Abstract
Based upon sensitivity experiments, this study aims to investigate the impact of increased atmospheric CO2 concentration, climate changes, and ongoing technological advancements on bean (Phaseolus vulgaris) and maize (Zea mays) yield. This investigation assumes that the atmospheric CO2 concentration evolves according to the A2 scenario. For these analyses we have used climate data as projected by climate simulations conducted with the HadCM3 climate model for both present day and greenhouse warming conditions. The results demonstrated that warming conditions associated with increased greenhouse gases as delivered by the HadCM3 model lead to reductions in the potential productivity of maize and beans for the years 2050 and 2080 by up to 30%. This thermal response is, however, damped by the highly efficient CO2 fertilization effect which is expected to increase bean productivity as compared to present day conditions. A similar investigation for maize yield revealed a different picture. It has been found that the CO2 fertilization feedback is much weaker and cannot cancel out the thermal effect. We have found, therefore, that climate changes as simulated to occur in the future are not favorable for increasing the maize yield in southeast Brazil. By the inclusion of the third forcing evaluated, representing technological advancements, it is demonstrated that improvements in the crop system reduce the negative effect associated with warmer climate conditions for both crops. We conclude that appropriate soil and technological management as well as genetic improvements may very likely induce an increase in bean and maize yield despite the unfavorable future climate conditions.

Keywords: climate change, crop yield, technology, CO2 fertilization

1. Introduction
The issue of the state of the climate in the 21st century is at the forefront of scientists’ concerns: issues include sea level rise and snow melting projections as well as the dynamical behavior of the climate system in terms of extreme events. While these issues have been extensively investigated, the impact of climate changes upon agricultural and food systems has not received the necessary attention; in particular there is a lack of systematic evaluation of climatic–yield trends (Lobell and Asner 2003). The last century was characterized by a substantial increase in world population, and consequently...
the need for increased food supply has been brought to the forefront of global issues. In general, to increase food production one may enlarge the planted area, maximize crop productivity to reach values close to potential productivity, or develop new crop varieties. It should be noted, however, that the productivity rate is tightly dependent on biophysical and social effects which are difficult to quantify and predict (Ewert et al. 2005). Moreover, the induced climate changes due to increased greenhouse gases in the atmosphere may be associated with remarkable changes in food availability and may also reduce the regions suitable for planting (Lobell et al. 2008, Luo et al. 2005, Richter and Semenov 2005, Zhang and Liu 2005).

Our understanding of the link between climate change and crop productivity has increased with the development of statistical crop models. Nevertheless, due to the high level of complexity regarding the crop yield–climate relationship, additional efforts have been made to improve these models, involving the interchange between climate variables and crop physiology. This has been partially achieved by applying a more sophisticated parameterization of physiological processes as well as by taking into account the influence of meteorological parameters for the different phenological stages of primary crops (Easterling et al. 2001, Parry et al. 2004). Statistical models, which are driven by net radiation and temperature as initial conditions, utilize the carbon budget to predict crop growth. However, they neglect other effects that may cause substantial modifications in crop productivity. Indeed, Easterling et al. (1998) argued that appropriate soil and technological management as well as genetic improvements have been responsible for the observed increase in crop productivity during the last 50 years. Moreover, evidence has been found that increased atmospheric CO₂ concentration may lead to increased crop productivity, in particular for C3 plants (e.g. Kinball et al. 1995, Tubiello et al. 2000). The last two decades have been punctuated by the development of more sophisticated crop models, with improved representation of crop phenology as a function of accumulated heat units (e.g. the CERES and EPIC models), as well as relatively detailed soil biogeochemical processes for carbon and nitrogen (e.g. Century, DNDC and EPIC). Recently, process-based models of different levels of complexity have been developed to estimate crop yield in different regions (Hansen 2005, Betts 2005).

Despite the subject’s relevance, limited attention has been paid to the relationship between CO₂-induced temperature and precipitation changes, as projected by the IPCC modeling results, and crop productivity (food supply) in the continent of South America. It should be noted that Brazil has become a major player in world soybean, maize, coffee, sugarcane and cotton markets, although long term timeseries of the yield of various crops in Brazil show wide fluctuations associated with the variability of weather, and the continuously changing economic environment. This may raise questions about the possible impact of anthropogenically induced climate change on crop productivity, since substantial modifications of the thermal and hydrological features of the climate system are expected to occur in the future. For instance, Lobell and Field (2007) show that simple measures of growing season temperatures and precipitation-spatial averages explain approximately 30% or more of year-to-year variations in global average yield for the world’s six most widely grown crops. For wheat, maize and barley, there is a clearly negative response of global yield to increased temperatures.

Therefore, our goal in this study is to provide an initial evaluation of the future potential productivity of maize (Zea mays) and beans (Phaseolus vulgaris, hereafter common beans) in the State of Minas Gerais, Brazil. The investigation is based upon climate predictions conducted with the HadCM3 coupled climate model (Hadley Centre for Climate Prediction, Met Office, UK), according to the A2 scenario that support the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC). Moreover, we have included the CO₂ fertilization effect and ongoing technological advancements. The choice of the State of Minas Gerais for this study may be justified by the fact that this Brazilian State is responsible for 14.5% (11%) of the beans (maize) produced in Brazil which represents 2% (0.5%) of world production. Minas Gerais is located in southeast Brazil, with total area of 588,383 km² (see figure 1). This area is larger than the area of Spain and Germany together. The paper is organized as follows: section 2 describes the design of the experiments to be analyzed, and an inter-comparison between modeling results and observational data. In section 3, climate anomalies of air temperature and precipitation induced by the inclusion of increased atmospheric CO₂ concentration are described. This section also includes the response of maize and beans associated with changes of temperature, CO₂ concentration and technological advancements. Section 4 summarizes our main findings.

2. Database and the design of the numerical experiments

To simulate the productivity of maize and common beans we have utilized three sets of equation: the first group includes meteorological quantities (e.g. radiation, temperature), while the second set of equations deals with the parameterizations of crop physiology (e.g. dry matter, photosynthesis). A module to reproduce the carbon budget is also included. This set of equations is solved by Model Maker 3.0 (Cherwell Scientific Publishing Ltd). The model configuration is presented in figure 2.

Based upon the amount of radiation and daily mean air temperature, the daily potential dry matter is simulated. The storage of maize and common bean biomasses is calculated daily from the gross photosynthesis rate estimated by using the non-rectangular hyperbola assumption (e.g. Thornley 1998). The carbon budget is defined as the dry matter resulting from the difference of daily assimilation and the maintenance respiration of maize/common beans. Afterward, the carbon gain is converted to dry matter through growth respiration. The physiological process is based upon the thermal time (growing degree days) necessary for reaching the flowering and maturation phenological stages. The simulation is therefore carried out until the maize and beans attain physiological
maturity. In what follows the modeling approach is described in some detail.

2.1. Growth and dry matter partition

The phenological stages is based upon a counter (ED) which varies from 0 to 2 in the sense that 0 is attributed to the emergence of seed, 1 to the flowering stage and 2 to maturation. Before the flowering phase the counter is set to:

$$ED = \frac{GD}{GDF}$$  (1)

where ED is the phenological stage, GD is the accumulated growing degree days and GDF stands for growing degree days needed to flowering.

After the flowering the counter is described by:

$$ED = 1 + \frac{(GD - GDF)}{GDT - GDF}$$  (2)

where GDT is the total growing degree days ($^\circ$C). The simulation is concluded when the counter reaches the value of 2.

Leaf area index (LAI) is calculated taking into account the specific leaf area index (SLAI) and the partition of the dry matter to the leaf (PF) ($LAI = SLAI \times PF$).

2.2. Carbon balance

As previously mentioned, the carbon budget is defined as the dry matter resulting from the difference of daily assimilation and the maintenance respiration of maize/common beans. Hence, the carbon gain is converted to dry matter through growth respiration. In order to estimate the gross daily photosynthesis the non-rectangular hyperbola assumption is applied as follows:

$$F_g = F_{gmax} \left( 1 + \left( \frac{\varepsilon I}{F_{gmax}} \right) \right) - \sqrt{\left( 1 + \left( \frac{\varepsilon I}{F_{gmax}} \right) \right)^2 - \frac{4 \left( \frac{\varepsilon I}{F_{gmax}} \right)^2}{2\theta}}$$  (3)

where $F_g$ is the gross photosynthesis rate, $F_{gmax}$ is the crop maximum photosynthesis rate, $\varepsilon$ is the photosynthetic efficiency (g CO$_2$ MJ$^{-1}$), which has been set to 10 for common
beans and 13 for maize, $I$ is the photosynthetically active radiation (PAR) and $\theta$ is the shape factor. $F_{gmax}$ may be determined from experiments conducted under controlled temperature and radiation. Goudriaan (1977) proposed that $F_{gmax}$ may be computed as $F_{gmax} = F_{gmaxtr}[(T - T_b)/(T_r - T_b)]$, in which $F_{gmaxtr}$ is the reference crop maximum photosynthesis rate (g CO$_2$ m$^{-2}$ day$^{-1}$), $T$ is the mean temperature ($^\circ$C), $T_b$ is the basal growth temperature ($^\circ$C), and $T_r$ is the reference temperature ($^\circ$C). The basal growth temperature ($T_b$) and the reference temperature ($T_r$) are set to 10 $^\circ$C and 20 $^\circ$C, respectively.

Calculation of maintenance respiration (MR) is based upon the dry accumulated matter (MS) as well as being a function of temperature changes (McCree 1974), as follows:

$$ MR = r_m \times MS \times Q_{10}^{(T - T_b)/10} $$

in which $r_m$ is the maintenance respiration coefficient (g CO$_2$ g$^{-1}$ MS$^{-1}$ day$^{-1}$) and $Q_{10}$ is the maintenance increment factor. $r_m$ can be experimentally obtained for a reference temperature; however, it should be modified for a distinct temperature (e.g. $r_m = r_{mtr}[(T - T_b)/(T_r - T_b)]$). $r_{mtr}$ is the reference maintenance respiration coefficient. Finally, the dry accumulated matter throughout the phenological stage, according to de Vries (1975), is estimated by

$$ \frac{dMS}{dt} = (F_g - r_m MS) r_c $$

where $r_c$ is the efficiency of carbohydrate conversion (g CO$_2$ g$^{-1}$ MS$^{-1}$).

Figures 2(b) and (c) show the model’s sensitivity to changes in temperature ($T_{med}$), the crop maximum photosynthesis rate ($F_{gmax}$), the photosynthetic efficiency ($\varepsilon$), and the shape factor ($\theta$). Based on this evaluation, it may be demonstrated that among the model’s parameters, temperature change plays the leading role in modifying crop productivity. For instance, a 20% increase in daily averaged $T_{med}$ would be associated with a 50% (30%) reduction of common bean (maize) yield. On the other hand, a drop in temperature by 20% results in a 30% and 50% augmentation in common bean and maize yield, respectively. Similar investigation for the other parameters ($F_{gmax}$, $\varepsilon$ and $\theta$) reveals that crop productivity exhibits a lower sensitivity to their variations at the upper end of the positive range. At the negative range, however, the simulated yields are more sensitive to changes in the photosynthetic efficiency ($\varepsilon$), in particular for common beans.

In order to predict crop productivity as a result of induced CO$_2$, climate changes and technological advancements one should first identify possible model bias under present day conditions. This may be obtained by forcing the crop model described above, with initial conditions based on observed timeseries. We have utilized daily values of maximum, minimum and mean air temperatures, and photoperiod (hours of daylight) between 1975 and 2005, collected at 19 weather stations from the Brazilian National Institute of Meteorology.
Figure 3. Modeled (cross) and experimental (straight line) area-averaged potential productivity of (a) common beans and (b) maize (kg ha$^{-1}$). (c), (d) The effect of technological factors for common beans and maize, respectively.

(INMET). By using these 19 weather stations one may be able to simulate the most productive areas for common beans and maize in the state of Minas Gerais (figure 1). To validate the model we have compared the simulated productivity with the experimental productivity of maize and common beans during the years 1999 and 2000. One should note that the experimental productivity was achieved under optimum weather, water and soil conditions (figures 3(a) and (b), straight lines). This experiment was conducted at the University of Viçosa experimental field, with the aim of providing data to validate our theoretical investigations. One may argue that a suitable calibration should be based upon year-on-year observed yield timeseries. However, this approach is not conducted here because the yield gap in Brazil may reach values as high as 50%. Since we are simulating potential productivity, comparison with an experiment carried out under optimum conditions seems to be reasonable. It might be noted, furthermore, that dry conditions due to precipitation changes in southeast Brazil is the primary factor responsible for reduction in crop yield. By conducting an experiment under optimum water availability and soil conditions it may be assumed that little change should be expected in the productivity throughout the years. The experimental productivity of maize and common beans was 11 500 kg ha$^{-1}$ and 4000 kg ha$^{-1}$, respectively. Based on figures 3(a) and (b), it is clear that the model proposed here is able to reproduce satisfactorily the experimental productivity of maize and common beans as a function of the oscillation in the timeseries due to the climate swings. One may note the reduction in the productivity of both crops as a response to El Niño conditions in 1983, 1992 and 1997. In contrast, the signature of La Niña conditions appears in 1989.

3. Greenhouse warming experiments

To evaluate the potential impact of human induced climate change on crop productivity we have utilized climate projections as simulated by the Hadley Centre for Climate Prediction and Research global coupled atmosphere–ocean (HadCM3) model. The atmospheric component of the model has 19 levels with a horizontal resolution of 1.25° of latitude and longitude. The oceanic component of the model has 20 levels with a horizontal resolution of 1.25° × 1.25°. A brief analysis of the present day and future climate as simulated by the HadCM3 model is provided in section 4. A more complete model description along with a list of references can be found at the IPCC DDC website (http://www.ipcc-data.org). For the analyses here, we have used the concentration of greenhouse gases according to the Special Report on Emissions Scenarios (SRES) A2. The SRES A2 scenario envisions population growth to 15 billion by the year 2100, rather slow economic, technological development and less concern for rapid economic development. In addition to the inclusion of climate forcing we have incorporated the effect of increased atmospheric CO$_2$ concentration on maize and common bean production according to the assumption of Ewert et al (2005).
This can be computed by the equation below:

\[ P_{CO_2} = \frac{f_{CO_2} \Delta CO_2}{100} + 1. \]  

Here \( P_{CO_2} \) stands for the effect of increased atmospheric \( CO_2 \) on the crop productivity; \( f_{CO_2} \) is the rate of productivity for unit \( CO_2 \) increase (\%/ppm); and \( \Delta CO_2 \) is the difference between the future \( CO_2 \) level and the amount of \( CO_2 \) in the year 2000. Tubiello et al (2000) argued that an increase of 350 ppm in the \( CO_2 \) concentration would lead to increased productivity in C3 and C4 plants by 25% and 10%, respectively. Therefore, by assuming a linear evolution of \( CO_2 \) one may find that the \( f_{CO_2} \) parameter is 7.14%/ppm for C3 and 2.9%/ppm for C4 plants. According to the A2 scenario, the \( CO_2 \) concentration is projected to be 440, 559 and 721 ppm in the years 2020, 2050 and 2080. One should note that the yield response to \( CO_2 \) changes is not entirely linear, as proposed here. Nevertheless, no final consensus exists on the impact of variation in the atmospheric \( CO_2 \) concentration on crop productivity, as discussed by Tubiello et al (2000). In fact, depending on the \( CO_2 \) range evaluated (e.g. 400–600 ppm), as shown by Long et al (2006), the response of yield to \( CO_2 \) may be assumed as linear. It is equally clear that the crop response is extremely reduced for levels of the atmospheric \( CO_2 \) concentration above 700 ppm. This situation is achieved in our study for the year 2080.

Present atmospheric \( CO_2 \) limits the performance of many agricultural crop plants, which therefore sense and respond to rising \( CO_2 \) through photosynthesis, a process by which leaves absorb \( CO_2 \) from the air to make the compounds required for plant growth. Several experiments and modeling studies have demonstrated positive effects of increasing atmospheric \( CO_2 \) concentrations on crop photosynthetic efficiency and water use, as discussed by Easterling et al (2001). They argued that C3 species, including soy beans, common beans and wheat, are more photosynthetically limited by available atmospheric \( CO_2 \) than C4 species with relatively efficient pathways (e.g. maize). Exposure of plants belonging to the C3 photosynthetic group (which produce a three-carbon acid as the first stable photosynthetic intermediate) to elevated \( CO_2 \) generally results in stimulated photosynthesis and enhanced growth (Vu 2004). C4 species, on the other hand, are efficient enough at utilizing carbon that they are not currently limited significantly by available atmospheric carbon. Therefore, they are nearly carbon saturated and any additional atmospheric carbon above ambient levels does little to increase photosynthesis. As discussed by Long et al (2006), crops sense and respond directly to rising atmospheric \( CO_2 \) concentration through photosynthesis and stomatal conductance, and this is the basis for the fertilization effect on yield. 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%.

Other forcing investigated here is the technological effect. This is incorporated as primary changes in genetic improvements as described below:

\[ PP_T = P_g + \int_{t_0}^{t} P_g \cdot f_{T, PPT} \]  

where \( PP_T \) is the technological effect on the potential productivity; \( P_g \) stands for the rate of genetic improvement, which for common beans we assumed as 1.6% year\(^{-1}\) and for maize 1.82% year\(^{-1}\), as suggested by Matos (2005). \( f_{T, PPT} \) is a parameter that represents the technological effect on potential productivity, which is assumed to be 0.8 for the 2020; 0.6 for 2050 and 0.4 for 2080 (Ewert et al 2005). These effects have been included for calculations of gross photosynthesis rate. For instance, in 2020 the technological effect on potential productivity of common beans would be responsible for a 27.2% increase in the potential productivity (i.e. \( PP_T(%) = 1.6 + (1.6 \times 0.8)(2020−2000) = 27.2 \)). It should be noted that the introduction of \( P_T \) in equations (7) will not result in a linear trend. It will follow a decay exponential curve as a function of time. The technological effect is shown in figures 3(c) and (d) for the State of Minas Gerais. The positive trend associated with appropriate soil and technological management as well as to genetic improvements is evident. These effects were responsible for an increase in common bean/maize productivity by up to 500% in 2000 as compared to 1975. Moreover, one may note the highly significant role of climate fluctuations on crop yield as the departure of the linear fit curve.

4. Results and discussions

An investigation of future climatic impacts on agricultural activities is tightly dependent on the capability of the model to simulate the current climate. It has been demonstrated that HadCM3 is able to reasonably simulate present day climate conditions in southeast Brazil (Ambrizzi et al 2007). A brief analysis of the present climate simulated by the HadCM3 model, in terms of precipitation and surface temperature, is shown in figures 4(a) and (b). One may note that for annual mean conditions the southeast part of Minas Gerais State is dominated by colder and more humid conditions compared to the northern part. This climate feature is primarily associated with recurrent stationary cold fronts as well as the presence of the South Atlantic convergence zone (SACZ) during the summer season. Turning to the climate features for the period 2090–2100, the HadCM3 model projects higher temperature and increased precipitation for most of Minas Gerais compared to present day conditions (figures 4(c) and (d)). Vera et al (2006), by analyzing several models results from IPCC, concluded that there is a general consensus among models that future precipitation changes would lead to an increase in summer precipitation over southeastern South America, and a reduction of winter precipitation over most of the continent with respect to present day conditions. These findings would favor increased crop productivity in southeast Brazil if there are no remarkable modifications in the daily distribution of precipitation, as compared to present day conditions. It may be stressed, however, that prolonged periods of drought or torrential rain would be associated with reduction of the crop yield.

In terms of temperature, values as high as 4 °C may be expected in the western part of Minas Gerais. Similar results have been found by Boulanger et al (2006) from an evaluation of five coupled climate models. Indeed, they suggested that
tropical South America could warm up by about 4 °C, while southeast South America would also undergo a near 2–3 °C average warming. Interestingly, this annual mean temperature trend is modulated by reduced amplitude of the seasonal cycle which leads to much milder winters. Moreover, they argued that all the SRES scenarios (A2, A1B and B2) have similar patterns and only differ in amplitude. SRES A1B differs from SRES A2 mainly for the late 21st century, reaching more or less an 80–90% amplitude compared to SRES A2. SRES B2, however, diverges from the other scenarios as soon as 2025. For the late 21st century, SRES B2 displays amplitudes, which are about half those of SRES A2.

Figures 5 and 6 show changes in potential productivity as a result of modifications of climate (temperature), CO₂ concentration and the technological improvement (genetic changes) as compared to the year 2000 for common beans and maize. The baseline values for the year 2000, 4167 kg ha⁻¹ for common beans and 11 829 kg ha⁻¹ for maize, were obtained from the validation experiment conducted at the University of Viçosa which was carried out under optimum environmental conditions. These figures show the individual effect of temperature (figures 5(a)–(c) and 6(a)–(c)); the joint effect of temperature and CO₂ changes (figures 5(d)–(f) and 6(d)–(f)), and finally, the combined crop response to all forcing agents (figure 5(g)–(i) and 6(g)–(i)). Although the increase in surface temperature is physically questionable, since there is no change in the forcing that may lead to warmer conditions, it is important to investigate the individual

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**Figure 4.** Annual mean surface temperature (a) (°C) and (b) precipitation (mm day⁻¹) as projected by the HadCM3 model for present day conditions. Annual mean anomalies between present day and the period 2090–2100 for temperature (c) and precipitation (d).
Figure 5. Predicted potential productivity for common beans. For changes in temperature alone in (a) 2020, (b) 2050 and (c) 2080; for changes in the joint effect of CO2 fertilization and temperature in (d) 2020, (e) 2050, (f) 2080; and the potential productivity as a result of all forcing agents (temperature, CO2 and technological advancements) in (g) 2020, (h) 2050, (i) 2080.

Impact of modifications in the thermal structure of the lower troposphere on crop productivity. It can be demonstrated that warming conditions would lead to reductions in the potential productivity of both crops for the years 2050 and 2080 by up to 30%. However, there exist areas with increased productivity for the year 2020 (figures 5(a)–(c) and 6(a)–(c)). This drop in potential productivity may be associated with the shortening of the phenological phase and subsequent increase in the maintenance respiration rate due to changes in the growing degree days. In fact, higher air temperatures accelerate plant phenology. Based upon calculations with the CERES-Wheat model, Rosenweig and Goldberg (1997) demonstrated that a 2°C increase in temperature could result in a drop of productivity by up to 20%.

Nevertheless, by including the CO2 effect a different picture emerges, in particular for common beans. One may note that the fertilization effect of CO2 plays an important role in increasing crop productivity despite warmer conditions compared to the year 2000. One might note that for maize the positive effect of increased CO2 concentration is not sufficient to compensate the negative effect associated with temperature forcing. These results show the crop dependence of the fertilization effect related to C4 and C3 species. The combined effect of CO2 changes and temperature on yield of maize and common beans are also dependent on the evolution of these agents, in the sense that comparison for the years 2050 and 2080 with 2020 display distinct spatial patterns which may reveal non-linearities associated with the coupling between CO2 changes and temperature. A similar result has been reported by Tubiello et al. (2000). Turning to analyses of the combined response of all forcings (temperature, CO2 and technology), an increase in the potential productivity is simulated for both common beans and maize as compared to the year 2000 (figures 5(g)–(i) and 6(g) and (h)). It is interesting to note that similar analyses for maize also show incremented values up to 40% and 90% with respect to 2000. Ewert et al. (2005) found values up to 40% and 140% increases in wheat productivity based upon the A2 IPCC scenario, combined with the CO2 fertilization effect and genetic improvements. It should be noted that our analyses discussed in the present study do not take into account crop diseases during the phenological phases.
5. Concluding remarks

Based upon modeling experiments we have investigated the impact of CO₂ fertilization, climate changes, and ongoing technological advancements on common bean and maize yields. For the analyses here we have used climate data projected by global climate simulations conducted with the HadCM3 climate model, according to SRES A2. The results demonstrated that warming conditions would lead to reductions in the potential productivity of both crops for the years 2050 and 2080 by up to 30%, primarily associated with the shortening of the phenological phase (accelerated plant phenology). This thermal response is, however, damped by the highly efficient CO₂ fertilization effect which is expected to increase the productivity of common beans. A similar conclusion may not be drawn for maize. In this case, the CO₂ fertilization feedback is much weaker and cannot cancel out the thermal effect. One may conclude therefore that the climate changes are not favorable for increasing the maize yield in southeast Brazil. Finally, the third forcing evaluated, which represents technological advancements, demonstrated that improvements in the crop system would reduce the negative feedback associated with warmer climatic conditions.

It is important to note that the results discussed here on maize and common bean productivity in southeast Brazil exhibit some limitations associated with the climate data used as initial conditions, as well as due to the modeling approach in terms of magnitude of the technological and the CO₂ fertilization effects. For instance, there is no consensus regarding future CO₂ (and in a few cases also other greenhouse gases) emission scenarios, which are designed to serve as inputs to general circulation models and facilitate assessments of the impact of climate change. The response of crops to climate changes is therefore tightly linked to the CO₂ emissions scenario used, since different greenhouse gas forcings would lead to a distinct climate response. Future research will hopefully narrow down these uncertainties of future CO₂ emissions data and those of climate model simulations considerably. For the time being we have to cope with the uncertainties still present.

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