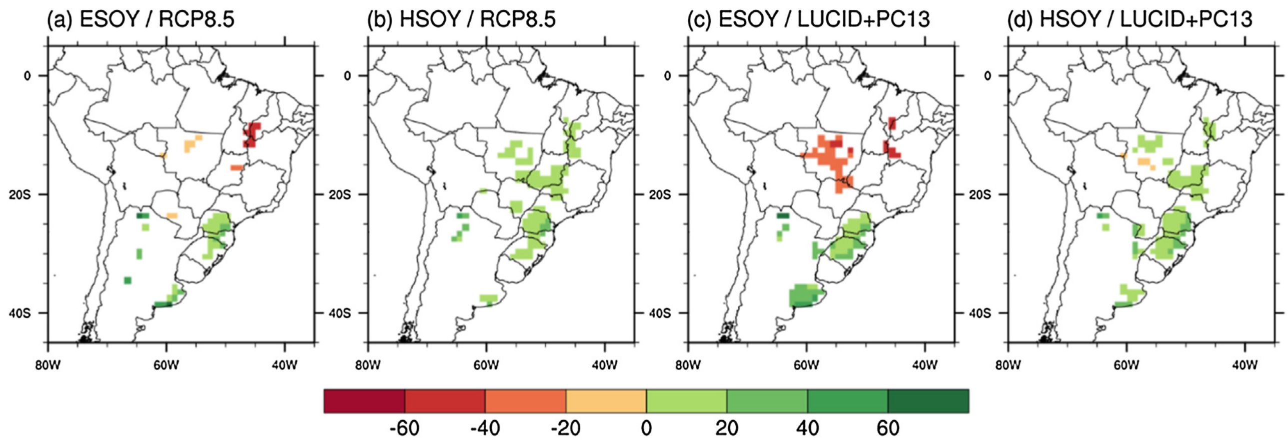

Fig. 3. Percentage change in soybean yield from 2011–2020 to 2041–2050 after climate change. In (a) and (b) atmospheric composition and land use trajectories are according CMIP5's RCP8.5 scenario. In (c) and (d), atmospheric composition trajectories are according to CMIP5's RCP8.5 scenario, but land use trajectories are according to Pires and Costa (2013) tropical deforestation scenarios. Only pixels with statistically significant changes in productivity according to Student's *t*-test ($\alpha = 5\%$) are shown.

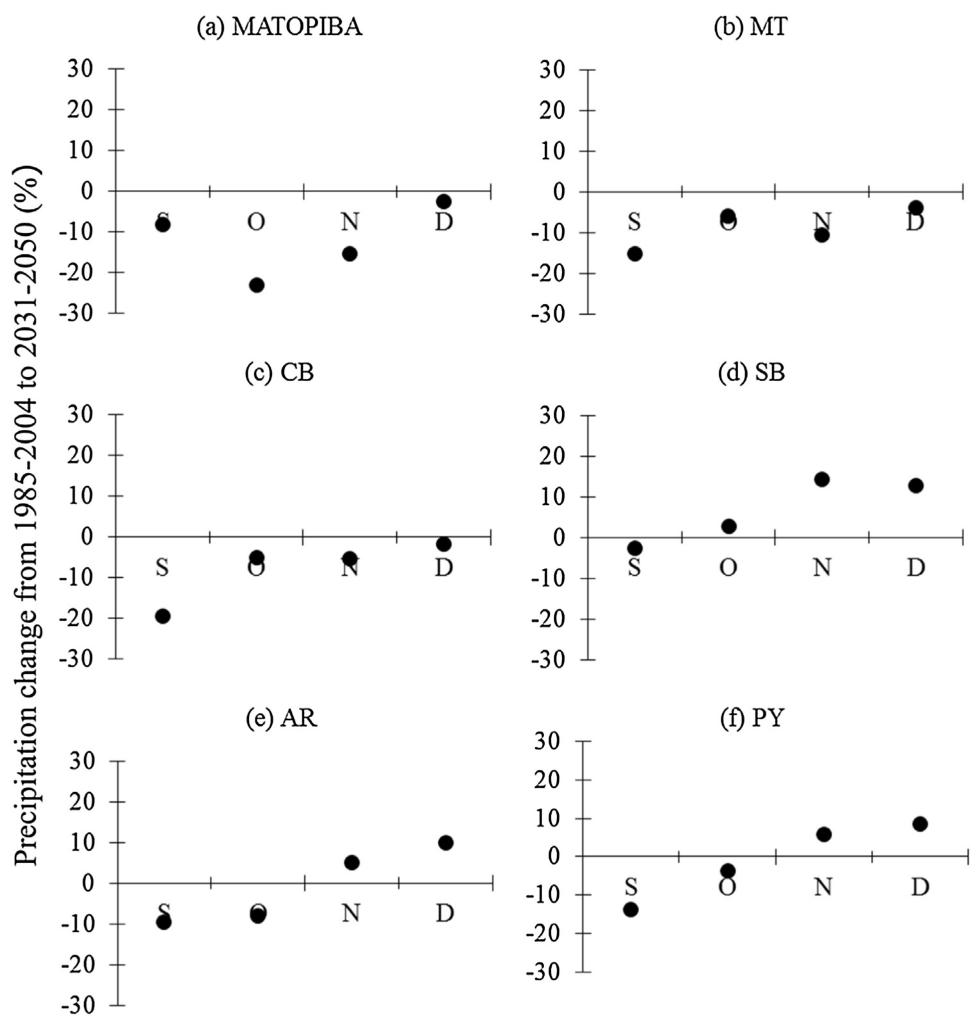

Fig. 4. Change in precipitation (%) from historical baseline (1985–2004) to the period 2031–2050 in RCP8.5 scenario for the months of September, October, November and December for the different soybean productive regions considered in our study.

demonstrate the importance of both the native Cerrado and tropical Amazon forest on the early onset of the wet season in these regions. In fact, precipitation in MATOPIBA, MT and CB decreases more in September-October than in November-December (Fig. 4a–c), with sharper decreases in the LUCID + PC13 scenario. This event coincides with the moment when double cropping farmers are sowing soybean in these regions. This decrease in precipitation in transition months causes an increase in the dry season duration, and has been widely reported in the literature, including modeling (Costa and Pires, 2010; Fu et al., 2013) and observational (Butt et al., 2011)

Table 2
Change in soybean productivity from 2011–2020 to 2041–2050 for different South American productive regions, for short-cycle cultivars (1600 GDD) planted on Sep 25th (ESOY). In the second column, both atmospheric composition and land-use change trajectories are according to RCP8.5. In the fourth column, atmospheric composition is according to RCP8.5 and land use change is according to (Pires and Costa, 2013). Cycle duration is longer in southern regions due to lower temperatures.

Region	ESOY productivity change according to RCP8.5		ESOY productivity change according to LUCID + PC13	
	$Y_{RCP8.5}$ (2041–2050)–$Y_{RCP8.5}$ (2011–2020) (%)	Average cycle duration (days)	$Y_{LUCID+PC13}$ (2041–2050)–$Y_{LUCID+PC13}$ (2011–2020) (%)	Average cycle duration (days)
MATOPIBA	−40.0*	93	−50.0*	90
MT	−11.1*	96	−30.0*	93
CB	−4.3	104	−11.8*	107
SB	11.9*	128	15.6*	129
AR	21.1*	128	21.1*	129
PY	0.0	99	0.0	100

* Statistically significant according to Student's *t*-test, $\alpha = 5\%$ (n = 10).

Table 3
Change in soybean productivity from 2011–2020 to 2041–2050 for different South American productive regions, for optimum cultivar and planting date (HSOY). In the second column, both atmospheric composition and land-use change trajectories are according to RCP8.5. In the fifth column, atmospheric composition is according to RCP8.5 and land use change is according to (Pires and Costa, 2013).

Region	HSOY productivity change according to RCP8.5			HSOY productivity change according to LUCID + PC13		
	$Y^{MAX}_{RCP8.5}$(2041–2050)–$Y^{MAX}_{RCP8.5}$(2011–2020) (%)	Average planting date	Average cycle duration (days)	$Y^{MAX}_{LUCID+PC13}$(2041–2050)–$Y^{MAX}_{LUCID+PC13}$(2011–2020) (%)	Average planting date	Average cycle duration (days)
MATOPIBA	10.8*	Dec 05	127	3.9	Dec 05	127
MT	7.9*	Dec 05	124	2.2	Dec 05	121
CB	9.1*	Nov 15	127	9.4*	Nov 25	132
SB	14.9*	Nov 05	138	15.7*	Nov 05	137
AR	16.7*	Nov 15	126	11.5*	Nov 15	131
PY	0.0	Nov 05	112	6.7	Nov 05	113

* Statistically significant according to Student's *t*-test, $\alpha = 5\%$ (n = 10).

studies. Regional assessment of CMIP5 scenarios indicates that a longer dry season in these regions could become the norm through the 21st century (Boisier et al., 2015; Fu et al., 2013). Moreover, since CMIP5 scenarios may underestimate future changes in land cover in South America and increases in the duration of the dry season have been associated with deforestation (Butt et al., 2011), the CMIP5 projections for the increase in the duration of the dry season in southern Amazonia are most likely underestimated.

Our simulations also show that MATOPIBA is predicted to be the most affected region, and may lose 40% (50%) of ESOY productivity according to RCP8.5 (LUCID + PC13). MT and CB ESOY productivity are also negatively affected by climate change until 2050, and RCP8.5 simulations show a more moderate decrease (11 and 4%, respectively) than LUCID + PC13 (30 and 11%, respectively) (Table 2). As LUCID + PC13 land-use scenarios are more severe than those of RCP8.5 in central-northern Brazil (MT, CB and MATOPIBA), the difference in productivity decrease between the two groups of simulations is probably related to a stronger negative biogeophysical signal associated with tropical deforestation. In Southern Brazil and Argentina, where the amount of deforested area is similar in RCP8.5 and LUCID + PC13, both groups of simulations indicate that ESOY productivity may increase by ∼12–21% until the middle of the century. In these cases, the change in precipitation after climate change is small (Fig. 4d–f), and this increase is most likely due to higher levels of CO_2.

For central-northern Brazilian regions, the results of the simulations are completely different if soybeans are planted under optimum climate conditions. As mentioned before, HSOY planting dates occur in November-December, when there are smaller negative effects of climate change in precipitation (Fig. 4). According to both RCP8.5 and LUCID + PC13, HSOY productivity may increase in South America until 2050 (Table 3), showing that adaptation through changes in planting dates or cultivars can offset the effects of climate change. In MATOPIBA, MT and CB, HSOY productivity may increase from ∼8 to 11% to according to RCP8.5. CB may increase by 9% according to LUCID + PC13 (Table 3). In general, southern regions (SB, AR) are the most favored (from 11 to ∼17% increase). These increases in yield are most likely a consequence of increased CO_2 atmospheric concentration.

3.2. Implications for double cropping systems in central-northern Brazil

Our simulations strongly indicate that future climatic conditions may be unfavorable to early-planted soybeans in central-northern Brazilian productive regions. Specifically, ESOY productivity is likely to decrease until the middle of the century, regardless of the scenario. Nevertheless, although climatic conditions become worse at the start of the crop calendar, Y improves for later dates (HSOY), indicating that adapting planting dates has the potential to offset soybean productivity losses caused by climate change.

Given that delaying planting dates improves productivity responses after climate change, we assess the opportunity to maintain highly productive double cropping systems by delaying the soybean planting dates to times of the year when the climate may be more favorable. As previously mentioned, commodity agriculture in central-northern Brazil occurs on large ranches where soybean cropland may be as extensive as 10,000 ha and the sowing operation may take 2–4 weeks. To simplify this analysis, we therefore consider the duration of an average planting operation to be 20 days.

We test new planting dates for short-cycle cultivars and choose a threshold date at which soybean may reach physiological maturity and can be harvested. We assume that farmers may take 20 days to harvest soybeans and sow maize, and that maize cycle lasts about 120 days and must reach physiological maturity in May—by which time the dry season has already started with potentially negatives effects on productivity. We consider that there is a high probability that a double cropping system is viable if soybean reaches physiological maturity by the beginning of January. Similarly, we consider that there is medium probability that a double cropping system is viable after climate change if soybean reaches physiological maturity by the middle of January. After this date double cropping systems are considered unviable.

Fig. 5 shows how productivity of early-planted soybean cultivars change in MATOPIBA (Fig. 5a) and MT (Fig. 5b) after adapting the beginning of the planting operation from Sept-25 to Oct-5, Oct-15, Oct-25, Nov-5, Nov-15, Nov-25, Dec-5 and Dec-15 after climate change. The 20-day sowing operation is marked by dashed boxes with values greater than the unit indicating an increase in yield. Black symbols indicate scenarios of high probability of successful double cropping systems (physiological mature soybean by January 1st), while grey symbols indicate medium probability of success (physiological mature soybean by January 15th), and white symbols indicate low probability of success (soybean reaches physiological maturity after the dates mentioned above), and a second crop would fail. As expected, progressively adapting planting dates to later than September 25 gradually decreases productivity losses (values smaller that the unit) and, at some point, Y starts to increase (values greater than the unit). Considering such behavior, it is possible to broadly estimate the time of year that adapting planting dates would lead to a minimum loss (or increase in Y) while there is still high probability that double cropping is viable.

In MATOPIBA (Fig. 5a), according to RCP8.5 delaying the beginning of the planting operation to October 5 in 2041–2050 may lead to an increase of Y (relative to soybean planted in 09/25 in the first decade—$Y_{09/25}$(2011–2020)) during almost all the planting operation. In this case there is medium to low probability that double cropping is viable in this region by the middle of the century. According to LUCID + PC13 delaying the beginning of the planting operation to October 5 in 2041–2050 may lead to a decrease of Y in the first 10 days of the planting operation (as opposite to RCP8.5) and to a moderate increase in Y for the last 10 days. Here, a double cropping system would be viable in only half of the large farms (those planted until October 15). Delaying the beginning of the planting to later than October 15 still does not allow a second crop, but soybean productivity is higher due to favorable climatic conditions and increased atmospheric CO_2 concentration.

In MT (Fig. 5b) the scenario is more pessimistic. According to both RCP8.5 and LUCID + PC13, even though delaying planting to October 5 leads to improvement in Y, the probability to plant two crops in the same agricultural calendar lowers (medium probability) in nearly all farms. Starting planting after October 15 gives a low probability to plant a second crop. Again, the main difference between the two simulations is that LUCID + PC13 leads to lower Y than RCP8.5. In summary, regardless of the scenario, the sustainability of highly productive double cropping systems may be threatened in Mato Grosso. In northern Mato Grosso, where the wet season is slightly longer (7–8 months), the prognosis is more optimistic. In these regions, starting planting on October 15 may still be viable since there is medium to high probability to plant a second crop and Y slightly increases (not shown). After this date, a double cropping system is still unviable in northern MT.

4. Discussion and conclusions

Sowing short-cycle soybean cultivars after the sanitary break is currently economically attractive for Brazilian producers for at least three reasons: (1) the probability of infection with rust is low, reducing the need to apply fungicides; (2) the market prices for early harvested soybean is higher than in the peak of harvesting sea-

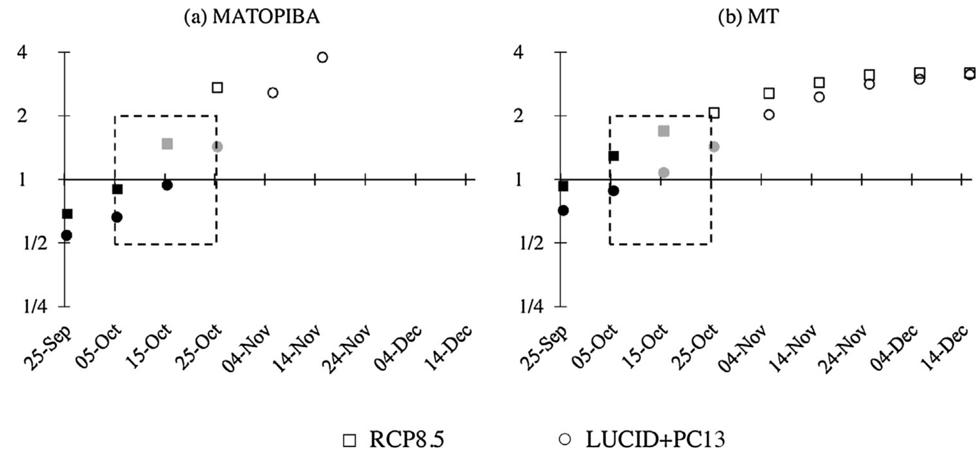

Fig. 5. Soybean productivity change [Y_d(2041–2050)/$Y_{09/25}$(2011–2020), where d are the planting dates assessed in this study] after climate change. Full black boxes (circles) represent soybean planting dates that lead to a high probability that double cropping systems are still viable according to RCP8.5 (LUCID + PC13). Full gray boxes (circles) represent soybean planting dates that lead to a medium probability that double cropping systems are still viable, also according to RCP8.5 (LUCID + PC13). Empty boxes (circles) represent soybean planting dates that may lead to unviable of double cropping system according to RCP8.5 (LUCID + PC13). Dashed boxes indicate the sowing windows.

son, and; (3) there is the climatic possibility to plant a second crop in the same agricultural calendar. For many farmers the possibility of increased profit offsets the risk of sowing soybean under uncertain climatic conditions (mainly precipitation) in the beginning of the wet season.

The results of our assessment strongly suggest that the average climate risk may increase for soybean planted after the sanitary break in the main productive regions in central-northern Brazil until 2050, regardless of the scenario, crop model or climate model used. This result is mainly caused by the predicted reduction in precipitation during the transition months from the dry to the wet season, when double cropping farmers are sowing soybean. In contrast to the general expectation that soybean yield may increase in an elevated atmospheric CO_2 concentration scenario (Porter et al., 2014), our simulations strongly suggest that the positive physiological effects of increased atmospheric CO_2 concentration may not be sufficient to offset the negative effects of dryer conditions during the cycle of early-planted soybean cultivars. Furthermore, continuing deforestation may lead to sharper decreases in productivity until 2050, indicating that the expansion of the agricultural frontier may cause negative feedbacks for agricultural productivity.

Moving planting dates of short-cycle cultivars from September 25 to October 5 in MATOPIBA and MT may slightly increase soybean productivity without recourse to any sophisticated technological technique. However, adopting such a strategy will decrease the probability of successful double cropping. Again, elevated levels of deforestation are predicted to have negative impacts, limiting productivity responses and leading to more modest increases in productivity as compared to lower deforestation scenarios.

If farmers still choose to adopt double cropping in central Northern Brazil, future sowing windows would have to narrow substantially (to 10 days, at maximum) for large farms that currently need several weeks to complete the planting operation. Our simulations strongly suggest that the sustainability of double cropping systems may be threatened in central-northern Brazil, and that clearing additional areas to offset productivity losses may result in negative feedbacks that further decrease productivity.

In contrast, sowing soybean in November-December when rainfall conditions are more favorable may reduce climate risk and even increase productivity. This is because soybean photosynthetic processes may be favored by higher atmospheric CO_2 concentrations. Nevertheless, sowing later in November-December carries an increased phytosanitary risk, higher production costs (through the increased use of fungicides) and precludes double cropping. Adopting such a strategy would therefore significantly decrease total grain output (soybean + maize) and profits in these regions.

According to all simulations, the regions most affected (currently producing 25% of Brazil soybeans and 12% of global soy) will be the major Brazilian production region (Mato Grosso) and MATOPIBA, where the exploration has begun more recently. The latter has attracted farmers from different parts of the country due to low land prices and a topography that facilitates mechanization. Indeed, MATOPIBA is one of the largest expanding agriculture frontiers in the world, and is considered by the Brazilian Ministry of Agriculture as strategic to the economic development of the whole country. While the government intends to support the development of local farmers (Decree 8.447), adaptation to climate change has not been considered in the MATOPIBA development strategy. Our results strongly suggest that such ongoing investment in the region is a high risk strategy if the risks associated to global and regional climate change are not adequately addressed.

In summary, soybean farmers in central-northern Brazil will soon be forced into some difficult trade-offs. Either plant immediately after the sanitary break and lose productivity while retaining the option to plant a second crop, or plant later and gain productivity at an increased risk of rust infection and losing the opportunity to plant a second crop. In either case, our simulations suggest that without further adaptation the current production of soybean and maize may not be sustainable in some major productive regions of Brazil. Effective and urgent adaptation strategies are required to maintain highly productive double cropping systems until the middle of the century, such as:

- technological solutions focused on the initial stages of soybean cycle, especially for short-cycle cultivars when water deficit will be larger (for example, new drought tolerant seeds to current cultivars, or the development of new drought tolerant cultivars);
- investment in high-yield short-cycle soybean and maize cultivars (90–100 days cycle each)—such cultivars already exist, but have low yields;
- incorporation of climate prediction in the Climate Risk Agricultural Zoning (or Zoneamento Agrícola De Risco Climático, in portuguese) recommendations. These recommendations, which are criteria for agricultural credit in Brazil, are based on past climate time-series and may miss some of the dynamics introduced by climate change, especially the shortening of the wet season.

If these adaptation strategies fail and productivity losses caused by the shortening of the wet season are confirmed, farmers may decide to shift to areas with more favorable precipitation regimes causing yet more deforestation. Such additional deforestation will cause further reductions in the length of the wet season and in rainfall in September and October, feeding back again on yields. In other words, large scale agricultural expansion in northern Brazil will cause the degradation of the climate regulation ecosystem service it relies on.

It is clearly essential to anticipate risks related to climate change, including climate change caused by the expansion of the agriculture frontier. It is also important to reinforce measures to halt deforestation in Northern Brazil, both in Amazonia and the Cerrado—where deforestation rates are high and there is weak conservation governance. In addition to the obvious conservation benefits of such measures, the preservation of tropical biomes in South America may, ironically, be one of the key strategies to maintain highly productive and globally important agricultural lands of Brazil.

Acknowledgments

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Appendix A. Climate models

With the objective to select suitable Climate/Earth System Models to represent future climate we chose to evaluate simulated historical precipitation, a variable that is essential to simulate rainfed agricultural productivity, but is one of the most poorly simulated physical processes in Earth System Models (ESMs).

Here we assess the historical simulations (1985–2004) of four global models from the *Coupled Model Intercomparison Project Phase models 5*—CMIP5 (Taylor et al., 2012) that contributed to the *Intergovernmental Panel on Climate Change Fifth Assessment Report* (IPCC AR5). Table A1 lists the models used in this study.

The seasonal climatology of simulated precipitation over South America for the period 1985–2004 was evaluated based on the Terrestrial Hydrology Research Group (THRG) database, published by Sheffield et al. (2006). Fig. A1 shows the daily mean precipitation (mm/day) for different South American Monsoon System (SAMS) phases (December–February (DJF), March–May (MAM), June–August (JJA) and September–November (SON)) as in THRG and as simulated by the selected CMIP5 models.

During the DJF and MAM periods, although general patterns are similar to THRG, CMIP5 models show some deficiencies. MIROC-ESM underestimates the South Atlantic Convergence Zone (SACZ) and therefore is drier than THRG. MRI-CGCM3, NorESM1-M and HadGEM2-ES models overestimate the intensity of the Inter Tropical Convergence Zone (ITCZ). However, models performance seems to be better during the JJA period, with good agreement with THRG in Central-South America. In SON, months that soybean is usually sowed in Brazil, all the models slightly underestimate precipitation in central Brazil, but represent it well it for Argentina and Paraguay.

According to the annual cycle for each productive region (Fig. A2), models generally underestimate precipitation for nearly all months in comparison to THRG. From all models, HadGEM2-ES has the best performance in central-northern Brazilian productive regions and is reasonably closer to THRG, although it slightly overestimates it from June to January.

In addition to the amount of water that precipitates monthly in the main productive regions, it is also crucial to asses if models adequately capture the wet season onset and cessation in the study region, especially in central-northern Brazil where double cropping farmers rely on the onset of rainfall to plant the first crop and also in the duration of the wet season to plant a second crop. Although there are different methodologies to define the wet season, here we focus on Arvor et al. (2014) method which is based on agronomic criteria. This method is based on the premise that, in order to have good productivity levels, soybean plants cannot be subjected to long dry periods after the beginning of the wet season.

We calculated the index of Anomalous Accumulation (AA), which is the cumulative difference between daily rainfall (R) in each day (n) and a reference value (R_{ref}) as in Eq. (A1):

$$AA(t) = \sum_{n=1}^{t} \left(R(n) - R_{ref} \right) \tag{A1}$$

We considered R_{ref} as 2.5 mm/day, representing the minimum water requirement of soybean plants in its early phenological stages. The onset and the cessation of the wet season are defined as the minimum and maximum values, respectively, in the AA series.

The wet season onset and cessation days in the baseline period (1985–2004) are shown in Fig. A3. Models ability to correctly simulate these dates varies among regions. In all regions except for PY models tend to delay the onset date in comparison to THRG. In average, models tend to simulate a 20-day delay in MATOPIBA (Fig. A3a), a 17-day delay in MT (Fig. A3b), a 16-day delay in CB (Fig. A3c) and a 24-day delay in SB (Fig. A3d). Models performance is better in AR and PY, where de difference in the onset dates are restricted to a few days (6 and −8 days, respectively). In addition, models simulation also tend to anticipate the cessation of the wet season in comparison to THRG (12 days in MATOPIBA (Fig. A3a), 16 days in MT (Fig. A3b), 32 days in CB (Fig. A3c), 50 days in SB (Fig. A3d), 26 days in AR (Fig. A3e) and 29 days delay in PY (Fig. A3f)).

Table A1
List of CMIP5 models used in this study.

Model name	Acronym	Institute
Model for Interdisciplinary Research on Climate	MIROC-ESM	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology
Meteorological Research Institute Coupled Atmosphere–Ocean General Circulation Model, version 3	MRI-CGCM3	Meteorological Research Institute (MRI)
Norwegian Earth System Model, version 1 (medium resolution)	NorESM1-M	Norwegian Climate Centre (NCC)
The Hadley Centre Global Environmental Model, version 2	HadGEM2-ES	Hadley Centre

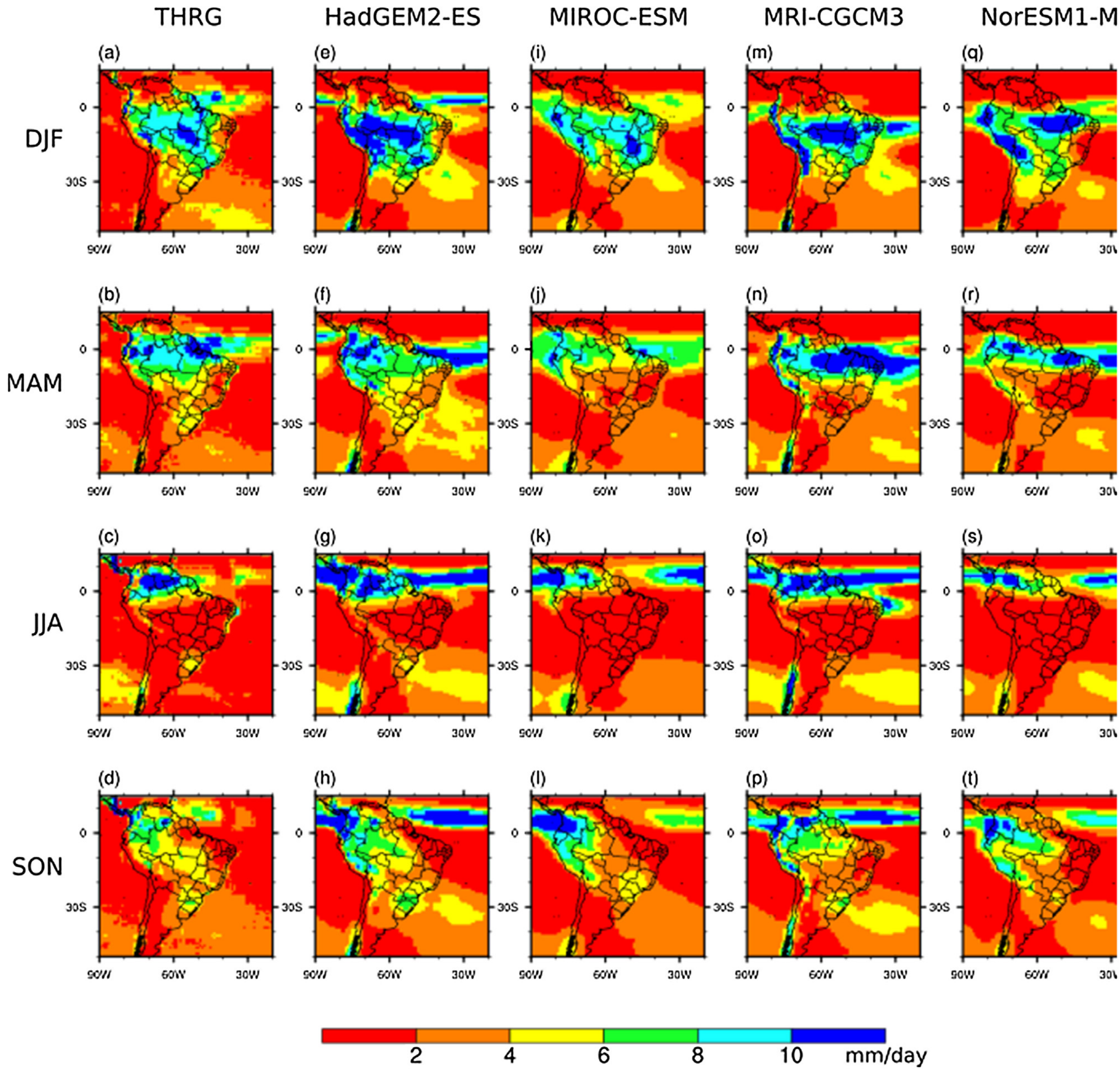

Fig. A1. Daily mean precipitation (mm/day) during the phases of the SAMS as in THRG (a-d) and simulated by HadGEM2-ES (e-h), MIROC-ESM (i-l), MRI-CGCM3 (m-p) and NorESM1-M (q-t).

In addition to simulating a delayed onset and cessation of the wet season in average, models also tend to underestimate the variability of these dates (Fu et al., 2013). Among all models, HadGEM2-ES performance is the most satisfactory in nearly all regions (Fig. A3).

This deficiency to correctly simulate the variability of the wet season onset and end dates in Southern Amazonia may be related to inability to correctly simulate changes in the convective inhibition energy and the position of the Subtropical Jet over South America in austral winter in IPCC AR5 models (Fu et al., 2013). Therefore, IPCC AR5 models simulation may also underestimate the changes in wet season onset and end dates in response to climate change until 2050.

Appendix B. Climate input for LUCID + PC13 simulations

To combine RCP8.5 and PC13 to create synthetic time evolution of global climate change with more severe land-use trajectories than RCP8.5, we adjusted LUCID climate outputs (precipitation; average, maximum and minimum temperature; wind speed; specific humidity and solar radiation) to PC13 climate anomalies, creating a new climate input for crop models referred to in this work as LUCID + PC13. More specifically, we adjusted LUCID daily data (Brovkin et al., 2013) to the monthly difference (or ratio) between a deforestation scenario of PC13 ($A_{20}C_{60}$, $A_{30}C_{65}$ A_{40C70}) and $A_{10}C_{60}$ (control) scenario.

For each month of the 2011–2050 period, we calculated the difference between the deforestation scenario and the control run for mean, maximum and minimum temperature (°C):

$$C_{df} = C_{d;LUCID} + \left(C_{m;scenario} - C_{m;A10C60}\right)$$

C_{df} = final daily climate input (emission + land use change scenario);

$C_{d;LUCID}$ = daily LUCID climate variable;

$C_{m;scenario}$ = monthly mean Pires and Costa (2013) climate variable ($A_{20}C_{60}$ from 2009 to 2020; $A_{30}C_{65}$ from 2021 to 2035; $A_{40}C_{70}$ from 2036 to 2050)

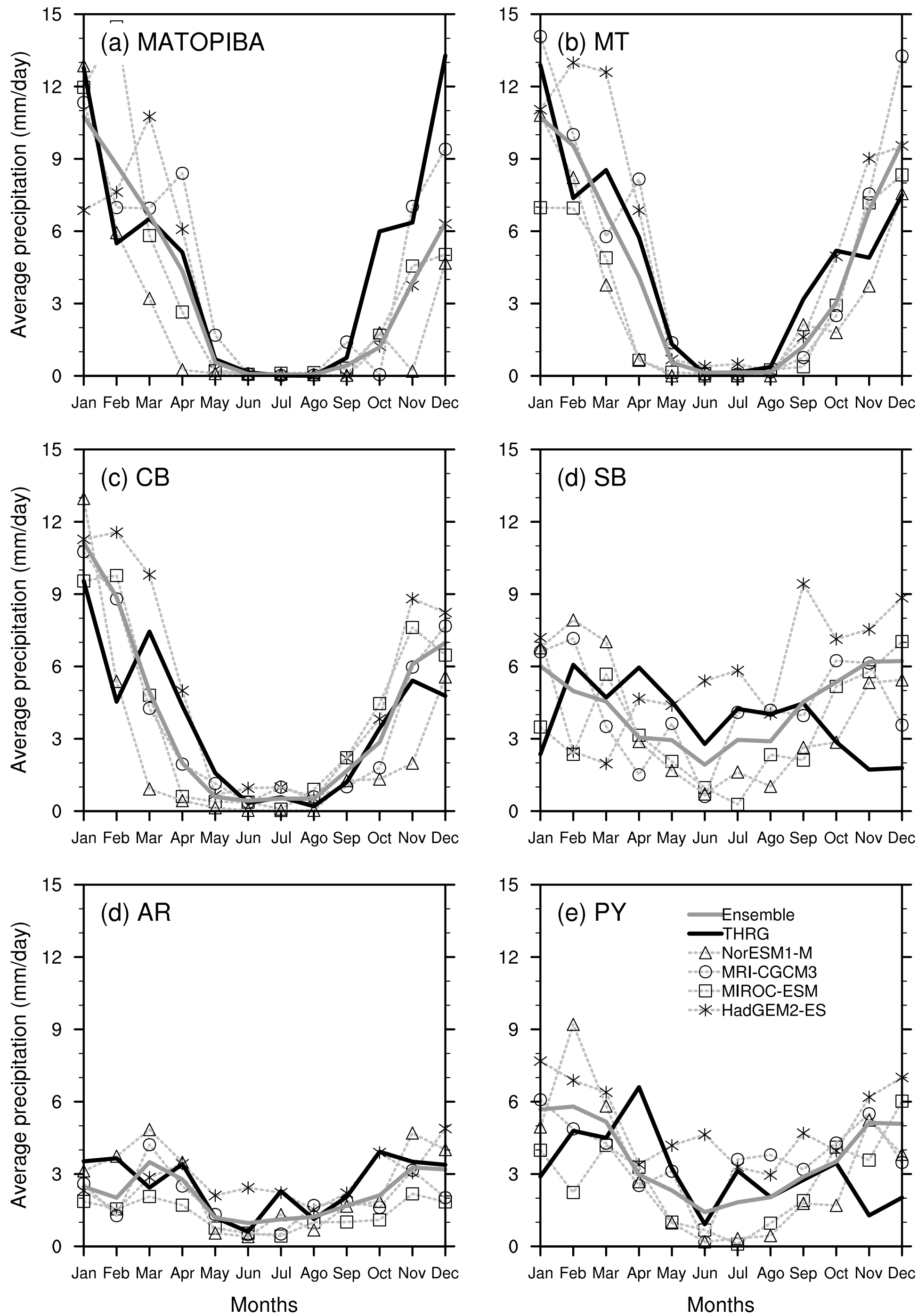

Fig. A2. Daily mean precipitation for each month of the period 1985–2004 as in THRG and as simulated by the models: MIROC-ESM, MRI-CGCM3, NorESM1-M and HadGEM2-ES. The monthly averages are calculated over the soybean planted area in South America (Fig. 2).

$C_{m;A10C60}$ = monthly mean climate for $A_{10}C_{60}$ Pires and Costa (2013) scenario.

For precipitation (mm/day), incoming solar radiation (W/m^2), wind speed (m/s) and specific humidity (kg_{H_2O}/kg_{air}) we used the same approach described above, but calculated the ratio, instead of the difference, between the climate scenario and the control run ($A_{10}C_{60}$):

$$C_{df} = C_{d;LUCID} x \frac{C_{m;scenario}}{C_{m;A10C60}}$$

Even though adding the climate anomalies of two different types of simulations (regional climate change and global climate change) may miss second order processes or feedbacks, it allows the representation of the most relevant processes involved. Indeed, Costa and Foley (2000), who conducted a full climate experiment to assess climate change caused by these different types of climate change, concluded that the interaction between the two processes is less than 10% of the sum of the individual processes.

Tables S1–S6 in the Supplementary material show the climate change that occurs during soybean growing season of each climate input simulated by RCP8.5 and estimated by LUCID + PC13, from 2011–2030 to 2031–2050, to all of the soybean productive regions considered in this study.

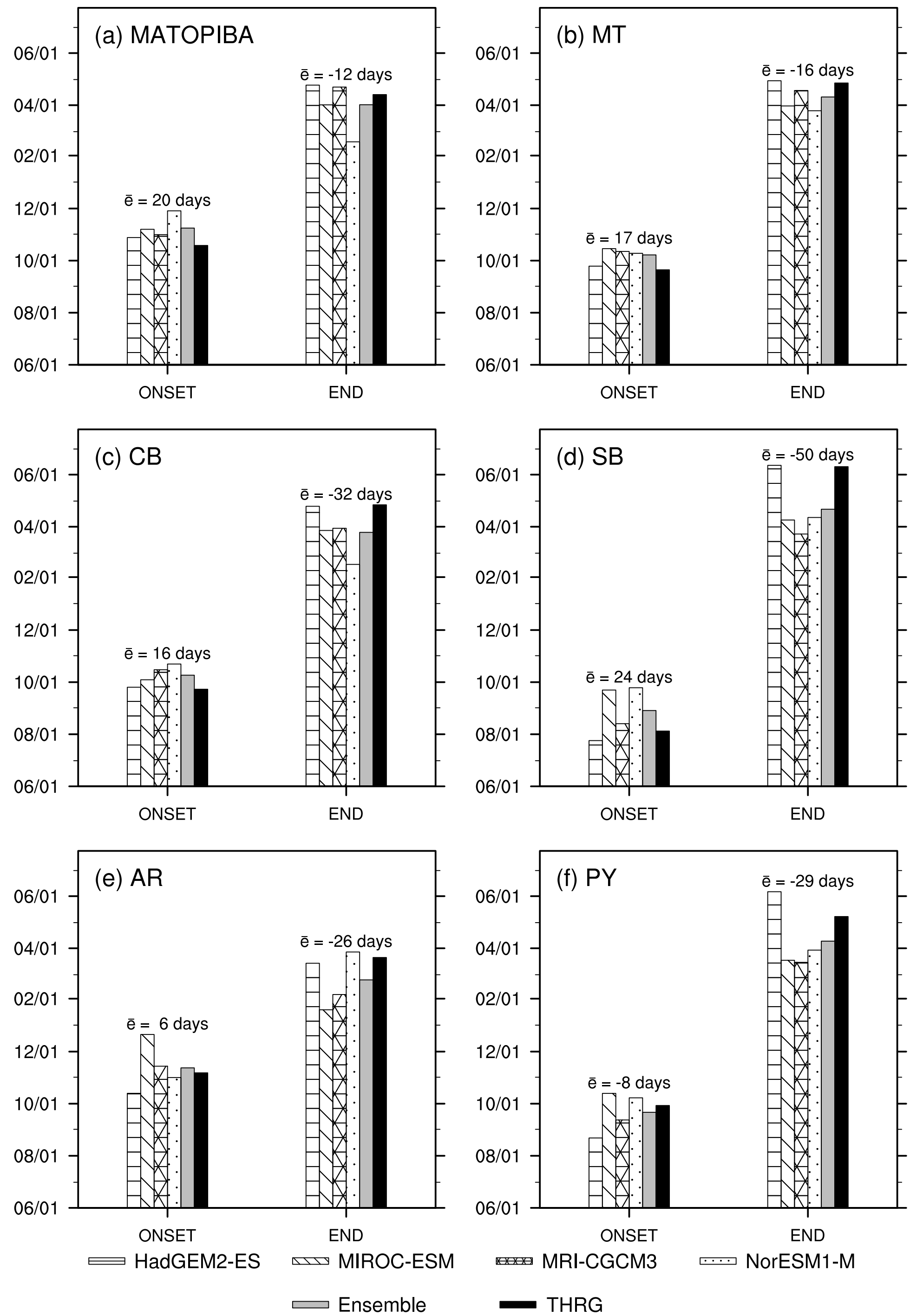

Fig. A3. Observed (THRG) and simulated wet onset and end dates in soybean productive regions during the baseline period (1985–2004).

Appendix C. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agrformet.2016.07.005.

References

Arvor, D., Dubreuil, V., Ronchail, J., Simões, M., Funatsu, B.M., 2014. Spatial patterns of rainfall regimes related to levels of double cropping agriculture systems in Mato Grosso (Brazil). Int. J. Climatol. 34, 2622–2633, http://dx.doi.org/10.1002/joc.3863.

Boisier, J.P., Ciais, P., Ducharne, A., Guimberteau, M., 2015. Projected strengthening of Amazonian dry season by constrained climate model simulations. Nat. Clim. Change 5, 656–661, http://dx.doi.org/10.1038/nclimate2658.

Bowman, M.S., Soares-Filho, B.S., Merrye, F.D., Nepstad, D., Rodrigues, H., Almeida, O., 2012. Persistence of cattle ranching in the Brazilian Amazon: a spatial analysis of the rationale for beef production. Land Use Policy 29, 558–568.

Brovkin, V., Boysen, L., Arora, V.K., Boisier, J.P., Cadule, P., Chini, L., Claussen, M., Friedlingstein, P., Gayler, V., Van den hurk, B.J.J.M., Hurtt, G.C., Jones, C.D., Kato, E., De noblet-ducoudre, N., Pacifico, F., Pongratz, J., Weiss, M., 2013. Effect of anthropogenic land-use and land-cover changes on climate and land carbon storage in CMIP5 projections for the twenty-first century. J. Clim. 26, 6859–6881, http://dx.doi.org/10.1175/JCLI-D-12-00623.1.

Butt, N., De Oliveira, P.A., Costa, M.H., 2011. Evidence that deforestation affects the onset of the rainy season in Rondonia. Brazil. J. Geophys. Res. Atmos. 116, 2–9, http://dx.doi.org/10.1029/2010JD015174.

Conab—Companhia Nacional de Abastecimento, 2015. Acompanhamento da safra brasileira de grãos Safra 2014/15., pp. 1–109 www.conab.gov.br.

Costa, M.H., Foley, J., 2000. Combined effects of deforestation and doubled atmospheric CO2 concentrations on the climate of Amazonia. J. Clim. 13, 18–34, http://dx.doi.org/10.1175/1520-0442(2000)013<0018:CEODAD>2.0.CO;2.

Costa, M.H., Pires, G.F., 2010. Effects of Amazon and Central Brazil deforestation scenarios on the duration of the dry season in the arc of deforestation. Int. J. Climatol. 30, 1970–1979, http://dx.doi.org/10.1002/joc.2048.

Costa, L.C., Justino, F., Oliveira, L.J.C., Sediyama, G.C., Ferreira, W.P.M., Lemos, C.F., 2009. Potential forcing of CO_2, technology and climate changes in maize (*Zea mays*) and bean (*Phaseolus vulgaris*) yield in southeast Brazil. Environ. Res. Lett. 4, http://dx.doi.org/10.1088/1748-9326/4/1/014013.

Dias, L.C.P., Pimenta, F.M., Santos, A.B., Costa, M.H., Ladle, R.J., 2016. Patterns of land use, extensification and intensification of Brazilian agriculture. Global Change Biol. 22 (8), 2887–2903, http://dx.doi.org/10.1111/gcb.13314.

FAOSTAT, 2014 FAOSTAT, 2014 http://faostat3.fao.org/download/Q/QC/E.

Fu, R., Yin, L., Li, W., Arias, P., Dickinson, R.E., Huang, L., Chakraborty, S., Fernandes, K., Liebmann, B., Fisher, R., Myneni, R.B., 2013. Increased dry-season length over southern Amazonia in recent decades and its implication for future climate projection. Proc. Natl. Acad. Sci. U. S. A. 110, 18110–18115, http://dx.doi.org/10.1073/pnas.1302584110.

Fuss, S., Canadell, J.G., Peters, G.P., Tavoni, M., Andrew, R.M., Ciais, P., Jackson, R.B., Jones, C.D., Kraxner, F., Nakicenovic, N., Le Quéré, C., Raupach, M.R., Sharifi, A., Smith, P., Yamagata, Y., 2014. Betting on negative emissions. Nat. Clim. Change 4, 850–853, http://dx.doi.org/10.1038/nclimate2392.

Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O., Townshend, J.R.G., 2013. High-resolution global maps of 21st century forest cover change. Science 342, 850–853, http://dx.doi.org/10.1126/science.1244693.

Justino, F., Oliveira, E.C., Rodrigues, R.A., Gonçalves, P.H.L., Souza, P.J.O.P., Stordal, F., Marengo, J., Silva, T.G., Delgado, R.C., Lindemann, D.S., Costa, L.C., 2013. Mean and Interannual Variability of maize and soybean in Brazil under global warming conditions. Am. J. Clim. Change 2, 237–253, http://dx.doi.org/10.4236/ajcc.2013.24024.

Kucharik, C.J., Twine, T.E., 2007. Residue, respiration, and residuals: evaluation of a dynamic agroecosystem model using eddy flux measurements and biometric data. Agric. For. Meteorol. 146, 134–158, http://dx.doi.org/10.1016/j.agrformet.2007.05.011.

Lapola, D.M., Martinelli, L.A., Peres, C.A., Ometto, J.P.H.B., Ferreira, M.E., Nobre, C.A., Leite, C.C., Moutinho, P., Sampaio, G., Strassburg, B.B.N., Vieira, I.C.G., 2014. Pervasive transition of the Brazilian land-use system. Nat. Clim. Change 4, 27–35, http://dx.doi.org/10.1038/NCLIMATE2056.

Lawrence, D., Vandecar, K., 2015. The impact of tropical deforestation on climate and links to agricultural productivity. 5, 27–36. doi:10.1038/nclimate2430.

Monfreda, C., Ramankutty, N., Foley, J.A., 2008. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. Global Biogeochem. Cycles 22, GB1022, http://dx.doi.org/10.1029/2007GB002947.

OECD-FAO, 2015. OECD-FAO Agricultural Outlook 2015–2024 10.1787/agr_outlook-2015-en.

Oliveira, L.J.C., Costa, M.H., Soares-Filho, B.S., Coe, M.T., 2013. Large-scale expansion of agriculture in Amazonia may be a no-win scenario. Environ. Res. Lett. 8, http://dx.doi.org/10.1088/1748-9326/8/2/024021.

Pires, G.F., Costa, M.H., 2013. Deforestation causes different subregional effects on the Amazon bioclimatic equilibrium. Geophys. Res. Lett. 40, 3618–3623, http://dx.doi.org/10.1002/grl.50570.

PRODES, 2015. Monitoramento da Floresta Amazônica Brasileira por Satélite. Instituto Nacional de Pesquisas Espaciais (INPE). São José dos Campos, São Paulo. Available in: www.obt.inpe.br/prodes.

Porter, J.R., Xie, L., Challinor, A.J., Cochrane, K., Howden, S.M., Iqbal, M.M., Lobell, D.B., Travasso, M.I., 2014. Food security and food production systems. In: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 485–533.

Riahi, K., Rao, S., Krey, V., Cho, C., Chirkov, V., Fischer, G., Kindermann, G., Nakicenovic, N., Rafaj, P., 2011. RCP 8.5-A scenario of comparatively high greenhouse gas emissions. Clim. Change 109, 33–57, http://dx.doi.org/10.1007/s10584-011-0149-y.

Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A.C., Müller, C., Arneth, A., Boote, K.J., Folberth, C., Glotter, M., Khabarov, N., Neumann, K., Piontek, F., Pugh, T., a, M., Schmid, E., Stehfest, E., Yang, H., Jones, J.W., 2014. Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. Proc. Natl. Acad. Sci. U. S. A. 111, 3268–3273, http://dx.doi.org/10.1073/pnas.1222463110.

Rotter, R.P., Carter, T.R., Olesen, J.E., Porter, J.R., 2011. Crop-climate models need an overhaul. Nat. Clim. Change 1, 175–177.

Sheffield, J., Goteti, G., Wood, E.F., 2006. Development of a 50-year high resolution global dataset of meteorological forcings for land surface modeling. J. Clim. 19, 3088–3111, http://dx.doi.org/10.1175/JCLI3790.1.

Soares-Filho, B.S., Nepstad, D.C., Curran, L.M., Cerqueira, G.C., Garcia, R.A., Ramos, C.A., Voll, E., McDonald, A., Lefebvre, P., Schlesinger, P., 2006. Modelling conservation in the Amazon basin. Nature 440, 520–523, http://dx.doi.org/10.1038/nature04389.

Soares-Filho, B.S., Rajão, R., Macedo, M., Carneiro, A., Costa, W., Coe, M., Rodrigues, H., Alencar, A., 2014. Cracking Brazil's forest code. Science 344, 363–364, http://dx.doi.org/10.1126/science.1246663.

Taylor, K.E., Stouffer, R.J., Meehl, G.A., 2012. An overview of CMIP5 and the experiment design. Bull. Amer. Meteor. Soc. 93, 485–498, http://dx.doi.org/10.1175/BAMS-D-11-00094.1.