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Impacts of elevated CO₂ concentration on the productivity and surface energy budget of the soybean and maize agroecosystem in the Midwest USA

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Abstract

The physiological response of vegetation to increasing atmospheric carbon dioxide concentration ([CO₂]) modifies productivity and surface energy and water fluxes. Quantifying this response is required for assessments of future climate change. Many global climate models account for this response; however, significant uncertainty remains in model simulations of this vegetation response and its impacts. Data from *in situ* field experiments provide evidence that previous modeling studies may have overestimated the increase in productivity at elevated [CO₂], and the impact on large-scale water cycling is largely unknown. We parameterized the Agro-IBIS dynamic global vegetation model with observations from the SoyFACE experiment to simulate the response of soybean and maize to an increase in [CO₂] from 375 ppm to 550 ppm. The two key model parameters that were found to vary with [CO₂] were the maximum carboxylation rate of photosynthesis and specific leaf area. Tests of the model that used SoyFACE parameter values showed a good fit to site-level data for all variables except latent heat flux over soybean and sensible heat flux over both crops. Simulations driven with historic climate data over the central USA showed that increased [CO₂] resulted in decreased latent heat flux and increased sensible heat flux from both crops when averaged over 30 years. Thirty-year average soybean yield increased everywhere (ca. 10%); however, there was no increase in maize yield except during dry years. Without accounting for CO₂ effects on the maximum carboxylation rate of photosynthesis and specific leaf area, soybean simulations at 550 ppm overestimated leaf area and yield. Our results highlight important model parameter values that, if not modified in other models, could result in biases when projecting future crop–climate–water relationships.

Keywords: agroecosystems, Agro-IBIS, carbon dioxide, evapotranspiration, latent heat flux, maize, sensible heat flux, soybean

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Introduction

Global environmental change will affect agroecosystems and will also be affected by agroecosystems because of their large spatial extent. Projections of future crop yield are vital to inform policy making and management to achieve food security in the face of population growth and global environmental change. On a global scale, agroecosystems increased in area by 12% over the last 40 years and now, along with pastures,

cover nearly 40% of the land surface (Ramankutty & Foley, 1999; Asner *et al.*, 2004; Foley *et al.*, 2005). Given the spatial extent of agroecosystems, the spatial variability in predicted future precipitation (NAST, 2000), and the possibility of increased frequency and severity of extreme weather events (Rosenzweig *et al.*, 2002), the response of agroecosystems to climate change and increasing carbon dioxide concentration ([CO₂]) may have a substantial effect on regional budgets of energy, water, and carbon (Sellers *et al.*, 1997).

A dynamic global vegetation model (DGVM) is an appropriate tool to predict the potential response of ecosystems to environmental changes. These models are being developed and used to fill the gap in our knowledge of how ecosystems respond to changes in climate and [CO₂], with the goal of incorporating these

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models into global climate modeling systems (e.g., Sitch *et al.*, 2003; Krinner *et al.*, 2005; Thornton *et al.*, 2007; Twine & Kucharik, 2009; Galbraith *et al.*, 2010); however, there are two key shortcomings of these models. First, until recently, DGVMs did not explicitly simulate agroecosystems. Instead, they used natural grasslands as proxies for agroecosystems, despite differences between agroecosystems and grasslands in structure, functioning, and management. Second, while the physiological equations in these models allow vegetation to respond to changes in atmospheric [CO₂], the most appropriate experimental methods for parameterizing and validating model analysis have been the subject of debate (Tubiello & Ewert, 2002; Long *et al.*, 2006; Tubiello *et al.*, 2007; Ziska & Bunce, 2007; Ainsworth *et al.*, 2008; Ziska *et al.*, 2012).

Many DGVMs are now including crop vegetation types in their framework (Kucharik, 2003; Bondeau *et al.*, 2007; Lokupitiya *et al.*, 2009; Shevliakova *et al.*, 2009; Smith *et al.*, 2010; Levis *et al.*, 2012), allowing their specific responses to factors of global environmental change to be simulated. Both C₃ and C₄ plants respond to increasing [CO₂] by closing stomatal pores, leading to decreased water flux to the atmosphere, increased soil moisture storage, and potentially increased runoff and streamflow (Gedney *et al.*, 2006; Bernacchi *et al.*, 2007; Betts *et al.*, 2007). Elevated [CO₂] consistently stimulates the productivity and yield of all major C₃ crops by directly stimulating photosynthetic CO₂ fixation and by ameliorating drought stress as a result of reduced plant water use (Ainsworth *et al.*, 2008; Leakey *et al.*, 2009a). Elevated [CO₂] can also stimulate yield of C₄ crops, but C₄ photosynthesis is CO₂-saturated under current day [CO₂] and physiological benefits are limited to reduced water use, which may in turn alleviate both biochemical and stomatal limitations to photosynthesis under drought (Leakey *et al.*, 2004, 2006b; Leakey, 2009; Markelz *et al.*, 2011). Therefore, any stimulation of yield appears to be limited to times and places of drought (Long *et al.*, 2006; Leakey, 2009). The physiological equations in DGVMs account for differences in C₃ and C₄ plants and should be able to simulate the effects of increasing [CO₂] on plant productivity and water use.

Evaluating plant response to elevated [CO₂] in DGVMs depends on data describing the responses of vegetation grown in enriched CO₂ environments. Measurements made in CO₂-enriched enclosures (e.g., chambers, glasshouses) have been very important in advancing mechanistic understanding of crop responses to elevated [CO₂] (Drake *et al.*, 1997; Ziska *et al.*, 1997); however, the so-called 'chamber effect', whereby the physical environment and soil within the chamber is unavoidably modified from the ambient environment, influences plant responses. Free-air CO₂

enrichment (FACE) experiments minimize perturbation of the environment by allowing plants to grow in ambient field conditions with pipes encircling the plots that release CO₂ over the vegetation canopy. Analysis of FACE results on the world's major crops have suggested that the CO₂ fertilization effect for C₃ crops is approximately half that observed in enclosure experiments (Long *et al.*, 2006; Ainsworth, 2008; Ainsworth *et al.*, 2008). This is significant because most models of future crop yield have been parameterized with data from enclosure studies, and could therefore be over-optimistic in their projections of future food supply. For example, yield stimulation of wheat by elevated [CO₂] in a FACE experiment was 50% less, on average, than projected by five different crop models for both well-watered and water-stressed conditions (Tubiello & Ewert, 2002). At the same time, many existing model projections of yield of C₄ crops, such as maize, have assumed a smaller but consistent stimulation of yield by elevated [CO₂] across space and time, which has not been observed in FACE studies to date (Leakey, 2009; Markelz *et al.*, 2011).

As a first step in simulating the response of agroecosystems to climate change and the resulting effects on ecosystem goods and services, we tested the Agro-IBIS DGVM in simulations of maize and soybean canopies grown at ambient [CO₂] (375–385 ppm) and elevated [CO₂] (550 ppm) over six growing seasons at the Soybean Free-Air Concentration Enrichment (SoyFACE) facility located in Champaign, IL. We then ran Agro-IBIS in simulations across the major soybean- and maize-growing regions of the United States to predict how increasing [CO₂] might affect the productivity of the maize-soybean agroecosystem and the resulting impacts on water and energy budgets.

Materials and methods

Capturing the response of soybean to [CO₂] in the Agro-IBIS DGVM

The manner in which short-term leaf-level changes in photosynthetic CO₂ fixation and stomatal conductance scale to long-term changes in canopy-scale carbon, water, and energy budgets depends on allometry, stoichiometry, phenology, physiological acclimation, canopy micrometeorology, and feedbacks across the plant–soil and plant–atmosphere interfaces. For example, responses of soybean to elevated [CO₂] downstream of stimulated photosynthesis include stimulated leaf dark respiration (Leakey *et al.*, 2009b), decreased specific leaf area (SLA, a measure of leaf area per unit mass; Ainsworth *et al.*, 2007), increased leaf area index (LAI; Dermoddy *et al.*, 2006), and longer growing periods (Dermoddy *et al.*, 2006). Soybean is not found to alter the efficiency of canopy light interception (Rascher *et al.*, 2010) or change allocation of

carbon between roots and shoots with increasing $[\text{CO}_2]$ (Ainsworth *et al.*, 2002); however, Morgan *et al.* (2005) found a greater proportion of change in biomass in leaves than in stems. At elevated $[\text{CO}_2]$, canopy latent heat flux decreases and sensible heat flux increases (Bernacchi *et al.*, 2007). Some studies have suggested that elevated $[\text{CO}_2]$ could lead to acclimation of stomatal function (Bunce, 2004), but this was demonstrated not to be the case at SoyFACE (Leakey *et al.*, 2006a). The importance of interactions between leaf, canopy, and soil processes means that evaluation of model performance against experimental data from canopy-scale fumigation experiments under field conditions is necessary.

The Integrated Biosphere Simulator, agricultural version (Agro-IBIS; Kucharik, 2003; Kucharik & Brye, 2003) is a DGVM and therefore simulates the photosynthetic and stomatal responses to changes in $[\text{CO}_2]$. For C_3 species, the model uses a widely tested semi-mechanistic model for photosynthesis (Farquhar *et al.*, 1980) and an empirical model for stomatal conductance (Ball *et al.*, 1987). These algorithms allow the model to respond dynamically to changing concentrations of CO_2 ; however, they contain parameters that must be fixed for different plant functional types (PFTs). Although these parameters have been shown to vary with different $[\text{CO}_2]$ in empirical studies, these values are not traditionally varied for different $[\text{CO}_2]$ in DGVMs. Our objectives in this study were threefold – (i) to evaluate the ability of the Agro-IBIS model to simulate canopy-scale variables by comparing them with observations made at SoyFACE after running the model with the default model parameter values, (ii) to use parameter values measured at SoyFACE to assess whether model performance could be improved, and (iii) to evaluate the model's ability to capture the measured response to a $[\text{CO}_2]$ of 550 ppm. We used experimental results from the SoyFACE facility on the effects of elevated $[\text{CO}_2]$ on plots of soybean over six growing seasons (2002 and 2004–2008). Using measurements at both ambient CO_2 concentrations and 550 ppm, we evaluated whether the model simulated the measured response in photosynthetic CO_2 assimilation, stomatal conductance, soybean phenology, biomass allocation, LAI, yield, latent heat flux (evapotranspiration), and sensible heat flux (Table 1).

Agro-IBIS parameters for soybean that are relevant for this study are listed in Table 2, along with their default and modified values. Two key parameters that vary between 375 and 550 ppm are the maximum carboxylation rate of photosynthesis ($V_{\text{c}, \text{max}}$ Ainsworth & Rogers, 2007) and SLA (described below). The maximum carboxylation rate of photosynthesis was prescribed based on direct measurement and adjusted for a reference temperature of 15 °C. This value is adjusted at each model time step according to leaf temperature, nitrogen stress, and water stress. Although initial and final carbon allocation fractions for stems and roots are similar between 375 and 550 ppm runs, carbon continues to be allocated to stems and roots for an additional 9 days after peak LAI is reached in the 550 ppm runs in order to more closely match observations of leaf and stem biomass. We adjusted allocation fractions in the model to obtain a best fit of simulated dry mass with measurements from 2002

Table 1 Data sources that were used in this study to evaluate Agro-IBIS performance for soybean and maize

Variable/Parameter	Soybean	Maize
Soybean phenology	Castro <i>et al.</i> (2009)	Not applicable
Stomatal conductance	Bernacchi <i>et al.</i> (2006)	Leakey <i>et al.</i> (2006b); Markelz <i>et al.</i> (2011)
Net assimilation	Bernacchi <i>et al.</i> (2006); Leakey <i>et al.</i> (2009b), Gillespie <i>et al.</i> (2012)	Leakey <i>et al.</i> (2006b); Markelz <i>et al.</i> (2011)
Leaf area index	Dermody <i>et al.</i> (2006); J. McGrath and E. Ainsworth, unpublished results	Leakey <i>et al.</i> (2006b); Markelz <i>et al.</i> (2011)
Soybean leaf, stem, and reproductive dry mass (2004–07)	This study	Not applicable
Biomass and Yield	R. Nelson unpublished results; This study	Leakey <i>et al.</i> (2006b); Markelz <i>et al.</i> (2011)
Energy fluxes	Bernacchi <i>et al.</i> (2007)	Hussain <i>et al.</i> (2013)

(Morgan *et al.*, 2005) and then used these parameter values in each subsequent model year (2004–2007).

Capturing the response of maize to $[\text{CO}_2]$ in the Agro-IBIS DGVM

Unlike soybean, the maize grown at SoyFACE at elevated $[\text{CO}_2]$ showed no change in allometric, growth, phenological, or acclimation responses under well-watered conditions, but was found to reduce canopy water use and conserve soil moisture (Leakey *et al.*, 2006b). During drought stress, elevated $[\text{CO}_2]$ ameliorated both stomatal and non-stomatal limitations to photosynthetic CO_2 fixation (Leakey *et al.*, 2004; Markelz *et al.*, 2011).

For C_4 species, Agro-IBIS uses a coupled model of photosynthesis and stomatal conductance (Farquhar & Sharkey, 1982; Collatz *et al.*, 1992). We used experimental results from the SoyFACE facility on the effects of elevated $[\text{CO}_2]$ on plots of maize over three growing seasons (2004, 2006, and 2008) to meet the same objectives as for soybean. Using measurements at both ambient CO_2 concentrations and 550 ppm, we evaluated whether the model simulated the measured response in photosynthetic CO_2 assimilation, stomatal conductance, total plant biomass, maximum (peak) LAI, yield, latent heat flux, and sensible heat flux (Table 1).

Table 2 Agro-IBIS parameterizations relevant to this study for soybean. Default values are those used in the previous version of Agro-IBIS before being parameterized in this study with data from the SoyFACE site. Final code values of $V_{c,max}$ and allocation fractions were based on measurements (roots were estimated) while values of SLA at 550 ppm were modified to attain model output consistent with observations

Parameter	Default Value	Final Code (375 ppm)	Final Code (550 ppm)
$V_{c,max}$ at 15 °C ($\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$)	65	40.53*	37.4*
Ball and Berry function for stomatal conductance slope (m), intercept (b)	9, 0.01	10.75 [†] , 0.01	10.75 [†] , 0.01
Specific leaf area (SLA; $\text{m}^2 (\text{kg C})^{-1}$)	70	Variable depending on growth stage (ca. 95–102) [‡]	82% of 375 ppm value of each growth stage
Fraction of aboveground biomass allocated to leaves (emergence – end of vegetative growth; remainder to stem)	0.85 – 0.00	0.47 – 0.00 [§]	0.47 – 0.00 [§]
Fraction of biomass allocated to stem (emergence – end of vegetative growth)	0.15 – 0.30 = 0 at maturity	0.53 – 0.25 [§] = 0 10 days after end of vegetative growth	0.53 – 0.25 [§] = 0 10 days after end of vegetative growth
Fraction of biomass allocated to roots (emergence – end of vegetative growth)	0.50 – 0.20 = 0 at maturity	0.35 (constant) = 0 10 days after end of vegetative growth	0.35 (constant) = 0 10 days after end of vegetative growth
Fraction of biomass allocated to reproductive (end of vegetative growth to maturity (ca. R7 stage))	1 - (fractions allocated to leaf + stem + root); increases from 0 to 1 after end of vegetative growth		
Fraction of total reproductive biomass in seed (fyield)	0.85	0.65 [§]	0.65 [§]
Maturity Group	Not applicable	3 [¶]	3 [¶]

*Bernacchi *et al.*, 2005.

[†]Leakey *et al.*, 2006b.

[‡]Ng & Loomis, 1984.

[§]Morgan *et al.*, 2005

[¶]Zhang *et al.*, 2007.

Agro-IBIS parameters for maize that are relevant for this study are listed in Table 3, along with their default and modified values. Based on the evaluation of model simulations with SoyFACE measurements (Table 1), none of the model parameters for maize needed to be varied between ambient and 550 ppm runs. Also of note is that the measured V_{max} (standardized to 15 °C) was found to be nearly half of the model default value.

The Agro-IBIS model and recent improvements

Model description. Agro-IBIS is a DGVM adapted from the Integrated Biosphere Simulator (IBIS; Foley *et al.*, 1996; Kucharik *et al.*, 2000) to simulate the growth and management of crops (Kucharik & Brye, 2003; Kucharik & Twine, 2007; Twine & Kucharik, 2008). The model includes all components of the IBIS model allowing it to simulate vegetation canopy physics, phenology, soil physics and hydrology, and ecosystem biogeochemistry. Agro-IBIS simulates the leaf-level processes of photosynthesis and stomatal conductance, and scales them to the canopy level to simulate fluxes of carbon, water, and energy based on the land-surface transfer scheme model (LSX; Thompson & Pollard, 1995). Photosynthesis and

respiration parameters are modified by leaf temperature, moisture stress, and nitrogen stress. The model captures the physiological response of C₃ and C₄ species to changes in [CO₂], simulating a decrease in stomatal conductance for both C₃ and C₄ species, and an increase in productivity for C₃ species (Cramer *et al.*, 2001); however, these responses to elevated [CO₂] have not previously been evaluated against observations.

Agro-IBIS simulates growth stages of crops according to environmental conditions. Crop growth stages of planting, emergence, grain or pod fill, senescence, and harvest are simulated based on accumulated growing degree-days if particular dates are not specified. Gridded data sets of planting and harvest dates across the United States are not available on a yearly basis; therefore, regional runs use functions based on the climate of each year to optimize these dates. Growth stages from emergence to maturity are predicted by the model, and used to determine the allocation of carbon to leaves, roots, stems, and reproductive components of the plant at each time step. Carbon that is allocated to the leaf is multiplied by the SLA at each time step and weighted by the fraction of the grid cell covered by each vegetation type to determine a grid cell value of LAI. The fraction of carbon allocation to leaves, roots, and stems decreases after peak LAI is reached and eventually

Table 3 Agro-IBIS parameterizations relevant to this study for maize. Default values are those used in the previous version of Agro-IBIS before being parameterized in this study with data from the SoyFACE site. See Kucharik & Brye (2003) for sources

Parameter	Default value	Final code (375 ppm)	Final code (550 ppm)
V_{\max} at 15 °C ($\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$)	70	34.14*	34.14*
Ball and Berry function for stomatal conductance slope (m), intercept (b)	4, 0.03	4, 0.03	4, 0.03
Specific leaf area (SLA; $\text{m}^2 (\text{kg C})^{-1}$)	50	51 [†]	51 [†]
Fraction of aboveground biomass allocated to leaves (emergence – end of vegetative growth; remainder to stem)	0.80 – 0.00	0.80 – 0.00	0.80 – 0.00
Fraction of biomass allocated to stem (emergence – end of vegetative growth)	0.20 – 0.00	0.20 – 0.00	0.20 – 0.00
Fraction of biomass allocated to roots (emergence – end of vegetative growth)	0.40 – 0.00	0.40 – 0.00	0.40 – 0.00
Fraction of biomass allocated to reproductive (end of vegetative growth to maturity)	1 – (fractions allocated to leaf + stem + root); increases from 0 to 1 after end of vegetative growth		

*Markelz *et al.*, 2011.†Leakey *et al.*, 2006b.

reaches 0 while at the same time allocation to reproductive components increases from 0 to 1. There is some time when allocation to all biomass components occurs in soybean to simulate semi-determinate cultivars, but maize carbon allocation shifts entirely from vegetative to reproductive components at grain fill.

Input requirements include soil texture class at each of 11 soil layers with variable depths, solar radiation, air temperature, precipitation, humidity, and wind. If hourly values are not available they are simulated through the use of empirical formulations (Campbell & Norman, 1998). Crops may optionally respond to inputs of irrigation and fertilizer.

Key improvements to Agro-IBIS. Three key improvements were made to the model structure that affect the simulation of photosynthesis, phenology, and carbon allocation of soybean. We replaced the default Arrhenius temperature functions of photosynthesis with functions that better simulate the variation of the $V_{c,\max}$ photosynthesis parameter with leaf temperature (Bernacchi *et al.*, 2001). We also replaced the default soybean phenology algorithm, which is based solely on thermal time, with one that includes functions of thermal time and photoperiod (Setiyono *et al.*, 2007). The new algorithm also forces the timing of growth stages to depend on crop maturity group (i.e., groupings of cultivars that mature at different biological rates). This function is necessary to simulate appropriate yields and time of maturity across the continental USA. The addition of these new functions eliminates the need to know the number of growing degree-days to maturity that was required in the default version of code and in some other soybean models. The new soybean model replaces a time invariant constant value of SLA, which varied only by crop type, with a function of accumulated temperature and incoming radiation (Ng & Loomis, 1984) that is constrained by SoyFACE observations. The value of soybean SLA now varies

throughout the growing period and from year to year. The fraction of carbon allocation to leaves and stems was adjusted based on measurements from 2002, and root allocation was fixed at a constant value (Table 2). Agro-IBIS now also includes a function that determines leaf area decline during maturation in both soybean (ca. R7 stage) and maize (Sacks & Kucharik, 2011).

Evaluating Agro-IBIS at the SoyFACE facility. We performed Agro-IBIS simulations to represent soybean and maize grown at the SoyFACE facility (40.03°N, 88.27°W) for the period 2002–2008. We did not evaluate the model in 2003 because crops were damaged by hail early in the season at the SoyFACE facility. The model was run at an hourly time step using hourly meteorological forcing data compiled from observations at Willard airport (40.04°N, 88.27°W) and the nearest Surface Radiation Network (SURFRAD) site (40.05°N, 88.37°W) (Vanloocke *et al.*, 2010).

We set soil texture class at each soil layer to match site characteristics of a Drummer profile (fine-silty, mixed, mesic Typic Endoaquoll; USDA Natural Resources Conservation Service; <http://soils.usda.gov/>). Nitrogen fertilizer application was simulated at the time of planting at rates equivalent to the field scale. Irrigation was not performed at the SoyFACE facility; therefore, we did not simulate this in the model runs.

The model was run for 2001–2008 with a control simulation of $[\text{CO}_2]$ fixed at 375 ppm for the entire run (hereafter referred to as 375-model), and again for an experimental simulation of $[\text{CO}_2]$ set to 550 ppm for the entire run (hereafter referred to as 550-model) using final code values listed in Tables 2 and 3. Each run contained a spin-up period with historic data from the CRU and NCEP/NCAR data sets (described below) with potential vegetation until 1910 and soybean for 1911–2000 for the grid cell in which the SoyFACE facility is located. The

spin-up period simulates the thousands of years of carbon accumulation in the soil under typical seasonal climate conditions of this site. The spin-up was continued until net soil CO₂ fluxes reached near equilibrium, representing realistic present day carbon budget dynamics.

Latent and sensible heat fluxes cannot be directly measured at SoyFACE because of the small flux footprint of the plots. Fluxes were estimated using the residual energy budget method based on the following conservation of energy principle

$$LE = R_{\text{net}} - H - G \quad (1)$$

where LE is latent heat flux, R_{net} is net radiation, H is sensible heat flux, and G is soil heat flux (Bernacchi *et al.*, 2007; Hickman *et al.*, 2010). The residual energy budget method estimates LE and H using measurements of net radiation, soil heat flux, and temperature of the air and surface (Huband & Monteith, 1986).

Implementing Agro-IBIS over the Midwest USA. After model performance was improved using measured parameter values, Agro-IBIS was used to examine the potential impacts of elevated [CO₂] on the maize-soybean ecosystem in the US east of the Rocky Mountains (50.0°N to 24.5°N, 106.5°W to 65.0°W). Two simulations were performed at a spatial resolution of 0.5° × 0.5° – one control simulation with [CO₂] set to 375 ppm for the entire run (hereafter referred to as 375-model), and a second experimental simulation with the [CO₂] set to 550 ppm for the entire run (hereafter referred to as 550-model). Each run contained a spin-up period similar to that performed for the site runs. Potential vegetation (i.e., vegetation that would grow in the absence of management) was simulated for 1751–1910 and initially prescribed according to Ramankutty & Foley (1998), soybean was simulated from 1911 to 1950, and soybean and maize were simulated for 1951–2000. To examine the impacts of elevated [CO₂] on agroecosystems, grid cells were only included in the analysis if they contained more than 10% fraction cover of maize and/or soybean according to the circa 1992 maps of Donner (2003).

We used weather and climate information derived from a combination of monthly climatic observations and daily, reanalyzed meteorological data on a 0.5° by 0.5° latitude/longitude grid to drive the model. These driver sets were created by combining 1961–1990 climatological mean values and 1901–2005 monthly mean climate data as given by the University of East Anglia Climate Research Unit data sets (CRU05; Mitchell & Jones, 2005; New *et al.*, 1999) with daily anomalies of meteorological data for 1948–2005 from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP/NCAR) reanalysis data set (Kalnay *et al.*, 1996; Kistler *et al.*, 2001). The monthly average precipitation values of these daily values were mathematically forced to equal the monthly CRU05 values. Using these data, Agro-IBIS calculates hourly values empirically using diurnal relationships of meteorological variables (Campbell & Norman, 1998).

Numerous varieties of soybean are grown across the United States to account for the range of climate conditions during the growing season. Our new soybean algorithm requires a maturity group value at each grid cell. We created a maturity

group map at 0.5° by 0.5° resolution based on the map provided by Zhang *et al.* (2007) to simulate the spatial variation in timing of soybean development in the regional runs.

Results

Evaluation at SoyFACE

Soybean photosynthetic CO₂ assimilation, stomatal conductance, phenology, and leaf area index. Measured midday values of photosynthetic CO₂ assimilation between ambient and 550 ppm increased by 22%, when averaged on 10 dates. Simulated midday values of assimilation from the same 10 days increased by 26% between 375-model and 550-model. Measured midday values of stomatal conductance between ambient and 550 ppm decreased by 18%, when averaged over 10 days. Simulated midday values of stomatal conductance from the same 10 days decreased by 22% between 375-model and 550-model. The new soybean algorithm produced improved agreement between simulations and observations of the timing of key soybean growth stages (Table 4; Castro *et al.*, 2009). The default code only simulated emergence, R5, and R7 stages of soybean growth so only these stages could be compared with the new code. While the new code showed no improvement in 2002, it substantially reduced late biases in stages R5 and R7 in 2004.

The default code simulated unreasonably high inter-annual variability in LAI, a delayed onset and offset of

Table 4 Soybean phenology from 2002 and 2004. Observation is the average day of year that four soybean plants within each of four ambient [CO₂] plots emerged, reached vegetative stage V1, and reproductive stages R1, R3.5, R5, and R7. Also shown is the difference in day of year of each stage reached between the Agro-IBIS default code and observation, and final code and observation. Positive values denote a late bias in Agro-IBIS and negative values denote an early bias

Year	Stage	Observation (Day of Year)	Agro-IBIS default code minus observation	Agro-IBIS final code minus observation
2002	Emergence	156	0	0
	V1	170		0
	R1	196		+2
	R3.5	218		−3
	R5	229	+4	−4
	R7	266	+2	+2
2004	Emergence	153	+9	+9
	V1	166		+4
	R1	195		+6
	R3.5	215		+3
	R5	223	+20	+4
	R7	263	+18	+5

growth, and an incorrect decline in LAI after the peak (Fig. 1a–e). Agro-IBIS simulation of soybean LAI at ambient $[\text{CO}_2]$ was improved when the new developmental algorithms were added and measured parameters were used. Soybean LAI in 375-model compared well with the observed timing of onset of leaf growth, peak LAI, and decline of LAI (Fig. 1a–e). While simulated peak LAI was generally between 5.5 and $6.5 \text{ m}^2 \text{ m}^{-2}$ during 2004–2008, observed peak LAI was between 6 and $7 \text{ m}^2 \text{ m}^{-2}$. The simulated LAI in 2002 showed the weakest relationship with observations but values were typical of the other years in this study. Analysis of observed values with 375-model LAI from

days that correspond with observations resulted in good model performance ($y = 1.03x + 0.05$, $R^2 = 0.80$; Fig. 1f) except for outliers in 2002.

Simulated soybean peak LAI was $0.5 \text{ m}^2 \text{ m}^{-2}$ (9%) greater in 550-model than 375-model, which is equivalent to the average effect of elevated $[\text{CO}_2]$ ($0.5 \text{ m}^2 \text{ m}^{-2}$ and +9%) in observations at SoyFACE (Fig. 1a–e; Table 5). Analysis of observed values with 550-model LAI from days that correspond with observations resulted in a regression and R^2 value similar to 375-model (Fig. 1f). When the model was run at 550 ppm without accounting for physiological acclimation (i.e., using parameters in the Final Code 375 ppm column in

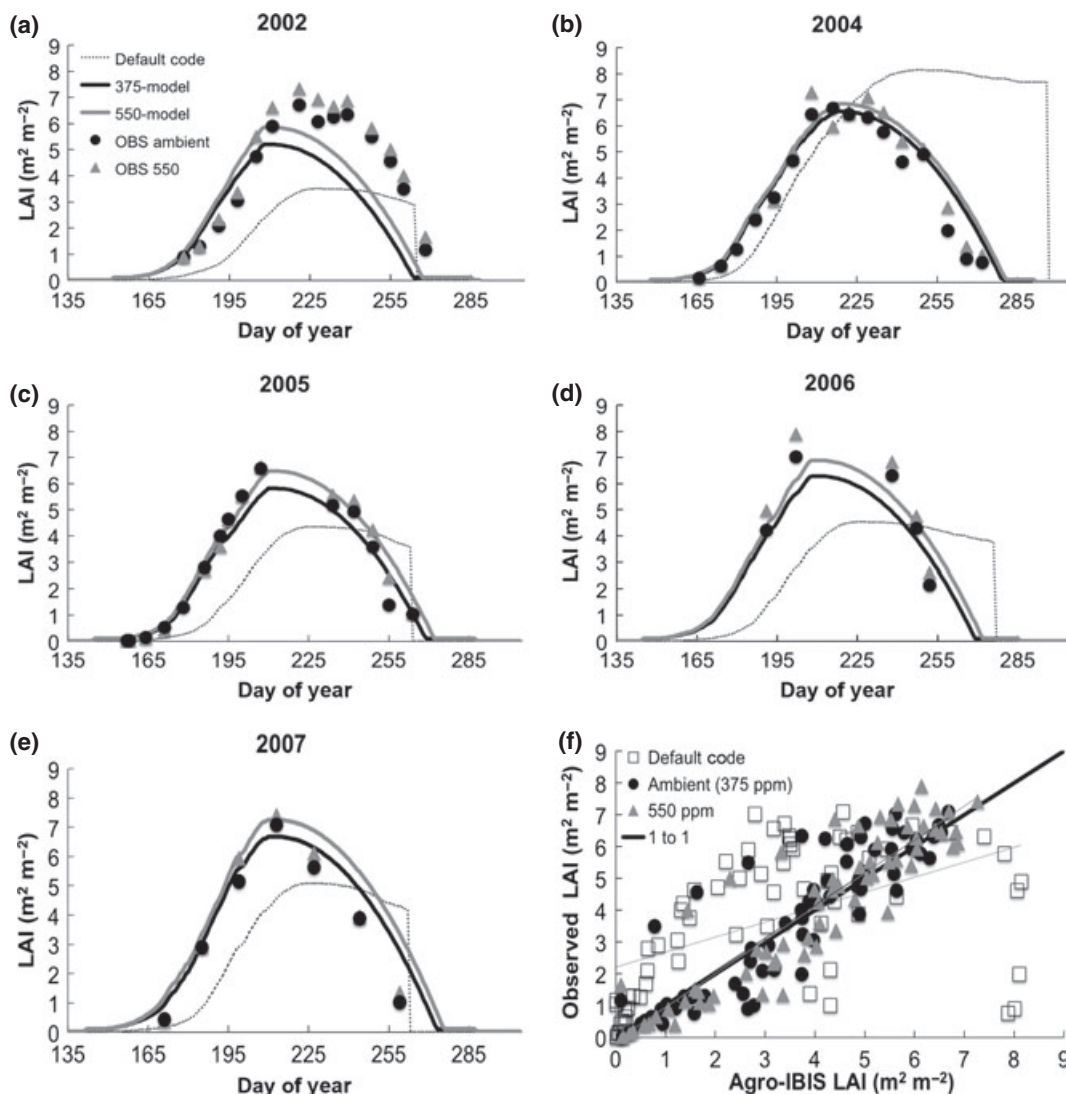


Fig. 1 Simulated and observed soybean LAI ($\text{m}^2 \text{ m}^{-2}$) at ambient (375-model = black line) and 550 ppm (550-model = gray line), and LAI simulated with the default code at 375 ppm (Default Code = dashed line) for 2002, 2004–2007 (a–e); and observed vs. simulated LAI with default code at 375 ppm (Default code; trend is dashed line; $y = 0.47x + 2.2$, $r^2 = 0.27$), final code at 375 ppm (Ambient (375 ppm); thin black line, $y = 1.03x + 0.05$, $r^2 = 0.80$) and at 550 ppm (550 ppm; gray line, $y = 1.05x + 0.10$, $r^2 = 0.83$) for 2002, 2004–2008 (f). Also shown is the 1 to 1 line (thick black line).

Table 5 Average (2002, 2004–07) percent increases in observed and Agro-IBIS simulated maximum biomass in leaf, stem, root, and seed (g dry matter m⁻²) and (2002, 2004–08) peak LAI (m² m⁻²) in soybean between ambient (375 ppm in model) and 550 ppm

	LAI	Leaf	Stem	Root	Seed (yield)
Observed	9	20	31	NA	11
Agro-IBIS	9	34	42	46	13
Agro-IBIS without correct 550 ppm parameters	44	38	33	32	17

Table 2 and setting input [CO₂] to 550 ppm), which is usually how DGVMs are run, the simulated increase in soybean LAI was 44%.

Soybean biomass. The general proportions of soybean biomass allocated to leaf, stem, and reproductive components (seed + pod) in 375-model and 550-model at various times throughout the growing season were simulated reasonably well compared to the observations for 2002 and 2004–07 (Fig. 2). Data for root biomass were not available. Leaf biomass was simulated very well throughout the growing season (Fig. 2a), and was only overestimated at the end of each growing season as leaves did not drop from plants in the model as quickly as was observed. Stem biomass does not decrease from the peak value in Agro-IBIS and resulted in an overestimation compared with measurements at the end of each growing season (Fig. 2b). Seed plus pod biomass is simulated well throughout the growing season (Fig. 2c).

Increases in all dry mass components between ambient and 550 ppm were seen in the simulations and observations (Fig. 2; Table 5). With accounting for

physiological acclimation Agro-IBIS overestimated the increase between 375 and 550 ppm compared with observations in leaves (34% vs. 20%) and stems (42% vs. 31%). When Agro-IBIS was run at 550 ppm without accounting for physiological acclimation, the simulated increase in leaf, stem, and root biomass was 38%, 33%, and 32%, respectively.

Soybean yield. Observations showed that approximately 65% of the carbon stored in the soybean reproductive component went into seed yield, and this value did not change significantly between ambient and 550 ppm. This fraction is a parameter in Agro-IBIS (fyield) and therefore was fixed at 65% in all runs. Over the 5 years, the average ambient observed yield was 382 ± 38 g m⁻² and the simulated yield was 360 g m⁻², while the average 550 ppm observed yield was 425 ± 44 g m⁻² and the simulated yield was 406 g m⁻².

Agro-IBIS simulated an average increase of 13% in soybean yield between 375-model and 550-model, while observations showed an 11% average increase. When Agro-IBIS was run at 550 ppm without accounting for physiological acclimation, the simulated increase in soybean yield was 17%.

Soybean surface energy budget. The surface energy budget has been simulated reasonably well at ambient [CO₂] by Agro-IBIS in maize and soybean through comparisons with eddy covariance measurements (Kucharik & Twine, 2007); therefore, here we focus on simulating the correct response in surface energy budget components between ambient and 550 ppm. Bernacchi *et al.* (2007) showed that LE above a soybean canopy decreased by 12% on average between ambient and 550 ppm. We analyzed the same data set but limited our analysis to hours between 0900 and 1600 to focus on periods of greatest change in photosynthesis and surface energy budget. Our analysis of observations showed LE to decrease by 58 MJ m⁻² (9%; 2002, 2004–

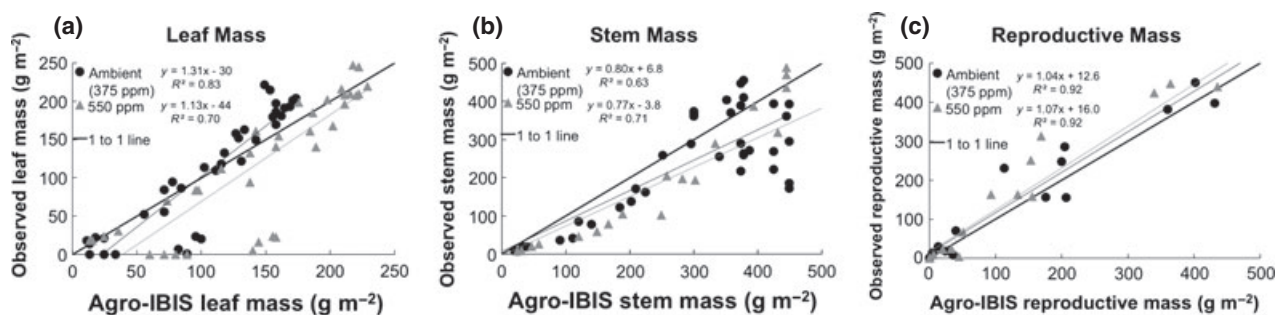


Fig. 2 Observed vs. simulated dry mass (g m⁻²) of soybean leaves (a), stems (b), and reproductive components (seed + pod; c) at the SoyFACE site at ambient (375 ppm in model; thin black line) and 550 ppm (gray line) for the 2002, 2004–2007 growing seasons. Also shown is the 1 to 1 line (thick black line).

Table 6 Absolute difference (550 ppm – ambient; MJ m⁻²) and percent difference (in parentheses) in energy budget components as simulated by Agro-IBIS and as estimated at SoyFACE for hours 0900–1600 for soybean on days of the year in 2002 (190–253), 2004 (190–253), 2005 (190–253), 2006 (190–253), and for maize in 2004 (190–244), 2006 (190–248)

Crop	Year	Sensible heat		Latent heat	
		Agro-IBIS	Observed	Agro-IBIS	Observed
Soybean	2002	20 (26)	43 (173)	–29 (–6)	–50 (–8)
Soybean	2004	9 (9)	83 (79)	–16 (–3)	–85 (–14)
Soybean	2005	7 (6)	34 (68)	–11 (–2)	–48 (–8)
Soybean	2006	8 (9)	46 (80)	–14 (–3)	–49 (–7)
Maize	2004	22 (15)	79 (43)	–30 (–8)	–58 (–9)
Maize	2006	19 (14)	36 (57)	–28 (–7)	–59 (–11)

2006 average) between ambient and 550 ppm. Despite reasonable agreement between the model and observations of midday assimilation and stomatal conductance, Agro-IBIS simulated an average decrease in LE of only 17.5 MJ m⁻² (3.5%) between 375 and 550 ppm (Table 6). Observations showed an average increase of 51.5 MJ m⁻² (100%) in H. The increase in H between ambient and 550 ppm was greatly underestimated in the model with an average increase of only 11 MJ m⁻² (12.5%) when averaged over all years. Because H increases at the expense of LE, there is little change in R_{net} and G in both the simulations and observations.

Maize photosynthetic CO₂ assimilation, stomatal conductance, and leaf area index. Observations showed an increase in maize assimilation between ambient and 550 ppm of 2.8 ± 3.6 mol m⁻² s⁻¹, when averaged on 9 dates. The average of all simulated values of assimilation for the same days resulted in a decrease of 0.3 mol m⁻² s⁻¹ between 375-model and 550-model. Simulated midday values of stomatal conductance in maize between ambient and 550 ppm decreased by 36%, when averaged over 9 days, while observations decreased by $29 \pm 14\%$. Agro-IBIS slightly overestimated peak maize LAI in 2006 compared with observations in both 375-model and 550-model by a little over 1 m² m⁻², but simulated values in 2008 within the observational uncertainty (Table 7). Observations showed no change in LAI between ambient and 550 ppm in either year. Agro-IBIS simulated a nearly negligible increase in LAI of 0.2 m² m⁻² in 2006 and 0.1 m² m⁻² in 2008.

Maize total biomass and yield. Leakey *et al.* (2006b) reported no significant differences in measured total biomass (i.e., stem, leaves, tassels, and cob at end of

Table 7 Peak maize LAI (m² m⁻²) at ambient and 550 ppm from SoyFACE observations and as simulated by Agro-IBIS

Year	Ambient (375 ppm in model)		550 ppm	
	Observed	Simulated	Observed	Simulated
2006	4.34 ± 0.17	5.48	4.26 ± 0.29	5.70
2008	4.52 ± 0.10	4.64	4.62 ± 0.24	4.71

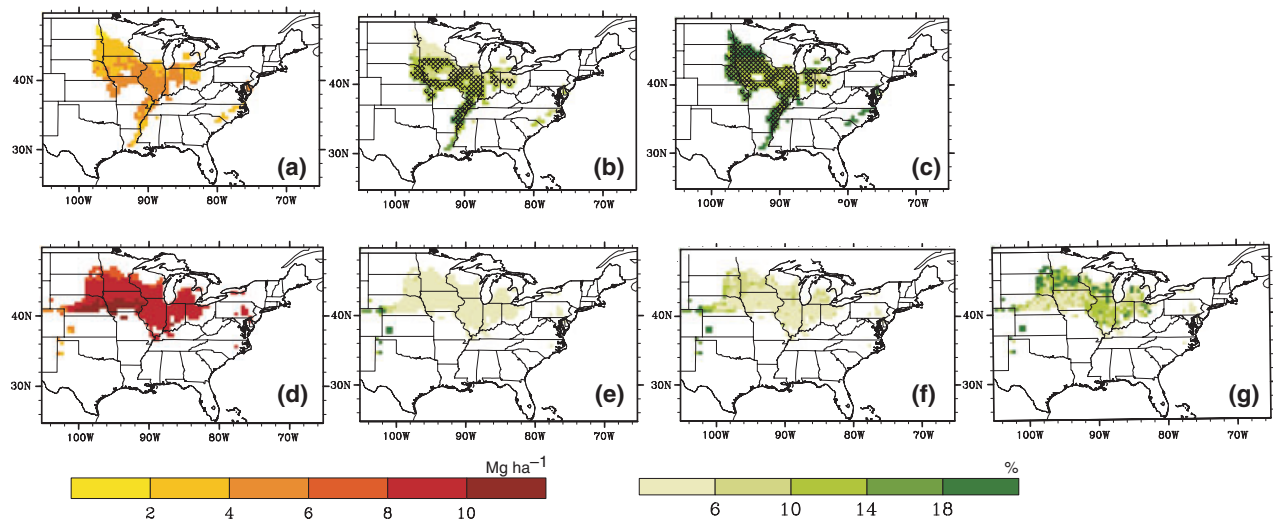
season) and yield between ambient and 550 ppm in maize (Table 8). Observed maize total biomass averaged from the 2004 and 2008 growing seasons was 19.64 Mg ha⁻¹ at ambient and 20.05 Mg ha⁻¹ at 550 ppm. Simulated total biomass averaged over the same 2 years was 18.80 Mg ha⁻¹ at 375 ppm and 18.71 Mg ha⁻¹ at 550 ppm. Observed maize yield averaged over the 2004 and 2008 growing seasons was 10.26 Mg ha⁻¹ at ambient and 10.41 Mg ha⁻¹ at 550 ppm. Simulated yield averaged over the same 2 years was 9.72 Mg ha⁻¹ at 375 ppm and 9.52 Mg ha⁻¹ at 550 ppm. Although the model simulates very small decreases in yield between 375 and 550 ppm, these are a result of internal variability in the model and suggest that there is no response to elevated [CO₂] at this site during these years. Agro-IBIS underpredicted total biomass and yield compared with observations in 2004; however, the lack of change in these variables between 375 and 550 ppm was consistent with observations.

Maize surface energy budget. Observations between the hours of 0900 and 1600 for a full maize canopy in 2004 and 2006 showed an average decrease in LE of 58.5 MJ m⁻² (10%) between ambient and 550 ppm. For the same times, Agro-IBIS simulated an average decrease in LE of 29 MJ m⁻² (7.5%) between 375-model and 550-model for 2004 and 2006 (Table 6). Despite the reasonable agreement in LE change between the model and observations, Agro-IBIS underestimated the increase in H as it did with soybean. The average simulated increase in H was 20.5 MJ m⁻² (14.5%), while observations produced an increase of 57.5 MJ m⁻² (50%).

Regional model runs. Simulated soybean yield averaged 5 Mg ha⁻¹ across the major soybean-growing region but varied spatially according to maturity group and climate and soil variations (Fig. 3a). We averaged results over the 1971–2000 period to include a period of time that represents a variety of environmental conditions (e.g., dry/wet years, warm/cool years). Simulations predicted an increase in soybean yield between

Table 8 Maize total biomass and yield (Mg ha⁻¹) at ambient and 550 ppm from SoyFACE observations and as simulated by Agro-IBIS

Year	Total Biomass				Yield			
	Ambient (375 ppm in model)		550 ppm		Ambient (375 ppm in model)		550 ppm	
	Observed	Simulated	Observed	Simulated	Observed	Simulated	Observed	Simulated
	Observed	Simulated	Observed	Simulated	Observed	Simulated	Observed	Simulated
2004	20.30	17.40	20.23	17.36	10.37	8.91	10.52	8.76
2008	18.97	20.20	19.86	20.06	10.15	10.52	10.29	10.28

**Fig. 3** Mean simulated soybean yield in Mg ha⁻¹ for 1971–2000 over the major soybean-growing region assuming 100% fraction cover (a); the percent change $(100 \times (550\text{-model} - 375\text{-model}) / 375\text{-model})$ in mean soybean yield for 1971–2000 with (b) and without (c) accounting for physiological acclimation; mean simulated maize yield in Mg ha⁻¹ for 1971–2000 over the major maize-growing region assuming 100% fraction cover (d); the percent change in mean maize yield for 1971–2000 (e), for the dry years 1971, 1976, 1983, 1988, and 1991 (f), and for 1988 alone (g). Hatching indicates the differences that are statistically significant at $P < 0.05$.

375-model and 550-model across the entire domain (Fig. 3b). The domain-wide average stimulation of soybean yield by elevated [CO₂] was 9%, with most grid cells showing less than a 14% increase. The largest increases were located in the southern and western portions of the domain. These average increases are similar to the increases found at SoyFACE (Morgan *et al.*, 2005) and are consistent with the meta-analysis results from Long *et al.* (2006) that found an average increase of 13% for soybean from FACE studies. When the simulation was run at 550 ppm without accounting for physiological acclimation, the domain-wide average increase in yield was 16% and the pattern of increase was different from the run with accounting for physiological acclimation (Fig. 3c). While the smallest increases were found in the northernmost region (e.g., Minnesota) in Fig. 3b, c shows the largest increases to be found in this region.

This highlights the importance of simulating physiological acclimation to elevated [CO₂].

Simulated maize yield varied spatially and averaged 9 Mg ha⁻¹ across the major maize-growing region (Fig. 3d). Differences in maize yield between 375-model and 550-model across the domain for the 1971–2000 period were not statistically significant ($P < 0.05$; Fig. 3e). This result is consistent with findings by Leakey *et al.* (2004) and Markelz *et al.* (2011), which found no stimulation in maize yield in the absence of drought. Agro-IBIS simulated a stimulation in maize yield during dry years. We selected years in which May to August rainfall was below one standard deviation of the 1971–2000 mean. When results from these years (i.e., 1971, 1976, 1983, 1988, and 1991) were averaged, yield increased slightly more everywhere but more so in northern areas (Fig. 3f). In 1988 alone, the driest year

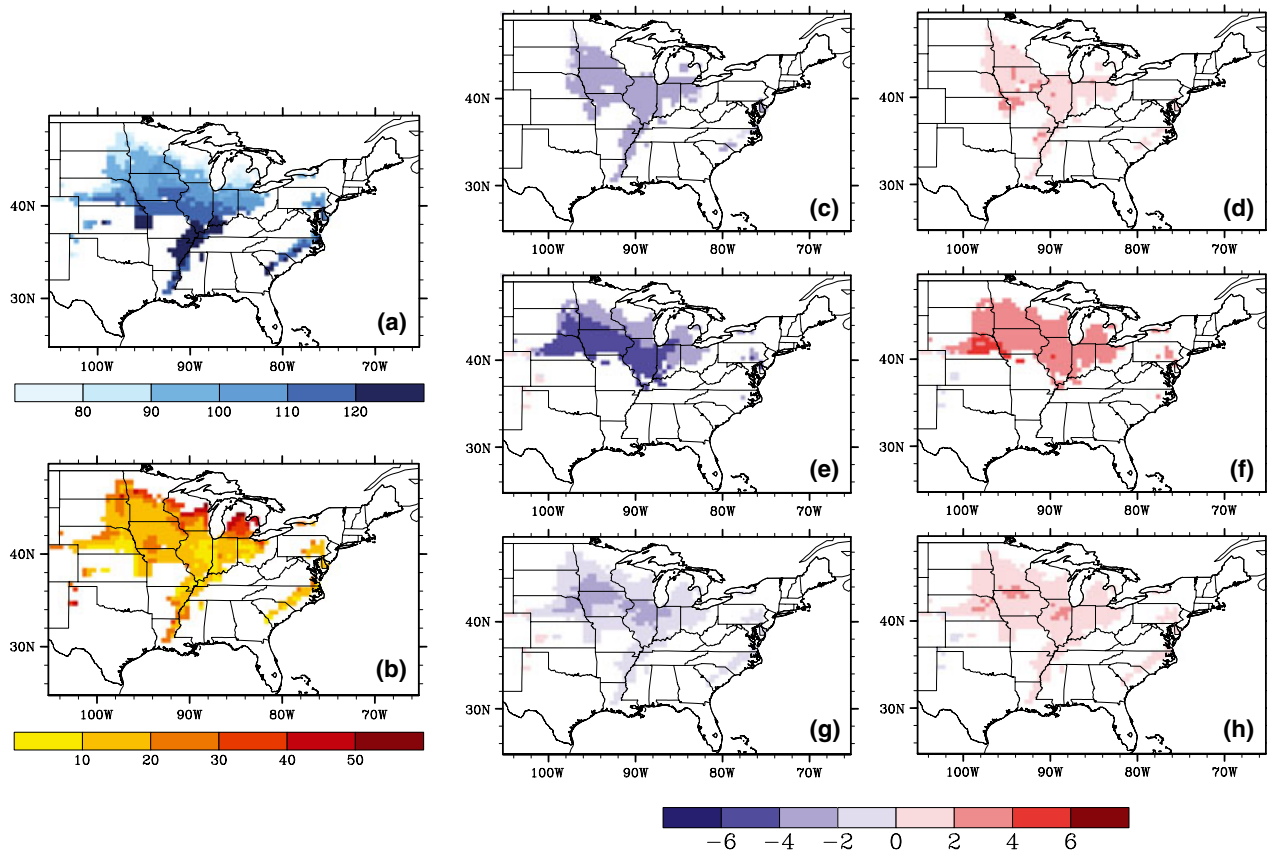


Fig. 4 Mean simulated June–July–August (JJA) latent heat flux (LE (a)) and sensible heat flux (H (b)) in W m^{-2} for 1971–2000 over the major maize and soybean-growing region with values representing current land cover (i.e., potential vegetation and maize and soybean according to fraction crop cover); and the change (550-model – 375-model) in mean JJA LE (c) and H (d) in W m^{-2} for 1971–2000 with 100% soybean cover; change in mean JJA LE (e) and H (f) with 100% maize cover; and change in mean JJA LE (g) and H (h) as weighted by the combined maize and soybean fraction cover. Hatching indicates the differences that are statistically significant at $P < 0.05$.

of the period in this region, yield was stimulated even more with largest increases in the north and smallest increases in Iowa and eastern Nebraska (Fig. 3g). Yield increased by 11% on average across the region in 1988.

Simulated LE peaked in summer (June to August or JJA) over most of the maize- and soybean-growing region as crops and natural ecosystems reached their maximum LAI and productivity (Fig. 4a). Latent heat flux values were largest in the southern portion of the domain and decreased toward the north. Sensible heat flux also peaked in JJA with largest values in the north (Fig. 4b). Between 375-model and 550-model, LE decreased everywhere over the domain when either soybean was grown everywhere (Fig. 4c) or maize was grown everywhere (Fig. 4e); however, none of the differences is statistically significant at $P < 0.05$. These differences mostly ranged between 2 and 4 W m^{-2} in soybean and 3 and 5 W m^{-2} in maize and represent a soil water savings of 7–17 mm in JJA. When weighted

by the combined fraction covers of soybean and maize, the largest decreases (2–4 W m^{-2}) were found in the heavily cropped regions of Illinois, northern Iowa, and eastern Nebraska (Fig. 4g). These largest decreases are equivalent to a 1–4% decrease in JJA LE and when averaged over the domain account for a ca. 4 mm savings in soil water over JJA.

Sensible heat flux increased between 375-model and 550-model everywhere over the domain when either soybean was grown everywhere (Fig. 4d), or maize was grown everywhere (Fig. 4f); however, none of the differences is statistically significant at $P < 0.05$. Sensible heat flux increased in soybean by less than 2 W m^{-2} and in maize by 2–4 W m^{-2} . When weighted by the combined fraction cover of soybean and maize, increases were generally less than 2 W m^{-2} across the region with the largest increases (2–4 W m^{-2}) spread throughout the heavily cropped regions of Illinois, Iowa, and eastern Nebraska (Fig. 4h). These largest increases are equivalent to a 15–80% increase in JJA H.

Discussion

The simulation of soybean phenology and growth was substantially improved when we incorporated a new phenology algorithm, updated the temperature response functions, and used observed parameter values to drive the model. The new phenology routine not only improved the simulation of when key growth stages start and finish, but also led to more realistic simulations of the seasonal course of LAI and SLA. Additional simulations driven with measurements of SLA showed a better comparison with observations of the stimulation in leaf and stem biomass (not shown); however, this is difficult to implement in these types of models because spatial-temporal gridded maps of SLA are not available. The simulated fraction of allocation of carbon to leaves, stems, roots, and pod in the model varies by growth stage but is fixed for each year. While we chose representative allocation fractions based on observations made in 2002 at the SoyFACE site (Morgan *et al.*, 2005), more research should be performed to examine simulated carbon allocation at other locations and under varied environmental conditions.

Our results highlight the need to appropriately parameterize C₃ plant functional types in DGVMs in elevated [CO₂] scenarios. When physiological acclimation to elevated [CO₂] was not considered (i.e., the same values of $V_{c,max}$ and SLA were used at ambient and elevated [CO₂]; Table 2), simulated yield at 550 ppm was overestimated and the locations of maximum and minimum yield change were different than when the model was appropriately parameterized (Fig. 3c). This overestimation in yield derives from an overestimation in photosynthetic carbon gain and LAI, which can lead to incorrect partitioning of available energy and errors in other canopy-scale variables. When the model accounted for physiological acclimation, the simulated stimulation in soybean yield was of a similar magnitude as that observed at the SoyFACE site. Other model variables including LAI and leaf, stem, and pod biomass compared well with observations in the appropriately parameterized model.

In contrast with soybean, maize showed no significant stimulation in yield at 550 ppm for the SoyFACE runs and at the regional scale when averaged over the 30-year period, but it did respond to drought stress. In 1988, one of the driest years on record in this region, the model predicted a stimulation that is similar in magnitude to the average stimulation of soybean yield. Drought will affect different locations in different ways; therefore, future work should examine how different locations respond given a similar decrease in water availability to further

quantify temperature–moisture–radiation–CO₂ relationships across the domain.

Agro-IBIS captured the transpiration response to elevated [CO₂] seen in observations (Bernacchi *et al.*, 2007) by decreasing the stomatal and canopy conductance of water, which resulted in a decrease in transpiration and LE. While simulated soybean stomatal and canopy conductance were decreased between 375 and 550 ppm (22% and 17%, respectively) to the same degree as seen in observations (Bernacchi *et al.*, 2007), simulated LE did not decrease as much as was estimated by measurements. The simulated decrease in maize LE was closer to observations; however, the simulated increase in H was underestimated. One cause of these discrepancies could be observational error. While the residual energy budget method likely overestimates the magnitude of LE, this bias is reduced by our evaluation of the change between the ambient and 550 ppm plots. Furthermore, Bernacchi *et al.* (2007) estimated a savings of 30–50 mm of water in the soil column below soybean during the growing season based on LE estimates, which corresponded with measurements of soil moisture change.

The second and more likely source of error is in the way Agro-IBIS scales from the leaf level to the canopy level through LAI. The LE is equivalent to evapotranspiration from the canopy, which includes evaporation from the soil and vegetation surfaces and transpiration from the vegetation. The only response to elevated [CO₂] from a closed canopy arises from transpiration. Transpiration is calculated as the product of canopy conductance, gradient in specific humidity between the leaf surface and canopy air, and LAI. Although canopy conductance was decreased appropriately in the model between 375 and 550 ppm, the decrease in transpiration is somewhat offset by increases in the specific humidity gradient and LAI. The gradient in specific humidity increases because as stomatal conductance decreases, leaf temperature increases and causes the saturated specific humidity at the leaf surface to rise. Leaf area index, though increasing in a manner consistent with observations (ca. 0.5 m² m⁻²), also leads to diminished decreases in LE at 550 ppm as a larger value of LAI is used to scale transpiration to the canopy than at 375 ppm. All of these scaling characteristics are consistent with theory (Field *et al.* 1995); however, discrepancies between how they are calculated in Agro-IBIS and observed in this data set led to differences in the estimated decrease in LE. While this scaling process correctly captures a decrease in LE between 375 and 550 ppm, the resulting magnitude of change is not as great as estimated in the observations, and therefore our estimates of regional change in LE and H are likely conservative and could be even larger than simulated

here. Few studies are available with which to compare our results. Cao *et al.* (2009) found canopy transpiration to decrease by 8% (a value between our simulated results and the observations) when averaged globally over all biomes, and Wullschlegel *et al.* (2002) found that significant decreases in stomatal conductance scaled to a nearly negligible response at larger scales because of interacting variables in a forest canopy. In contrast, Drewry *et al.* (2010), using a 15-layer canopy model calibrated for use at SoyFACE, simulated decreases in LE and increases in H that were comparable to those estimated by measurements. Future work should examine changes to canopy architecture in relation to surface layer turbulent fluxes in more detail and improve how these processes are simulated in DGVMs.

Because our study domain is characterized by a humid climate, and much of it is drained for agriculture, the water saved by increasing $[\text{CO}_2]$ would likely ameliorate periodic episodes of water stress between rain events or if soil storage capacity is exceeded it could end up as streamflow. While surface warming as a result of global climate change will likely lead to increased surface drying (Dai *et al.*, 2004), over the last 50 years evapotranspiration has increased in the coterminous USA by 55 mm (Karl & Knight, 1998; Milly & Dunne, 2001; Walter *et al.*, 2004), and precipitation and streamflow have also increased throughout much of the United States (Karl & Knight, 1998; Lins & Slack, 1999; Groisman *et al.*, 2004; Schilling *et al.*, 2008). Gedney *et al.* (2006) have suggested that streamflow trends are already reflecting plant response to increasing $[\text{CO}_2]$; however, increases in dewpoint temperatures from increases in transpiration in northern Illinois over the past few decades have been hypothesized to result from advances in agricultural management, including increased planting densities (Changnon *et al.*, 2003). Increases in precipitation combined with higher dewpoints related to agriculture can result in increases in cloud cover (Elliott & Angell, 1997), which changes the atmospheric forcing. This is just one example of the complex feedbacks between the land and atmosphere that will be altered with future climate change and land use change. Our modeling results highlight the need for continued improvements in GCMs of all components of the water cycle and interactions with the biosphere if we are to decrease uncertainty of future impacts of climate change on an evolving agricultural landscape.

The crop-climate modeling community has identified objectives that will improve the ability of crop models to predict crop growth and development (Rotter *et al.*, 2011). These include improving the simulation of plant response to increases in $[\text{CO}_2]$, developing high-quality field data for model testing, and developing better

methods to estimate productivity at the regional scale. In response to this call and as a step toward improving DGVMs for use in Earth Modeling Systems, we have for the first time, evaluated and improved a DGVM with measurements from a FACE study to appropriately simulate the response of soybean and maize to $[\text{CO}_2]$ of 375 and 550 ppm. Simulations with the Agro-IBIS model found that soybean yield is increased by ca. 10% between 375 and 550 ppm; a result that is comparable to observations made at the SoyFACE facility. Our results suggest that if other DGVMs behave like Agro-IBIS, without accounting for physiological acclimation they might overestimate the increase in C_3 crop productivity. The biases we found in this study almost certainly extend to other vegetation types. For example, results from an 11-year study of photosynthetic response of 13 grasses in Minnesota suggest that the long-term grassland stimulation to $[\text{CO}_2]$ might be overestimated in models (Lee *et al.*, 2011). We recommend continued evaluation of models with manipulative field studies – especially Earth System models in which the atmosphere and land surface interact to modify canopy conductance and surface energy fluxes. We urge the modeling community to evaluate models from the leaf to canopy scale.

Our model simulations correctly captured the decrease in latent heat flux and increase in sensible heat flux between 375 and 550 ppm; however, the magnitude of change in soybean and in sensible heat flux in maize was underestimated compared with observations. During dry years, the decrease in latent heat flux ameliorated drought stress in soybean and maize, and led to a stimulation in maize yield of ca. 10%. The water saved in the soil through the reduction in LE is small and, though important during periods of drought, will likely be outweighed over longer time periods by stronger effects of climate change (NAST, 2000; Thomson *et al.*, 2005).

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