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Simulation of CO_2 enrichment and climate change impacts on soybean production**

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A b s t r a c t. The potential doubling of atmospheric CO_2 concentration and associated changes in temperature and precipitation are crucial issues for agricultural productivity. The CROPGRO-Soybean model in decision support system for agro-technology transfer v4.5 to simulate soybean (*Glycine* max cv. Pioneer 93B15) grown in an elevated CO_2 environment was calibrated and validated. Crop growth and yield data were obtained from a series of experiments conducted in central Illinois at the soybean free air CO_2 enrichment facility from 2002 to 2006. The model was applied to simulate the possible impacts of climate change on soybean yield in the region for the future years of 2080-2100, centred on 2090. The model reproduced the measured soybean growth and yield well under ambient and elevated CO_2 conditions. For the period from 2081 to 2100, soybean yield was projected to decrease due to elevated temperature but to increase due to elevated precipitation and CO_2 concentration, achieving counterbalance. The adverse impacts of the warming conditions on soybean yield can be mitigated by late planting within an optimum planting range (day of year 145 to 152) as a management option, as well as by controlling genetic responses to thermal days in the reproductive stage.

K e y w o r d s: carbon dioxide, climate change, soybean, crop model

INTRODUCTION

According to the Fifth Assessment Report (5AR) of the Intergovernmental Panel on Climate Change (IPCC), natural and anthropogenic greenhouse gases (GHGs) such as CO_2, CH_4, N_2O, and halocarbons are drivers of climate change (IPCC, 2013). CO_2 is the most abundant gas among those GHGs. The concentration of atmospheric CO_2 has increased from approximately 280 parts per million (ppm) by volume in the pre-industrial period to more than 400 ppm today, with an average rate of 1.8 ppm per year. Approximately 87% of anthropogenic CO_2 emission resources are generated from the burning of fossil fuels including coal, natural gas, and petroleum (Le Quéré *et al*., 2009). The accumulation of anthropogenic GHGs directly leads to global warming. Many global datasets of near-surface temperature indicate that the Earth surface has warmed by 0.3-0.9°C since the 1970s (Hansen *et al*., 2005). IPCC 5AR (2013) has predicted that this global warming trend may continue with likely increases for 2081-2100 in the ranges of 0.3-1.7, 1.1-2.6, 1.4-3.1, and 2.6-4.8°C under Representative Concentration Pathways (RCPs) of 2.6, 4.5, 6.0, and 8.5, respectively, relative to 1986-2005 temperatures. Moreover, the projected global warming is also expected to be accompanied by variations in atmospheric moisture flux. In the middle- and high-latitude regions of North America, the ensemble mean of the projected multi-model set projects a 10-20% increase in annual mean precipitation in the 2080s.

Initially, many elevated CO_2 experiments were conducted in growth chambers. Cure and Acock (1986) summarised the early experiments and reported the responses of 10 important crops to doubled CO_2 concentration. Soybean was selected as the most CO_2-sensitive crop among the 10 crops, showing overall yield enhancement of approximately 29±8%, as well as a short-term CO_2 exchange rate (CER) increase of 78±20% and an acclimated CER increase of 42±10%. Compared with that, for other crops, the gas permeability of soil is more important for soybean due to N-fixing activities that occur in the soil. Moreover, the methods applied for studying crop responses to elevated CO_2 in the field have been discussed in many studies (Lawlor and Mitchell, 1991; Morison and Lawlor, 1999). The two most relevant agronomy methods are open-top chambers (OTCs) (Kimball *et al*., 1983) and the free air CO_2 enrichment (FACE) system (Hendry *et al*.,1993). Previous

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studies showed relatively significant fertilization effects of CO_2 in both C3 and C4 crops in OTCs with observed yield enhancements of approximately 31% for wheat, 32% for soybean, and 18% for maize and sorghum at 550 ppm CO_2 (Long *et al*., 2006). In FACE experiments, a CO_2 increase at 550 ppm resulted in yield enhancements of 12% for rice, 13% for wheat, and 14% for soybean (Kimball *et al*., 2002). Yields of sorghum and maize were not affected by elevated CO_2 (Conley *et al*., 2001; Leakey *et al*., 2006) or were affected only when elevated CO_2 was accompanied by drought stress (Samarakoon and Gifford, 1996). These results indicate that yields of most crops are influenced by elevated CO_2 levels. In contrast, reduced stomatal conductance and transpiration are additional reasons for the measured crop yield enhancement under water stress conditions. Because the upper optimum temperature of most soybean varieties ranges from 20 to 30°C (Baker *et al*., 1989), an increase in air temperature would also significantly limit production.

Although field experiments such as FACE for soybeans (SoyFACE) are conducted at a single location and typically at a single CO_2 concentration, crop models can be more flexibly employed for reproducing production responses at a broader geographical scale and for a wider range of conditions. In addition, crop growth models are capable of reproducing physiological responses. Crop growth simulation models have been widely used by many scientists to study crops grown in various environmental conditions. Well-calibrated and highly tested agricultural system models are essential tools for integrating various chemical, physical, and biological processes and their interactions in agronomic systems (Ma *et al*., 2008). Such models can provide daily or seasonal overall simulations of biomass, leaf, root, and other organ development in addition to yield and other related parameters. The CROPGRO modules in decision support system for agro-technology transfer (DSSAT) software (Jones *et al*., 2003) are valuable tools for scientific research, field management, and policy-making (Boote *et al*., 1996). Sau *et al.* (1999) used CROPGRO to simulate soybean growth in several non-stressed conditions. Ruíz-Nogueira *et al.* (2001) also applied the model for simulations of soybeans grown under water-limited conditions. Irmak *et al*. (2005) used the model to predict yields under various combinations of precipitation, temperature, and solar radiation conditions at an aggregate scale in high-latitude regions, and they summarized and discussed the methods for estimating soybean yield by using grid cells. Roberto *et al*. (2006) investigated the responses of soybean and maize crops to individual and simultaneous climate change variables of precipitation, solar radiation, and temperature. Most studies focus on the response of soybean yield to individual environmental factors; few have evaluated model performance for simulations of soybean grown in elevated CO_2 conditions.

The objectives of the present study were to calibrate and evaluate the CROPGRO-soybean module in DSSAT v4.5 for simulations of soybeans grown in the FACE experiments conducted in central Illinois. The calibrated model was then applied to simulate soybean yield variations in the Midwest region, USA, due to changes in temperature and precipitation associated with elevated CO_2 concentrations of 538 and 936 ppm under climate change scenarios of Representative Concentration Pathway (RCP) 4.5 and 8.5, respectively, for the years 2081 to 2100 (IPCC 2013).

MATERIALS AND METHODS

Cropping system data were obtained from experiments conducted from 2002 to 2006 at the SoyFACE facility which was been previously described in detail (Ainsworth *et al.,* 2004). Briefly, the soil type at the site was a deep Flanagan/Drummer soil series, typical of wet, prairie soils of central Illinois. In the experiments, half of the 32 ha site was planted each year with maize (*Zea mays*) and half with soybean; these crops were rotated annually. Soybean (cultivar Pioneer 93B15) was planted with a mechanical seed planter at 152nd, 147th, 149th, 145th, 145th day of year (DOY) in: 2002, 2003, 2004, 2005, and 2006, respectively. Row spacing was 0.38 m, and planting density after emergence was approximately 20 plants m^{-1}. Each year, four ambient and four elevated (CO_2) octagonal plots 20 m in diameter were created. From 2002 to 2006, the target (CO_2) was 550 ppm, and CO_2 was delivered by using the FACE design of Miglietta *et al.* (2001). No N fertilizer was applied during crop growth because of the N-fixing ability of soybean. Weather data including daily solar radiation, temperature, precipitation, and wind speed were collected by an on-site weather station. Data describing soybean phenology, growth, physiology and yield responses to elevated CO_2 have been previously published (Twine *et al*., 2013 and references within).

The CROPGRO module is a crop simulation model used to compute plant growth and development on a daily basis (Jones *et al*., 2003); these parameters are now contained in DSSAT v4.5 (Hoogenboom *et al.,* 2012). CROPGRO was developed as a deterministic and mechanistic model for the simulation of the physical, chemical, and biological processes of legume groups such as soybean, peanut, fava bean, chickpea, cowpea, dry bean, and velvet bean. Demands for C and N for tissue growth are compared with supplies of these substrates to determine the daily growth and C and N composition of each growing tissue. Balance concepts between C and N are used to describe the tissue growth of various plant components (Boote *et al.,* 2008). Leaf photosynthesis in CROPGRO is formulated with a modified Farquhar and von Caemmerer (1982) approach in which only the Ribulose 1.5 bisphosphate (RuBP)-limited part is used to simulate the responses of net leaf photosynthesis to CO_2 concentration. The net rate of CO_2 assimilation

(A) per unit leaf area ($u$mol m^{-2} s^{-1}) is determined with the following asymptotic exponential light-response equation (Alagarswamy *et al.,* 2006):

$$A = A_{max}\ [1.0 - \exp(-QE \times PPF/A_{max})], \qquad (1)$$

where: A_{max} is the light-saturated A (defined at 30°C, 350 $u$mol CO_2 per mol, 21% O_2, leaf N concentration of 55 g kg^{-1}, and reference specific leaf weight (SLWREF) of 35.0 g m^{-2} leaf area); QE is the quantum efficiency of the leaf, referenced at the same conditions; and PPF is photosynthetic photon flux. Temperature and CO_2 effects on QE and A_{max} are also modelled by using a modified Farquhar and von Caemmerer (1982) method. CROPGRO simulates canopy photosynthesis by using a hedge-row light interception model and leaf-level photosynthesis parameters (Pickering *et al.,* 1995).

The overall mathematical structure of the model is based on the differential equation representation of mass balances presented by Wilkerson *et al.* (1985) for the original SOYGRO soybean model. In this new generic crop growth model, daily rate equations were added to the CROPGRO module family to account for the storage and use of C in excess of that required to grow tissue mass in one day. More detailed theoretical concepts used in the CROPGRO model were reported by Boote *et al.* (1998).

Cropping system data from the soybean FACE experiments in 2002 and 2004 were used for model parameterisation of CROPGRO-Soybean. The minimum driving input parameters of the model could generally be sorted into four sources as climate, soil properties, field management, and crop genotype data. Climate variables used in this study were solar radiation (MJ m^{-2} day^{-1}), maximum and minimum temperatures (°C), and precipitation (mm). Soil parameters applied for the simulations are presented in Table 1. To develop the genetic coefficients for the simulation of the cultivated soybean variety, Pioneer 93B15, an iterative approach was employed through trial-and-error within an optimum range for each genetic coefficient to match the measured phenology and yield values with the simulated values. The developed genetic coefficient values are presented in Table 2. We selected the daily canopy photosynthesis approach for all simulations in this study.

The accuracy of the calibrated model was evaluated by using the 2005 and 2006 FACE experimental data. Simulated crop yield, seasonal biomass, and leaf area index (LAI) were compared with the measured values for model validation. In both processes of calibration and evaluation, we used the paired t-test (SAS v9.2, SAS Institute, Cary, NC, USA) and two statistics indices of root-mean-square deviation ($RMSD$) (Eq. (2)) and model efficiency (E) (Eq. (3)):

$$RMSD = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - M_i)^2}, \qquad (2)$$

$$E = 1 - \frac{\sum_{i=1}^{n}(S_i - M_i)^2}{\sum_{i=1}^{n}(M_i - M_{avg})^2}, \qquad (3)$$

where: S_i is the ith simulated value, M_i is the ith measured value, M_{avg} is the averaged measured value, and n is the whole number of data. E values are equivalent to the coefficient of determination.

A model sensitivity study was performed to ensure the model capability of reproducing crop growth data under various modified climate situations. Climate data in Champaign-Urbana, Illinois, from 1990 to 2010, collected by

T a b l e 1. Soil parameters applied for the simulation of soybean grown at the free air CO_2 enrichment facility at the University of Illinois, Urbana-Champaign, Illinois, USA using CROPGRO-soybean

Variable	Description	Value			
SALB	Albedo (fraction)	0.20			
SLU1	Evaporation limit (cm)	15.00			
SLDR	Drainage rate (fraction day^{-1})	0.50			
SLRO	Runoff curve number	75.00			
SLB	Depth, base of layer (cm)	35	103	118	150
SLLL	Lower limit (cm^3 cm^{-3})	0.074	0.072	0.063	0.061
SDUL	Upper limit, drained (cm^3 cm^{-3})	0.255	0.254	0.246	0.236
SSAT	Upper limit, saturated (cm^3 cm^{-3})	0.335	0.331	0.322	0.325
SRGF	Root growth factor (g cm^{-3})	1.000	0.233	0.122	0.065
SBDM	Bulk density, moist (%)	1.20	1.32	1.43	1.55
SLOC	Organic Carbon (%)	5.60	1.25	0.35	0.10
SLHW	pH in water	7.2	7.2	8.0	8.0

Table 2. Genetic coefficients developed for the simulations of the soybean cultivar, Pioneer 93B15 using CROPGRO-soybean

Variable	Description	Value
DL	Critical short day length below which reproductive development progresses with no day-length effect (for short-day plant; hour)	12.8
PPSEN	Slope of the relative response of development to photoperiod with time	0.264
EM-FL	Thermal days between plant emergence and flower appearance	15.0
FL-SH	Thermal days between plant first flower and first pod	5.5
FL-SD	Thermal days between first flower and first seed	16.0
SD-PM	Thermal days between first seed and physiological maturity	32.0
FL-LF	Thermal days between first flower and end of leaf expansion	25.0
LFMAX	Maximum leaf photosynthesis rate at 30°C, 350 ppm CO_2, and high light (mg CO_2 m^{-2} s^{-1})	1.05
SLAVR	Specific leaf area of cultivar under standard growth conditions (cm^2 g^{-1})	375.0
SIZLF	Maximum size of full leaf (cm^2)	180.0
XFRT	Maximum fraction of daily growth that is partitioned to seed + shell	1.0
WTPSD	Maximum weight per seed (g)	0.19
SFDUR	Seed filling duration for pod cohort at standard growth conditions (photothermal days)	15.0
SDPDV	Average seed per pod under standard growing conditions (per pod)	2.05
PODUR	Time required for cultivar to reach final pod load under optimal conditions (photothermal days)	14.5
THRSH	Threshing percentage	77.0
SDPRO	Fraction protein in seeds (g protein per g seed)	0.405
SDLIP	Fraction oil in seeds (g oil per g seed)	0.205
ECO#	Code for the ecotype to which this cultivar belongs	SB0301

the Illinois State Water Survey, were obtained and used as the baseline data for the study. The baseline data were then modified with nine CO_2 concentrations (200, 300, 368, 480, 580, 700, 800, 950, and 1 200 ppm), ten changes (-2, -1, 0, 1, 2, 3, 4, 5, 6, and 7°C) of temperature, and eleven changes (-50, -40, -30, -20, -10, 0, 10, 20, 30, 40, and 50%)of precipitation amounts in terms of proportion from the baseline data. The modified climate data were used for soybean simulation in response to different climate variables.

The evaluated CROPGRO-Soybean model was applied to simulate the potential impacts of climate change for a 20-year period from 2081 to 2100, centred on 2090. We used the specific future climate changes of temperature and precipitation for central North America under climate change scenarios of RCP 4.5 and RCP 8.5 (Table 3) which were projected by using 42 and 39 global climate models (GCMs) in the multi-model set associated with CO_2 concentrations of 538 and 936 ppm, respectively (IPCC, 2013). An ensemble of the GCMs was used for each 20-year projection (2081 to 2010) based on the 20-year baseline (1991 to 2010) to include inter-year climate variability. Projected variations in temperature, precipitation, and atmospheric CO_2 concentration were superimposed over the 20-year baseline. The calculated average temperature increase was then added to the daily minimum and maximum temperatures; a similar procedure was conducted for precipitation and CO_2 concentration. These individual climate variables were combined as the projected future climate conditions to simulate the effects of climate change on soybean production. The effects of individual variables were also studied separately.

The simulated soybean yields of the projected years with those of the baseline years were compared to present the crop yield responses to the individual and combined climate factors. The mean values of the simulated yields for different projection years were tested statistically to determine the differences between baseline yields and each projection year yield by using the PROC NPAR1WAY nonparametric test (SAS v9.2, SAS Institute, Cary, NC, USA). The differences in the mean and variance were analyzed by using the Wilcoxon two-sample test.

T a b l e 3. Median and extreme values of temperature and precipitation projections for central North America under climate change scenarios of RCP 4.5 and RCP 8.5 using 42 and 39 global models, respectively (IPCC, 2013). The area mean temperature and precipitation responses were averaged for each model over all available projections for the 2081 to 2100 period from the Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations and for observations of the 1986 to 2005 period

Climate change scenario	Division	Annual temperature response	Annual precipitation response
		°C	%
RCP 4.5	Median	+2.6	+3
	Extreme	+4.3	−4
RCP 8.5	Median	+5.1	+7
	Extreme	+7.4	−14

RESULTS

Overall, the simulated seasonal biomass and LAI of soybean matched with the corresponding measured values with reasonably acceptable agreement in 2002 and 2004 (Fig. 1). However, the daily biomass values for both ambient and elevated CO_2 treatments were underestimated from 90 to 130 days after planting (DAP) in 2002 and were overestimated from 100 to 130 DAP in 2004. The LAI values were also accordingly underestimated in 2002 and overestimated in 2004. Most of the differences between simulated and measured ensemble averages of the biomass and LAI were within 1.0 t ha^{-1} and 0.5 m^2 m^{-2}, respectively (Table 4). *RMSE* and *E* of the biomass were 0.978-2.295 t ha^{-1} and 0.77-0.93, respectively, for all treatments; those for LAI were 0.59-1.24 m^2 m^{-2} and –0.09-0.87. The simulated seed yields agreed with the measured seed yields

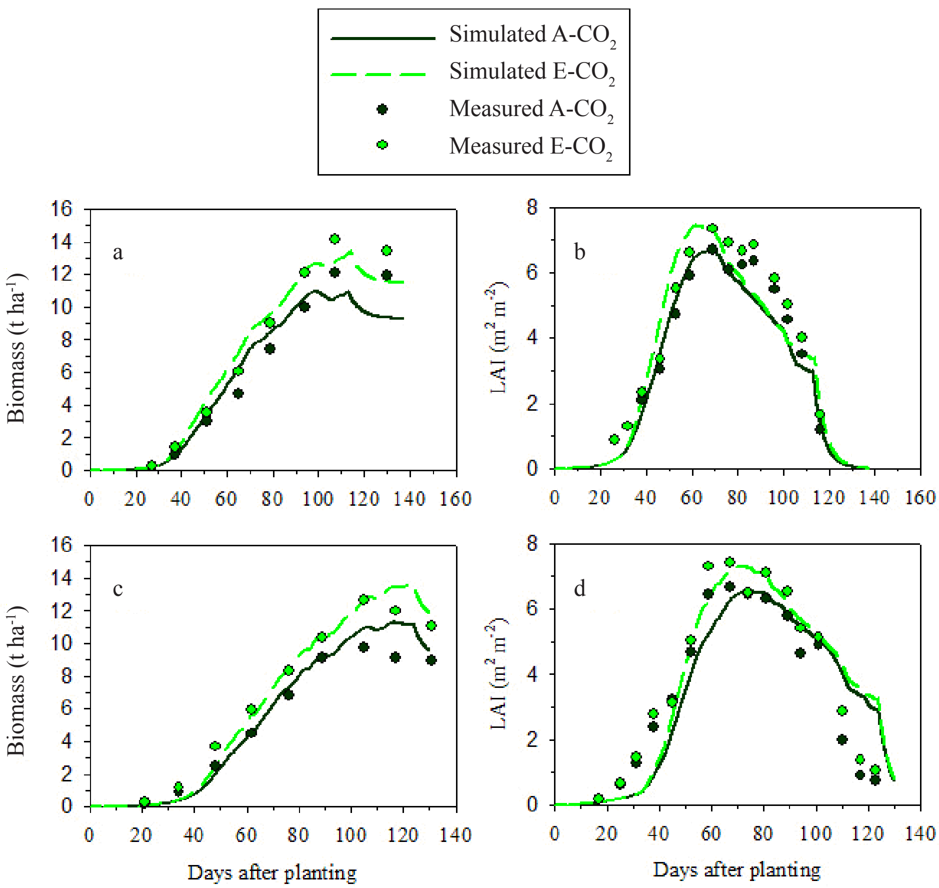

Fig. 1. Seasonal changes in simulated versus measured biomass and leaf area index (LAI) of soybean in ambient CO_2 (A-CO_2) and elevated CO_2 (E-CO_2) treatments in: 2002 a and b, and 2004: c and d for parameterisation using the experiment data of free air CO_2 enrichment.

T a b l e 4. Root-mean-square difference (*RMSD*) and model efficiency (*E*) for the measured and simulated seasonal average values of biomass and leaf area index (LAI) for different treatments in 2002 and 2004 in parameterization

Year	Treatment	Measured	Simulated	*RMSD*	*E*
		Biomass (t ha^{-1})			
2002	A-CO_2	6.291	5.806	1.060	0.94
	E-CO_2	7.487	6.814	1.040	0.95
2004	A-CO_2	5.753	5.816	1.093	0.90
	E-CO_2	7.271	6.828	1.163	0.96
		LAI (m^2 m^{-2})			
2002	A-CO_2	4.15	4.15	0.84	0.84
	E-CO_2	4.59	4.55	0.69	0.90
2004	A-CO_2	3.57	3.50	1.62	0.52
	E-CO_2	3.99	4.20	1.47	0.65

A-CO_2 – ambient CO_2, E-CO_2 – elevated CO_2.

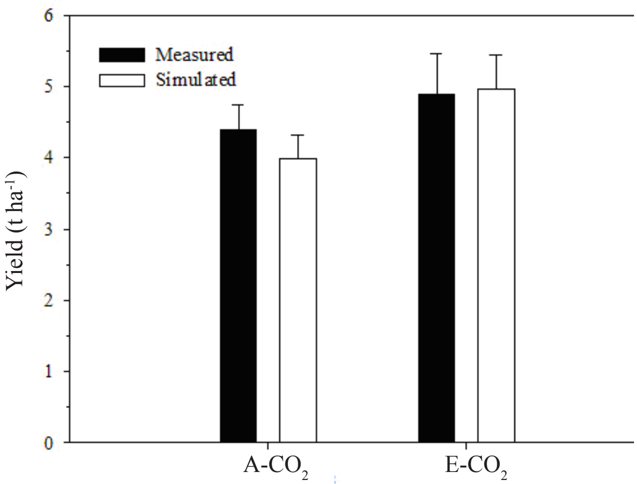

Fig. 2. Comparisons between simulated and measured values of soybean yield for A-CO_2 and E-CO_2 treatments at the University of Illinois, Urbana-Champaign, Illinois, USA, for the model parameterisation using the 2002 and 2004 experiment data of free air CO_2 enrichment. Vertical bars represent ±1 standard error (n = 2).

for both ambient and elevated CO_2 regimes with no significant differences according to a paired t-test (p = 0.302) (Fig. 2). *RMSD* and *E* of the seed yield for all treatments were 0.22 t ha^{-1} and 0.67, respectively. The measured yield enhancement due to elevated CO_2 relative to an ambient CO_2 (E/A) ratio of 1.15 was reproduced at 1.28 in 2002, whereas that of 1.07 for measured yield was reproduced at 1.23 for the simulated yield in 2004.

Most simulated values were well reproduced with deviations of transient biomasses of ~0.3 t ha^{-1} and LAIs of ~0.4 m^2 m^{-2} for the measured means for both the ambient and the elevated CO_2 treatments in both 2005 and 2006 (Fig. 3). The calculated *RMSD* and *E* of the biomasses for all the treatments were 1.040-1.163 t ha^{-1} and 0.77-0.93, respectively, whereas those of LAI were 0.59-1.24 m^2 m^{-2} and –0.09-0.87 (Table 5). The simulated seed yields were in marginal agreement with the corresponding measured seed yields according to a pared t-test (p = 0.07), although some arithmetic deviations were shown between the simulation and measurement (Fig. 4). RMSD and *E* of the seed yield for all treatments were 0.24 t ha^{-1} and −0.1, respectively. The enhancement effect of elevated CO_2 on soybean yield was reasonably well reproduced with the model evaluation. The *E/A* ratio of 1.17 for the measured yield was reproduced at 1.26 for the simulated yield in 2005, whereas that of 1.11 for the measured yield was reproduced at 1.19 for the simulated yield in 2006.

The analysis of the sensitivity of the model-simulated yield to the drivers of climate change effects was conducted by using 20 years of climate data as the baseline. The simulated soybean yield showed typical responses to varying temperature, precipitation, and CO_2 concentration (Fig. 5). The responses of crop yield to varying temperature showed a parabolic curve pattern. The yield increased from -2 to -1°C, where it reached a peak, then declined as the temperature increased from 1 to 7°C. The soybean yield responses to varying precipitation and atmospheric CO_2 concentration showed a logarithmic curve pattern. With increasing precipitation, the yield increased linearly from 50% to 110% and began to plateau at 120%. As CO_2 concentration

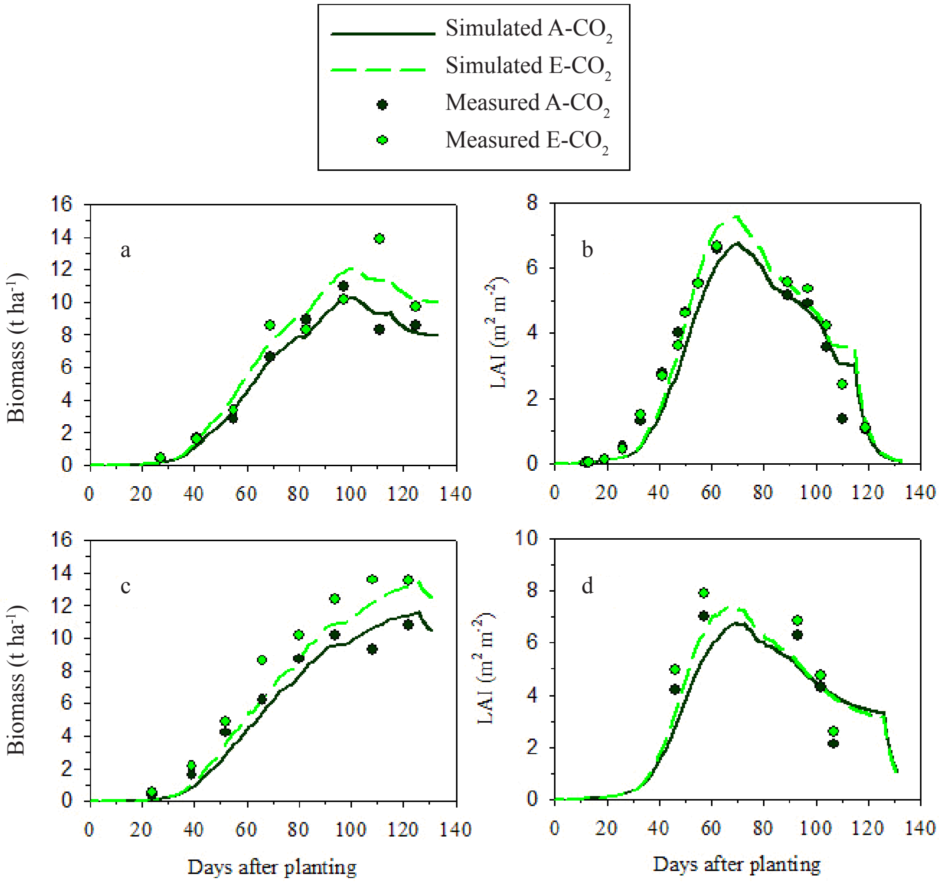

Fig. 3. Seasonal changes in simulated versus measured biomass and leaf area index (LAI) of soybean in ambient CO_2 (A-CO_2) and elevated CO_2 (E-CO_2) treatments in: 2005 a and b, and 2006 c and d for validation using the experiment data of free air CO_2 enrichment.

T a b l e 5. Root-mean-square difference (*RMSD*) and model efficiency (*E*) for the measured and simulated seasonal average values of biomass and leaf area index (LAI) for different treatments in 2005 and 2006 in validation

Year	Treatment	Measured	Simulated	*RMSD*	*E*
		Biomass (t ha^{-1})			
2005	A-CO_2	6.037	5.679	0.978	0.93
	E-CO_2	6.999	6.692	1.130	0.93
2006	A-CO_2	6.037	5.313	1.344	0.87
	E-CO_2	6.999	6.112	2.295	0.77
		LAI (m^2 m^{-2})			
2005	A-CO_2	2.77	2.38	1.27	0.67
	E-CO_2	2.93	2.65	0.82	0.87
2006	A-CO_2	4.79	4.40	1.81	-0.09
	E-CO_2	5.41	4.83	1.60	0.24

A-CO_2 – ambient CO_2, E-CO_2 – elevated CO_2.

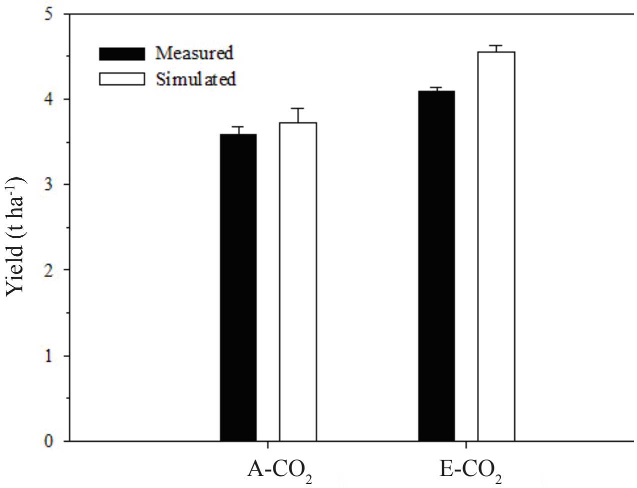

Fig. 4. Comparisons between simulated and measured values of soybean seed yield for A-CO_2 and E-CO_2 treatments at the University of Illinois, Urbana-Champaign, Illinois, USA, for the model validation using the 2005 and 2006 experiment data of free air CO_2 enrichment. Vertical bars represent ±1 standard error (n = 2).

increased, the simulated yield increased rapidly from 100 to 500 ppm (~100 ppm higher than the current 395 ppm). The yield began to plateau from 600 ppm to 1 200 ppm.

The individual effects of projected climate changes in CO_2, temperature, and precipitation on yield were evaluated by using statistical comparisons between 2100 and the current year (Table 6, Fig. 5), and the combined effects were presented by using box and whisker plots (Fig. 6). Significant enhancement effects on soybean yield were shown at the projected CO_2 concentrations of 538 ppm and 936 ppm in comparison with the baseline CO_2 concentration of 370 ppm. As the temperature increased to 2.6 and 5.1°C, crop yields decreased significantly ($p < 0.05$) according to the Wilcoxon two-sample test. Yields under different precipitation scenarios were projected to remain unaffected but to decrease marginally ($Pr = 0.0609$) only in the case of 14% less than the baseline condition (extreme, Table 3).

In simulations using four combinations of temperature and precipitation projections associated with the CO_2 concentrations of 538 ppm for RCP 4.5 and of 936 ppm for RCP 8.5 (Table 3), crop yields decreased significantly ($Pr < 0.05$) under the elevated temperature and precipitation of +7.4°C and -14 %, respectively (Table 7).

We selected the extreme climate change scenario from the above combined effects of temperature, precipitation, and CO_2, and we simulated the impacts on soybean yield under three planting regimes using five genetic coefficients of interest. As shown in Table 2, these coefficients represent thermal days between first flower and end of leaf expansion (FL-LF), thermal days between plant first flower and first pod (FL-SH), thermal days between first flower and first seed (FL-SD), thermal days between plant emergence and

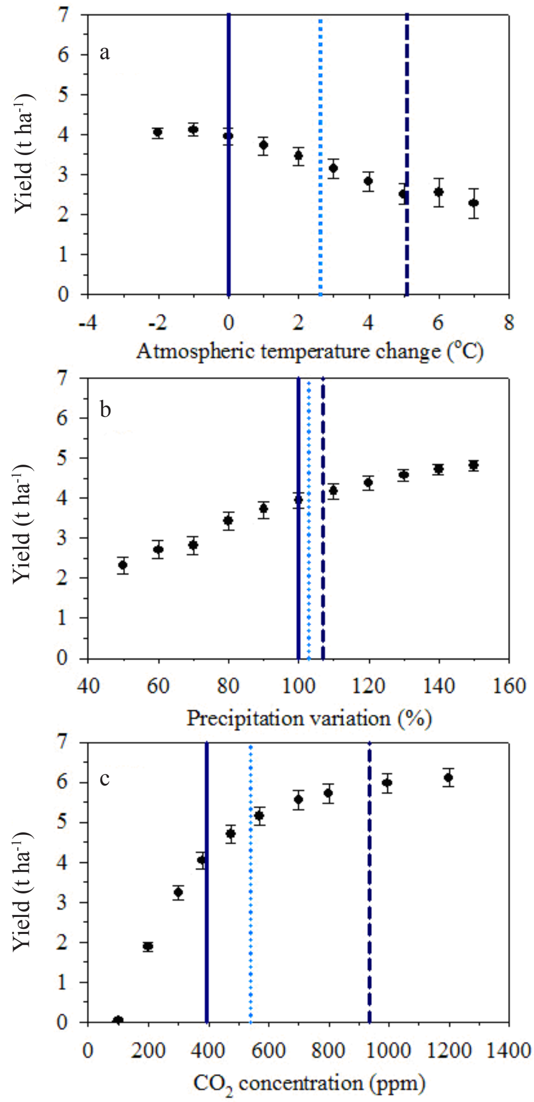

Fig. 5. Simulated yield responses of soybean to changes in: a – atmospheric temperature, b – precipitation, and c – CO_2 concentration. Solid vertical lines represent the current status of each variable; dotted and dashed vertical lines represent the potential regional climate changes for central North America under RCP 4.5 and RCP 8.5 scenarios of each variable, respectively. Vertical bars represent ±1 standard error (n = 20).

flower appearance (EM-FL), and thermal days between first seed and physiological maturity (SD-PM). This regime is an adaptation strategy that uses these five genetic coefficients to explore a potentially adaptable optimum trait (*ie*, thermal days) of the cultivar for the extreme changing climate condition as well as to identify optimum planting windows that amend the negative projected effects of climate change under this scenario (Fig. 7). Simulations were performed from the parameterised base values to examine the adaptabilities predominantly to the elevated temperatures. The simulation results show that increases in soybean yield are expected in late planting and with an increase in SD-PM.

T a b l e 6. Statistical analysis for the simulated yield data of the responses to changes in only CO_2, temperature, and precipitation under climate change scenarios (CC) of RCP 4.5 and RCP 8.5 from 2081 to 2010

CC scenario	Division	Yield	Wilcoxon*
		t ha^{-1}	*Pr* > |Z|
Baseline	–	3.961	–
	CO_2 538 ppm	5.028	0.0041
RCP 4.5	Temp. +2.6°C	3.321	0.0391
	Precip. +3%	4.029	0.6149
	CO_2 936 ppm	5.904	<0.0001
RCP 8.5	Temp. +5.1°C	2.546	0.0013
	Precip. +7%	4.108	0.4504

*Wilcoxon two-sample test, and the values represent normal (Z) approximation probability (*Pr*).

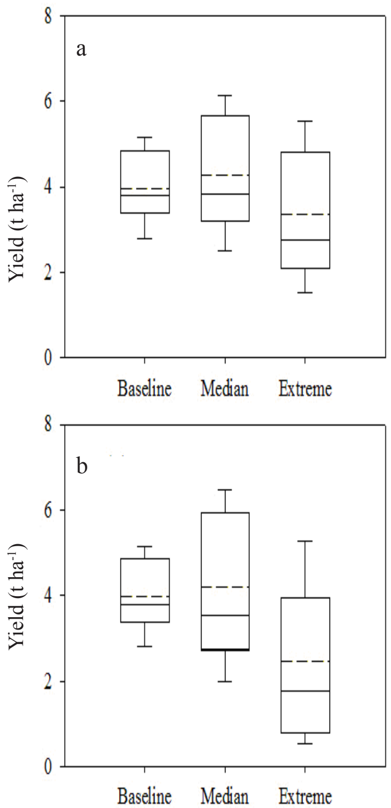

Fig. 6. Simulated soybean yields in response to combinations of temperature, precipitation, and CO_2 for the climate change projections from 2081 to 2010 under: a – RCP 4.5 and b – RCP 8.5 scenarios in comparison with the current status (baseline). Median and extreme regimes represent the median and extreme temperature and precipitation projections for central North America under 42 and 39 global models according to the climate change scenarios of RCP 4.5 and RCP 8.5, respectively (IPCC, 2013). Error bars and the peripheral box represent the 10th, 25th, 75th, and 90th percentiles of the yield data, showing the median (solid line) and mean (dashed line) in the box.

DISCUSSION

CROPGRO-Soybean in DSSAT v4.5 was used to model soybean biomass, LAI, and yield at ambient and elevated (CO_2). The validated model using data from SoyFACE was then applied to simulate soybean yields for the past 20 years (1990-2010) and for projected years of 2081-2100, centred on 2090, under RCP 4.5 and RCP 8.5 scenarios (IPCC, 2013). A model sensitivity test including yield responses to various levels of temperature, CO_2, and precipitation was also performed to ensure that the model could react to individual climate variables. We determined that the model could reproduce yield responses to these climate variables reasonably well. The results are consistent with other studies on soybean responses to different climate variables (Alagarswamy *et al*., 2006; Li *et al*., 2013; Roberto *et al*., 2006).

The other crop models in DSSAT have simulated the effects of the FACE experiments on crop yields and growth parameters (Ko *et al*., 2010; Tubiello *et al*., 1999). We also demonstrated that CROPGRO-Soybean is competent for simulating CO_2 effects on the yield and growth of soybean grown under the FACE system. Nevertheless, the model somewhat overestimated the measured biomass and LAI of late season 2004, although the yield was reproduced reasonably well (Fig. 2).

Our result of the sensitivity responses to temperature and precipitation generally corresponded to that reported by Goldblum (2009). In that study, soybean yield was negatively correlated with mean monthly temperature and positively correlated with precipitation in central and southern Illinois during summer. We assumed that although the responses of soybean to temperature and precipitation change can vary according to variety and location, the general trend in the responses remained consistent with the current results.

Table 7. Statistical analysis for simulated soybean yields of the responses to climate change combinations of temperature, precipitation, and CO_2 under climate change scenarios of RCP 4.5 and RCP 8.5 for the future years 2081 to 2010 in comparison with the baseline in three different planting dates

Day of year	Division	Yield	
		RCP 4.5	RCP 8.5
		t ha^{-1}	
	Baseline	3.961	3.961
152	Median	4.269ns	3.954ns
	Extreme	3.774ms	2.380*
	Baseline	3.963	3.963
147	Median	4.153ns	3.802ns
	Extreme	3.665ms	2.182*
	Baseline	3.959	3.959
145	Median	4.110ns	3.772ns
	Extreme	3.603ms	2.132*

*, ms, and ns represent very significantly different at 1% ($p < 0.01$), marginally different at 10% ($p < 0.1$) and not significantly different at 10% ($p \geq 0.1$) from the baseline yield according to the Wilcoxon two-sample test, respectively.

Yields were projected to increase with elevated CO_2, decrease with elevated temperatures, and vary depending on precipitation changes in comparison with the baseline (Fig. 5). The projected warming and decrease in precipitation (*ie* 14% less than the baseline condition) both caused negative effects on yield. However, the results show that changes in projected yield are dependent on the extent of changes in temperature and precipitation.

Changes in yield in relation to the combined effects of CO_2, temperature, and precipitation were generally attributed to temperature and CO_2 (Fig. 6). Soybean yield was projected to decrease under the climate combination including an extremely high temperature of +7.4°C. It appeared that the yield increases due to elevated CO_2 and precipitation would be offset by the yield decrease due to elevated temperature. Temperature effects dominate this relationship, which is consistent with that reported in other studies. Schlenker (2008) reported that soybean yields increase in temperatures up to a critical threshold of 30°C and are significantly harmed above that temperature. In addition, Adams *et al*. (1990) reported that future changes in tempe rature associated with an increase in atmospheric CO_2 could lead to increases in crop water demand.

Crop production in the future can be adapted to climate change by implementing alternative management practices and introducing new genotypes adaptable to future climate conditions (Dhungana *et al.,* 2006). As climate changes, the synchrony between climate and plant communities is disturbed. Adaptation technologies include efforts to reach new synchronisation between climate and plant communities (Cutforth *et al.,* 2007). We hypothesised that in the climate of central Illinois, late planting of soybean crops may help the plants experience their pod-filling periods after the higher temperatures. Our results showed that late planting within an optimum planting range (day of year 145 to 152) may help increase soybean yield in the case of extreme climate change conditions (*eg* +7.4°C). Other management options for mitigating the negative impacts of change climate include developing irrigation practices for increased water use efficiency and developing seeding and residue management practices that conserve water.

Appropriate cultivar selection to adapt to warming conditions would be feasible only if sufficient plasticity occurs in photoperiod and vernalisation requirements of crop plants (Masle *et al.,* 1989); the current crop model used in the simulations considers such adaptabilities. Our results showed that controlling thermal days in the reproductive stages can help mitigate the adverse impacts of the warming conditions on soybean yield. This finding supports a generally acceptable concept that developing new cultivars of a crop requires identification of genetic traits that will help the crop to effectively adapt to the warming climate. These genetic adaptation strategies include developing cultivars able to tolerate or avoid summer heat and drought, developing cultivars adaptable to the warming climate and longer growing seasons, and identifying cultivars that have increased heat and water stress tolerance.

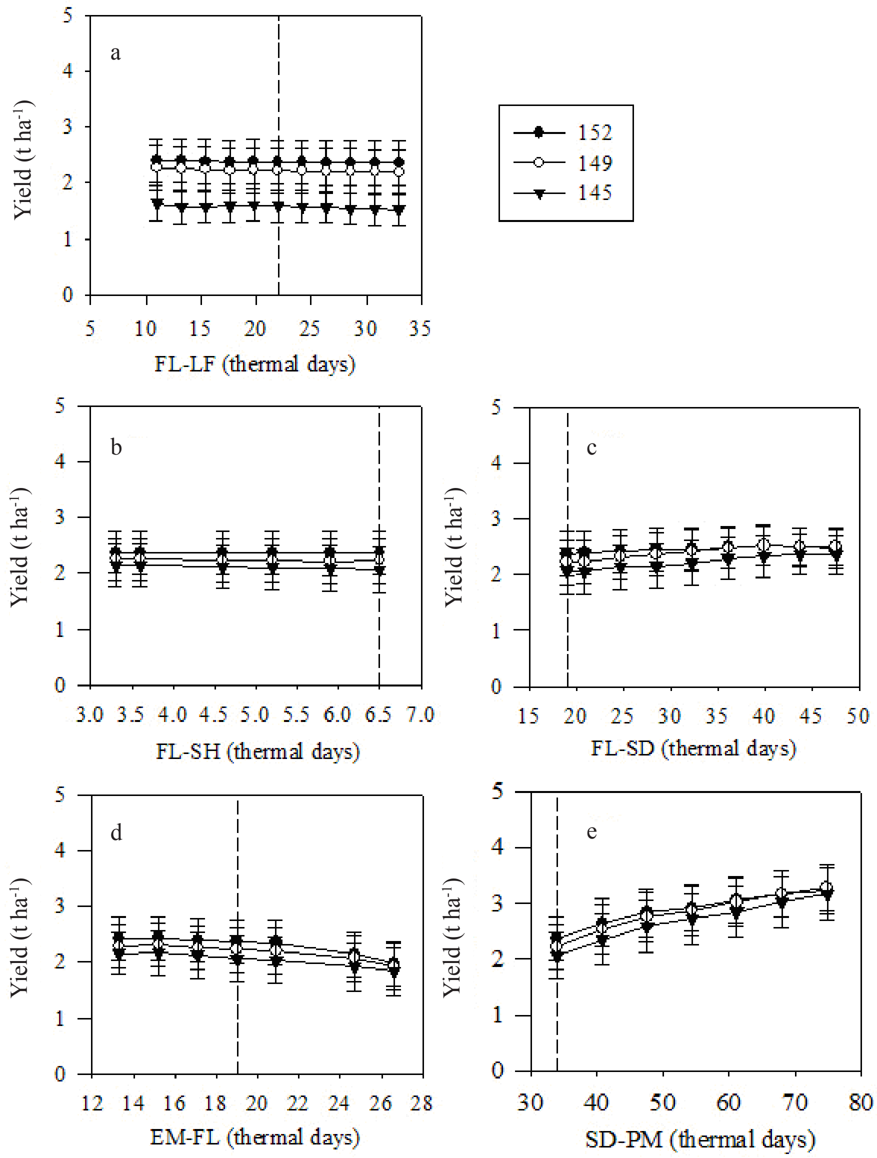

Fig. 7. Simulated soybean yield responses to changes in temperature-sensitive genotype coefficients in the future climate change projection of the extreme condition (+7.4°C in mean air temperature and −14% in precipitation) according to the climate change scenario of RCP 8.5 under various planting regimes, planted on day of year (DOY) 152, DOY 149, and DOY 145. a – thermal days between first flower and end of leaf expansion (FL-LF), b – that between plant first flower and first pod (FL-SH), c – that between first flower and first seed (FL-SD), d – that between plant emergence and flower appearance (EM-FL), e – that between first seed and physiological maturity (SD-PM). Dashed lines and vertical bars represent the current status of each variable and ±1 standard error (n = 20), respectively.

CONCLUSIONS

1. CROPGRO-soybean model in decision support system for agro-technology transfer v4.5 was successfully calibrated and validated for simulating soybeans grown in free air CO_2 enrichment experiments in central Illinois. Simulated biomass, leaf area index, and yield agreed with the measured values within a statistically acceptable range of error.

2. Enhancement of crop yield caused by potentially elevated CO_2 and precipitation projected would be overshadowed or counterbalanced by the effects of increased temperature. Moreover, we demonstrated that a successfully validated and tested model is a feasible tool for analysing the possible impacts of climate change on regional soybean production.

3. The CROPGRO-soybean model provided a valuable preview of the crop responses to the driving factors of climate change including CO_2, temperature, and precipitation.

4. The results obtained can be used as a reference for policymakers in devising strategies to ensure food security.

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