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Incorporation of crop phenology in Simple Biosphere Model (SiBcrop) to improve land-atmosphere carbon exchanges from croplands

E. Lokupitiya[1], S. Denning[1], K. Paustian[2,3], I. Baker[1], K. Schaefer[4], S. Verma[5], T. Meyers[6], C. Bernacchi[7], A. Suyker[5], and M. Fischer[8]

[1]Department of Atmospheric Science, Colorado State University, Fort Collins, CO 80523, USA
[2]Department of Soil and Crop Sciences, Colorado State University, Fort Collins, CO 80523, USA
[3]Natural Resource Ecology Lab, Colorado State University, Fort Collins, CO 80523, USA
[4]National Snow and Ice Data Center, University of Colorado, Boulder, CO 80309, USA
[5]School of Natural Resources, University of Nebraska-Lincoln, USA
[6]NOAA/ARL/ATDD, Oak Ridge, TN 37830-2456, USA

[7] Department of Plant Biology, University of Illinois at Urbana-Champaign, Champaign, IL 61820, USA
[8] Lawrence Berkeley National Laboratory, Environmental Energy Technologies Division, Atmospheric Science Department, Berkeley, CA 94720, USA

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Correspondence to: E. Lokupitiya (erandi@atmos.colostate.edu)

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Abstract

Croplands are man-made ecosystems that have high net primary productivity during the growing season of crops, thus impacting carbon and other exchanges with the atmosphere. These exchanges play a major role in nutrient cycling and climate change related issues. An accurate representation of crop phenology and physiology is important in land-atmosphere carbon models being used to predict these exchanges. To better estimate time-varying exchanges of carbon, water, and energy of croplands using the Simple Biosphere (SiB) model, we developed crop-specific phenology models and coupled them to SiB. The coupled SiB-phenology model (SiBcrop) replaces remotely-sensed NDVI information, on which SiB originally relied for deriving Leaf Area Index (LAI) and the fraction of Photosynthetically Active Radiation (fPAR) for estimating carbon dynamics. The use of the new phenology scheme within SiB substantially improved the prediction of LAI and carbon fluxes for maize, soybean, and wheat crops, as compared with the observed data at several AmeriFlux eddy covariance flux tower sites in the US mid continent region. SiBcrop better predicted the onset and end of the growing season, harvest, interannual variability associated with crop rotation, day time carbon uptake (especially for maize) and day to day variability in carbon exchange. Biomass predicted by SiBcrop had good agreement with the observed biomass at field sites. In the future, we will predict fine resolution regional scale carbon and other exchanges by coupling SiBcrop with RAMS (the Regional Atmospheric Modeling System).

1 Introduction

Trends in global warming and climate change have drawn more attention towards anthropogenic emissions of greenhouse gases. Carbon dioxide (CO_2) has been identified as the main anthropogenic greenhouse gas contributing to climate change (IPCC, 2007). Land-atmosphere exchanges of energy, water vapor and CO_2 play a major role in climate change and its long-term consequences. A powerful way to evaluate these exchanges is to model the fluxes between the land and atmosphere using reliable land surface models, while evaluating the outcome against observed data. The performance of those models depends on how well they can simulate the vegetation properties and dynamics over time and space. This study focuses on estimating the CO_2 exchanges in cropland ecosystems, evaluated against AmeriFlux eddy covariance flux tower sites with maize, soybean, and wheat crops (Fig. 1). During the growing season, the presence of crops significantly impacts CO_2 fluxes, as well as albedo, roughness length, Bowen ratio, and soil moisture. Therefore, an accurate representation of crop phenology (i.e., timing of different growth stages) and physiology is important in predicting carbon and other exchanges of these managed ecosystems.

Croplands include a variety of species with different phenology and physiology. Crops have either C3 or C4 photosynthetic pathways and the associated differences in plant anatomy and physiology. Croplands have unique dynamics as managed ecosystems that are mostly governed by the dates of planting and harvest, crop rotation, tillage, fertilization, irrigation, and pest control. Most croplands are characterized by high rates of CO_2 uptake and net primary productivity (NPP) over their short growing seasons. Although certain croplands may physically resemble grasslands (i.e. compared to forests), they differ substantially in terms of seasonality, phenology and physiology, and harvested products, which can account for 40–60% of the above ground biomass (Hay, 1995; Prince et al., 2001; Rao et al., 2002; Heard, 2004) that is exported after the crop reaches maturity. Therefore models that simulate agricultural ecosystems should have a good representation of the crop phenology and physiology that are associated with the unique properties of these ecosystems.

Most of the existing models for simulating phenology, physiology, growth, carbon, nutrient and water fluxes of specific crops, are complex, process-based models and have used different strategies in simulating cropland dynamics. For instance, Gervois et al. (2004) and de Noblet-Ducoudré et al. (2005) combined an existing agronomy model (STICS), which has the ability to simulate several crops, to the soil-vegetation atmosphere scheme of an existing dynamic global vegetation model (ORCHIDEE), to improve the carbon and water exchanges from croplands predicted by the latter model. Similarly, the suite of CROPGRO and CERES models (e.g., Jones and Kiniry, 1986; Kiniry, 1991; Ritchie, 1991; Boote et al., 1998) were developed to simulate crop-specific detailed physiology and phenology of several cereals, legume and other crops. These models have detailed physiology, represented by algorithms for estimating photosynthesis, dry matter partitioning, water, and energy fluxes from crop vegetation. Recent work at the National Center for Atmospheric Research (NCAR) includes the addition of crop-related information (i.e. planting, allocation, phenology, etc.) from Agro-IBIS model (i.e. a process-based, terrestrial ecosystem model; Kucharik and Byre, 2003) to improve the cropland representation by the land surface parameterization in the Community Land Model (CLM; S. Levis, personal communication, 2008). The above models have complex physiology and built in phenology mostly governed by temperature (i.e. thermal time or growing degree days).

The Simple Biosphere model (SiB) has been used in estimating land atmosphere exchanges at both global and regional scales (Sellers et al., 1996a, b; Baker et al., 2008). SiB simulates the biological processes of photosynthesis and respiration and the physical processes of turbulent transport between the land surface and the boundary layer. Biophysical models such as SiB were originally developed to estimate surface fluxes of latent heat, sensible heat, and momentum in General Circulation Models (Sellers et al., 1986, 1992, 1994, 1997; Los, 1998). The ecosystem fluxes are estimated from leaf-level calculations using scaling assumptions (Sellers et al., 1992) based on nutrient distribution in the canopy.

Originally, planting and harvest events and the presence of alternating crops, etc., were not well represented in SiB. The basis for carbon, moisture, and energy fluxes predicted by SiB was the leaf area index (LAI) and fraction of photosynthetically active radiation (fPAR) derived from remotely sensed NDVI. The NDVI products minimize cloud contamination by using 15-day or monthly maximum value composites. Interpolation between these composite values leads to mismatches between the actual period of crop presence in the field and that predicted by the NDVI, and the time compositing unrealistically extends the growing season. Any effects from partly-cloudy pixels, aerosols, and smoke, etc., on NDVI, are also reflected in the predicted LAI and fPAR. Compositing also occurs in space as well as time, leading to misrepresentation between the pixel used for the NDVI and the actual conditions in the field. The NDVI and the respiration formulation does not account for crop harvest, forcing an annually balanced carbon budget, when in reality much of the biomass is removed from the site. The result is unrealistic simulated biomass and carbon fluxes, indicating the need for a new crop phenology scheme to reflect highly managed crop ecosystems.

To improve the functionality of SiB over cropland ecosystems, we developed and evaluated offline crop-specific phenology (and physiology) models for major C3 and C4 crops. We coupled these models with SiB, to replace the use of NDVI in predicting LAI and improve the accuracy of the predicted fluxes by SiB. The new model is referred to as SiBcrop. The climate driven dynamic phenology scheme within SiBcrop simulates the daily biomass in different plant pools, LAI, and specific events during crop growth cycle such as planting, emergence, vegetative and reproductive growth stages (Fehr et al., 1971; Ritchie et al., 1992, 1996), harvesting, etc. We evaluated the performance of SiBcrop for corn and soybean, by using observed data at two agricultural eddy covariance flux tower sites in the US Midwest, which have a good record of these crops grown in rotation: Bondville, Illinois (Meyers and Hollinger, 2004), and Mead, Nebraska (Suyker et al., 2004; Verma et al., 2005). We also evaluated the performance of SiBcrop for wheat, using observed data from the Southern Great Plains eddy covariance flux tower site (Fischer et al., 2007) under the Atmospheric Radiation Measurement (ARM) program, in Oklahoma; currently this site, known as ARM-SGP, is the only active wheat site under the AmeriFlux program.

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2 Materials and methods

2.1 Simple biosphere model

The parameterization of photosynthetic carbon assimilation in SiB is based on enzyme kinetics originally developed by Farquhar et al. (1980), and is linked to stomatal conductance and thence to the surface energy budget and atmospheric climate (Collatz et al., 1991, 1992; Sellers et al., 1996a; Randall et al., 1996). The model has been updated to include prognostic calculation of temperature, moisture, and trace gases in the canopy air space, and the model has been evaluated against eddy covariance measurements at a number of sites (Baker et al., 2003; Hanan et al., 2004; Vidale and Stöckli, 2005; Philpott et al, 2007). SiB has been coupled to the Regional Atmospheric Modeling System (RAMS) and used to study PBL-scale interactions among carbon fluxes, turbulence, and CO_2 mixing ratio (Denning et al., 2003) and regional-scale controls on CO_2 variations (Nicholls et al., 2004; Corbin et al., 2008; Wang et al., 2007). Other recent improvements include biogeochemical fractionation and recycling of stable carbon isotopes (Suits et al., 2005), improved treatment of soil hydrology and thermodynamics, and the introduction of a multilayer snow model based on the Community Land Model (Dai et al., 2003).

The current version (version 3.0) of SiB (i.e. SiB3) requires the vegetation state, vegetation type, soil characteristics, and weather data as input data. The vegetation state refers to time-dependent properties such as Leaf Area Index (LAI), aerodynamic roughness length, and absorbed fraction of incident visible light (fPAR). The vegetation type determines the physical characteristics of the canopy that do not vary with time, such as the canopy height, leaf transmittance, and photosynthetic capacity (Sellers et al., 1996b). Soil type determines soil hydraulic and thermal properties (Clapp and Hornberger, 1978). Weather data consists of temperature, wind speed, precipitation (convective and stratiform), and down-welling radiation (shortwave and longwave, direct and diffuse).

Historically, SiB has used prescribed vegetation parameters derived by remote sens-ing (Sellers et al., 1996b). At global scale, this approach allows realistic simulation of spatial and temporal variations in vegetation cover and state (Denning et al., 1996a, b; Schaefer et al., 2002, 2005; Baker et al., 2008). At the underlying pixel scale, however, phenology products derived from satellite data must be heavily smoothed to remove dropouts and artifacts introduced by frequent cloud cover. An inevitable trade-off between cloud-induced "noise" in the leaf area and time compositing systematically stretches the seasonal cycle by choosing data late in each compositing period in spring, and early in each composite in fall. Therefore, in this study, we have addressed this problem, by developing and testing a prognostic phenology sub model for SiB, rather than using satellite data for specifying crop phenology, while incorporating better parameterization for cropland ecosystems.

We modified the parameters within SiB to better represent soybean (*Glycine max* L.; C3), maize (*Zea mays* L.; C4), and wheat (*Triticum aestivum* L.; C3), the dominant crops in the US mid western region. Crop specific information and data from past literature were used in modifying the existing parameter values (Table 1). We also modified the algorithm for respiration control, to allow for harvest removal. In SiB, an annual respiring carbon pool is calculated assuming that carbon in the total net photosynthetic assimilation (i.e. gross photosynthesis – canopy maintenance respiration) is added to, and partitioned among the litter and soil layers, and respired within a year, causing an overall annual zero net ecosystem exchange. We modified the annual net photosynthetic assimilation carbon added on the ground (i.e. within different litter and soil layers), to include only the fraction of carbon left after the removal of the harvest (Table 1). We also set the physiological fractions (C3 vs. C4) of the crops in such a way that it could represent any crop rotation, where each subsequent term's crop is planted on the residue of the previous crop.

2.2 Phenology in SiBcrop

Phenology events and growth stages were determined by the growing degree days and the number of days since planting. Phenology was calculated once a day within

SiBcrop (Fig. 2). The model allocates sub hourly photosynthetic carbon to four different plant pools (leaves, stems, roots and products (flowers, grain, and pods) depending on seasonal development. The daily carbon allocation to leaves was used to update LAI, which was then used to calculate photosynthesis during the following day. We assumed that the crop plants were not limited by nitrogen and other nutrients, as they were well fertilized (SiB has indirect representation of nitrogen limitation through Rubisco dynamics within the photosynthetic mechanism). The parameters and functions used in the phenology submodel were specific for different crops, growth stages and plant pools.

2.2.1 Detailed scheme

Planting dates for crops were set at the seventh consecutive day on which the air temperature remained above a crop-specific optimal temperature for germination; planting date was readjusted if the temperature dropped below a certain threshold after the initial 7-day period (Pedersen, 2003; Pedersen and Lauer, 2004; USDA, 1997). Plant emergence, subsequent growth stages and phenology events were set based on accumulated growing degree days (Eq. 1) and the number of days since planting (Taylor et al., 1982; Wells et al., 1986; Ritchie et al., 1996; Heard, 2004).

$$GDD = \sum (T_{\text{mean}} - T_{\text{base}}) \tag{1}$$

where GDD is the accumulated daily growing degree days; T_{mean} is the average daily temperature (°C); T_{base} is the base temperature (10°C for corn and soybean, and 0°C for winter wheat), above which the growing degree days start to accumulate (there is no accumulation of GDDs below the base temperature or above an optimal temperature, which is 30°C for maize and soybean, and 26°C for winter wheat; Neild and Newman, 1986; McMaster and Wilhelm, 1998; Cornell University Cooperative Extension, 2008).

In the earliest stages of plant growth, photosynthesis is insufficient to support the development of new biomass. Initial plant growth was assumed to be derived from stored carbon in the seed.

The initial biomass values at emergence (Green and Sudia, 1969; Blum et al., 1980; Smiciklas et al., 1992; Richardson and Bacon, 1993; Pinhero and Fletcher, 1994; Hameed et al., 2003) were set considering the average planting density based on the plant and row spacing typical for each crop. Starting from the day of emergence, a daily LAI value was estimated based on leaf carbon (details follow), for deriving fPAR and estimating sub hourly photosynthetic assimilate, respiratory carbon (i.e. both ground and canopy respiration) and other fluxes during the following day. During the early phase of vegetative development, in which the carbon stored in the seed is utilized for growth (Peterson et al., 1989; McWilliams et al., 1999; Nielsen, 2007), the daily biomass addition/gain rate was set to be optimal, assuming that the seedling is not nutrient limited and that growth is dependent on the temperature and moisture availability (2). The growth rate followed a linear ramp during the initial seedling development.

$$M_d \approx M_{\text{init}} + \left(t * \frac{(M_{\max} - M_{\text{init}})}{\tau_{\text{seed}}} \right) * C_M * C_T \tag{2}$$

where M_d is the daily biomass carbon (C) addition/gain rate in the seedling during the initial phase (i.e. the phase in which the seed stored carbon is utilized), assuming optimal nutrient availability (g C m^{-2} d^{-1}); t is time in days (d) between a given day in the initial phase and the day of emergence; $M_{\max}$ is the maximum potential biomass carbon addition rate by the end of the initial phase; M_{init} is the initial biomass carbon addition rate (g C m^{-2} d^{-1}), estimated based on the initial biomass on the day of emergence, assuming that carbon constitutes 45% of the biomass; τ_{seed} is the time in days (d) between the emergence and the end of the early phase during which the seed stored carbon is utilized; C_M and C_T are moisture and temperature dependent coefficients (derived using the information given in de Vries et al. (1989); dimensionless).

During rest of the growth cycle after the above initial seedling phase, daily photosynthetic assimilate (accumulated sub hourly photosynthetic carbon) was used as the basis in deriving the daily increments in biomass carbon.

The biomass carbon added on each day was allocated to different plant pools at crop specific growth stages (Fig. 3), set by the growing degree days and the number of days since emergence (Fig. 4; Puckridge, 1972; Taylor et al., 1982; Wells et al., 1986; Yamagata et al., 1987; Gregory and Atwell, 1991; Ritchie et al., 1996; Gregory et al.,1997; Gómez-Macpherson et al., 1998; McMaster and Wilhelm, 1998; Wilhelm, 1998; Heard, 2004). At the end of each day, the carbon in each pool was calculated by subtracting the growth and maintenance respiration (details follow) from the daily biomass carbon allocation; the amount of leaf carbon was used to calculate a daily LAI value (3). Senescence was induced when the leaf respiration exceeded daily leaf growth, causing biomass loss. Following the vegetative phase of growth, further allocation to leaves was significantly reduced during the subsequent reproductive phase of growth (Figs. 3 and 4). The crop was harvested after it reached physiological maturity, allowing some field drying (Fowler, 2002; Neilson et al., 2005).

$$\mathrm{LAI} = \mathrm{C}_{\mathrm{leaf}} * 2 * \mathrm{SLA} \tag{3}$$

where LAI is leaf area index ($\mathrm{m}^2\,\mathrm{m}^{-2}$); C_{leaf} is the amount of leaf carbon ($\mathrm{g\,m}^{-2}$); SLA is specific leaf area ($\mathrm{m}^2\,\mathrm{g}^{-1}$)

2.2.2 Estimation of growth and maintenance respiration

On each day, growth respiration (estimated using the combination of crop-specific growth respiration coefficients for different plant pools) was calculated as a function of biomass carbon allocated to each plant pool. Growth respiration in each pool was the amount of $\mathrm{CO_2}$-C emitted in the formation of new crop biomass (4):

$$R_{g(i)} = \mathrm{alloc}_{(i)} * \mathrm{coeff}_{g(i)} \tag{4}$$

where $R_{g(i)}$=growth respiration ($\mathrm{g\,CO_2{-}C\,m^{-2}\,d^{-1}}$); i=1–4 (1=roots; 2=leaves; 3=stems; 4= products (e.g. flowers and grain); $\mathrm{alloc}_{(i)}$=daily biomass carbon allocation to each plant pool ($\mathrm{g\,C\,m^{-2}\,d^{-1}}$); $\mathrm{coeff}_{g(i)}$=growth respiration coefficient ($\mathrm{g\,CO_2{-}C\,g^{-1}}$ biomass carbon in the ith pool d^{-1}; Table 1).

Maintenance respiration was calculated considering the fraction of the total non-structural carbohydrate and protein carbon (Thornton et al., 1969; Evans et al. 1984; Reekie and Redmann, 1987; Kiniry, 1993; Beauchemin et al., 1997; Allen et al., 1998; Blum, 1998; Brouquisse et al., 1998; Collar and Askland, 2001) within different plant carbon pools on each day, considering a temperature dependent Q_{10} function with a base temperature of 25°C. In deriving the maintenance respiration coefficients in terms of carbon, the carbon percentage in dry weight was considered as 45% (Buchanan and King, 1993; Bolinder et al., 1997; Vanotti et al., 1997; Burgess et al., 2002; Torbert et al., 2004). Carbon emission as CO_2-C in maintenance respiration for each plant pool was predicted from the carbon in each plant pool and maintenance respiration coefficients specific to each pool and crop type (Table 1; Eq. 5):

$$R_{m(i)} = W_{(i)} * \text{coeff}_{m(i)} * f_{\text{TNC},p(i)} * Q_{10}^{(T-20)/10} \qquad (5)$$

where R_m=maintenance respiration (g CO_2–C m^{-2} d^{-1}); i=1–4 (1=roots; 2=leaves; 3=stems; 4=grain); W= cumulative carbon in the ith pool (g C m^{-2} d^{-1}); ${}_t\text{coeff}_{m(i)}$=maintenance respiration coefficient (g CO_2–C emitted g^{-1} carbon in the ith pool d^{-1}; Table 1); $f_{\text{TNC},p(i)}$=fraction of carbon in non structural carbohydrates (TNC) and proteins of the ith pool (this was estimated considering that TNC have 45% carbon and proteins have 53% carbon (Hopkins et al., 1929; de Vries et al., 1989)); Q_{10}=Q_{10} coefficient (i.e. 2.0 (Norman and Arkebauer, 1991; Gourdriaan and Van Laar, 1994)); T=temperature (°C).

2.2.3 Evaluation of the model performance

The performance of SiBcrop was evaluated by comparing the observed and predicted CO_2 fluxes and LAI at three AmeriFlux eddy covariance flux tower sites with crops: Bondville, Illinois (IL), and Mead, Nebraska (NE), and ARM-SGP site, Oklahoma (OK).

The Bondville site (latitude 40.0061000; longitude –88.2918667; elevation 300 m) is located in central Illinois and has operated since August 1996 (Meyers and Hollinger, 2004). It has rainfed, no-till maize and soybean crops grown in rotation (maize in odd numbered years and soybean in even numbered years). The Mead site (latitude 41.1796670; longitude −96.4396460; elevation 363 m) is located in Saunders county in eastern Nebraska (Suyker et al., 2004). Mead has both irrigated and rainfed sites, and only the rainfed site was chosen for this study. This site has operated since 2001 also with rainfed no-till maize and soybean grown in rotation. At these sites, maize plants grow to a height of 2.5 (Mead, NE) to 3.0 m (Bondville, IL), and soybean plants grow to a height of about 0.9 m.

The ARM-SGP site (latitude 36.60499954; longitude −97.48840332; elevation 300–320 m), which has been active since 1999, is located in Grant county, Oklahoma. This site has winter wheat as the main crop, in addition to some pasture and summer crops such as corn, soybean, and sorghum (Fischer et al., 2007). For the current study, the years which exclusively had the winter wheat crop with recorded observed CO_2 flux measurements (i.e. end of 2002–2004) were chosen to evaluate the performance of SiBcrop for wheat. Wheat plants at this rain fed site grow to a height of about 0.5 m.

SiBcrop could be run at any spatial resolution, with the availability of suitable weather data. For this study we used a time step of 30 min. Each eddy covariance site was simulated as a single homogeneous spatial unit for periods with observed data, using meteorological forcing from 6-hourly NCEP-DOE Reanalysis 2 (Kalnay et al., 1996) weather data, and crop information as given in the AmeriFlux website. Soil texture was derived from the NRCS State Soil Geographic (STATSGO) database. For the control runs with original SiB, AVHRR NDVI data interpolated from monthly Global Inventory of Modeling and Mapping Studies, version "g" (GIMMSg; Tucker et al., 2005) data were used in estimating LAI and fPAR.

Sub hourly, diurnal, and annual net ecosystem exchange (NEE; i.e. respiration-photosynthesis), LAI, and biomass values predicted by SiBcrop for each site were compared against observed data. The annual NEE cycles were formulated based on the monthly means derived from sub hourly fluxes. Seasonality and the year-to-year variation in the carbon fluxes, LAI, and biomass were compared and studied considering the presence of single crop (winter wheat) and crop rotation (i.e. alternating maize and soybean crops as at Bondville and Mead sites) in the field.

3 Results and discussion

3.1 SiBcrop simulations for summer crops (corn and soybean)

SiBcrop was able to predict the planting and harvest events and the changing phases within crop development and growth cycle, in terms of LAI, biomass carbon, and carbon fluxes for these sites, with more accuracy than the original SiB.

The maximum LAI predicted for maize in different years ranged between 5.0 $m^2\,m^{-2}$ and 6.3 $m^2\,m^{-2}$ at Bondville, and between 5.0 $m^2\,m^{-2}$ and 6.0 $m^2\,m^{-2}$ at Mead. The maximum LAI predicted for soybean ranged between 4.6 and 5.7 $m^2\,m^{-2}$ at Bondville, and between 3.9 and 5.3 $m^2\,m^{-2}$ at Mead. These predicted ranges were acceptable based on the observed ranges at these two sites, except that the model over predicted the maximum LAI observed for Mead during certain soybean years. For instance, in 2002, the maximum LAI observed at Mead site was 3.0, while the mean LAI predicted by SiBcrop was 3.9. Compared to the LAI estimates based on NDVI in original SiB, SiBcrop predicted LAI values that had better synchrony with the observed LAI in the field (Fig. 5). In 1999, the NDVI-based LAI was higher at the initial phase of the growing season and peaked at a later time than the LAI observed in the field and that predicted by SiBcrop. This pattern of variation in the remotely sensed NDVI could be attributed to the mixed pixels (in the early phase), cloud contamination and the interpolation scheme, as described before.

In addition to the prognostic equations in SiB, SiBcrop predicted biomass carbon in different plant pools, LAI, etc., from the phenology scheme by the end of each day. The variation in carbon in different plant pools until physiological maturity at Bondville site is illustrated in Fig. 6. Among the different plant pools, the highest amount of carbon was observed for the products, and the total biomass (both above- and below ground) estimated for maize was much higher than that for soybean (Table 2). Maize in both Bondville and Mead sites had 55–60% of the total carbon in the products at harvest (grains, cobs, and husks), while roots, leaves and stems shared the remainder of the carbon. By converting the biomass carbon to biomass (by multiplying by 2.2) and considering a grain weight of about 80 percent of the total products at harvest (Heard, 2004), we estimated a Harvest Index that ranged between 0.52 and 0.55, for maize at both sites. These results are in agreement with the reported range (i.e. 0.4–0.58) by Prince et al. (2001) and Heard (2004; Harvest Index 0.54). The average root:shoot ratio estimated at harvest across the maize years was 0.18. This was similar to the average root:shoot ratio observed by Anderson (1988).

The aboveground and total biomass predicted for soybean at Mead was slightly higher compared to Bondville (Table 2). The predicted biomass of products (seeds and pods) at harvest ranged between 44–49% and 38–43% of the total soybean biomass (across different years) at Bondville and Mead, respectively. Considering that the 70% of the product at harvest (i.e. beans and pods together) was beans (Hanway and Weber, 1971a, b; Buyanovsky and Wagner, 1986), we estimated a Harvest Index that ranged between 0.37 and 0.41 during the years with soybean. This Harvest Index range fell within the range (i.e. 0.37–0.45) reported by Rao et al. (2002) and that reported by Spaeth et al. (1984; Harvest Index range 0.25–0.6). The estimated average root:shoot ratio soybean at harvest was 0.18. This ratio fell within the range (of 0.14–0.19) observed by Allmaras et al. (1975), and it was slightly higher than the value of 0.15 observed by Silvius et al. (1977) for non-stressed plants, and the highest value (i.e. 0.126), among the values reported by Taylor et al. (1982).

When the biomass carbon was converted to the biomass in each plant pool, we found that the model predicted values for both crops were acceptable based on the values found in certain past studies (Taylor et al, 1982; Ritchie et al., 1996; Heard, 2004). For instance, the average biomass carbon predicted by SiBcrop for maize leaves, stems, and products at harvest for Mead site were 103.5, 136.7, and 487.1 $\mathrm{g\,C\,m^{-2}}$, respectively. Assuming that carbon is 45% of the total dry weight, the carbon content in maize leaves, stems, and products according to Heard (2004) were 92.2, 120.3, and 476.7 g C m^{-2}, respectively. Similarly, the average biomass carbon predicted by SiBcrop for soybean roots, leaves, stems, and products at harvest for Bondville site were 58, 44.5, 115.4, and 186.2 g C m^{-2}, respectively. Calculated average carbon (i.e. 45% of dry weight) for rain fed soybean leaves, stems, and products based on the dry weights reported by Taylor et al. (1982) were 35.3, 111.0 and 180.0 g C m^{-2}, respectively. Compatibility of the predicted biomass values by SiBcrop were further tested by the comparisons against the measured total aboveground biomass (converted to carbon) for the two sites. Although the biomass carbon values in both crops were closely simulated, predicted values were slightly higher than the observed biomass at Mead site and mixed results were found for Bondville (Fig. 7).

Seasonal and interannual variation in carbon fluxes of cropland systems were poorly predicted in the control simulations (Fig. 8a). However, SiBcrop clearly showed the rotation of maize (C4) and soybean (C3) in the field, with maize having a much higher carbon uptake. SiBcrop also better predicted the seasonality associated with the crop growth cycle (Fig. 8b). Similar results were observed for Mead, as well (Fig. 11b). With original SiB, there was no synchrony between the NEE curves of the predicted and observed data (Figs. 8a and 11a). However, with further modification of certain SiB parameter values (Table 1), and by using predicted phenology, we were able to improve the model performance significantly. Considering the presence of only maize during odd numbered years (as in the field) and increase of V_{max} and high temperature inhibition for maize, allowance of removal of harvest, and incorporating new phenology scheme in SiBcrop helped improve the magnitude of predicted NEE and the compatibility with observed data in the field for maize (Figs. 9b and 11c). Similarly, considering the presence of only soybean in the field during even numbered years and predicting carbon fluxes through LAI derived from the phenology scheme, substantially improved the synchrony and compatibility of the predicted values with observed NEE for soybean (Fig. 10). Thus the new phenology scheme within SiBcrop helped better predict the magnitude and seasonality of the carbon fluxes and LAI, compared to the control simulation.

The highest NEE values predicted by SiBcrop for maize were more than 80 percent of the observed values in the field. The maximum predicted carbon drawdown by maize as represented in NEE, ranged between 15 and 20 µmol m^{-2} s^{-1} in the annual cycles based on monthly averages, and ~60 µmol m^{-2} s^{-1} at sub hourly scale (Figs. 8 and 9). In the diurnal cycle, the highest predicted NEE occurred between 12 and 3 p.m. NEE was positive before ~7 a.m., since it was dominated by respiration (Figs. 8c and 11d).

The predicted carbon fluxes for maize were mostly comparable to the observed fluxes, and occasionally there were outliers in the observed data as well, which were more noticeable in the data at sub hourly time scale.

The maximum NEE observed and predicted by SiBcrop for the soybean years was ~5 µmol m^{-2} s^{-1} in the annual cycles based on monthly averages (Fig. 8b), and the maximum values at sub hourly scale were between 15 and 20 µmol m^{-2} s^{-1} in both sites; however, observed maximum was mostly between 20 and 30 µmol m^{-2} s^{-1} at sub hourly scale (Fig. 10). Results showed the lower carbon uptake due to lower photosynthetic efficiency in soybean, compared to maize, although soybean has a higher V_{max}. The predicted NEE values for soybean were still less than the observed values.

3.2 Simulations for winter wheat

The average maximum Leaf Area Index predicted for winter wheat at ARM-SGP site was 3.0 m^2 m^{-2}, and predicted LAI was within 0.5 m^2 m^{-2} compared to the observed LAI (Fig. 12b). The predicted LAI had similar variation and good synchrony with the observed LAI.

The sub hourly predicted NEE for wheat followed a similar pattern of variation. However, the maximum observed diurnal NEE was mostly between 20–30 µmol m^{-2}, while the maximum predicted NEE was between 15 and 20 µmol m^{-2} (Fig. 12a and d). When the annual cycles with monthly averages were taken, the model yielded slightly higher NEE compared to the observed, although the same pattern of variation could be seen with respect to seasonality. Carbon uptake in early vegetative stages was relatively low from planting towards the end of the year until the spring green-up in the following year, during which period the plants also undergo vernalization (i.e. cold requirement for the transition from vegetative to reproductive growth; Bierhuzen, 1973; Brooking, 1996; Ritchie, 1991). Rapid growth and higher carbon uptake (i.e. NEE) was observed after the spring green-up in the following year (Fig. 12c).

According to SiBcrop simulations, the average total aboveground biomass carbon for winter wheat was 292 g m^{-2} (Table 2), which was consistent with the average observed in the field, 270 g m^{-2}, where the typical measurement error was about 5%. The average harvest index based on SiBcrop runs was 0.41, while the recorded harvest indices for the crop usually ranged between 0.32 and 0.43 (Sharma et al., 1987; Gent and Kyomoto, 1989; Prince et al., 2001). The total biomass carbon averaged over the years with winter wheat was 375 g C m^{-2}. Considering a 45% carbon in dry matter, this converts to 834 g m^{-2} dry matter. This falls within the range of total dry matter weights given by Wilhelm (1998) for winter wheat under different tillage andnitrogen fertilization rates (i.e. between 636 and 848 g m^{-2} dry matter).

Overall, SiBcrop showed improved performance in predicting carbon fluxes on croplands, compared to the control simulations with original SiB. However, SiBcrop still seems to slightly underpredict the CO_2 uptake at sub hourly scale, mostly by C3 crops, although a similar pattern of variation and seasonality was seen as observed in the field. So far we have developed these phenology schemes for three main C3 and C4 crops, and our aim is to expand it to other major crops. Further testing of SiBcrop using more sites at locations with different climates and weather variability is warranted. In the future, SiBcrop will be coupled with the Regional Atmospheric Modeling System (RAMS; Pielke et al., 1992; Corbin et al., 2008), a mesoscale meteorological (non-hydrostatic) model, to estimate time-varying exchanges of carbon, water, and energy, and the performance of this regional modeling system is planned to be tested against the observations at a variety of spatial scales.

4 Conclusions

The phenology and physiology scheme we developed was simple and detailed enough to predict LAI values to be used within SiB. LAI and NEE produced by SiBcrop for maize, which is a crop with C4 physiology, were closer in value and had better synchrony with the observed data in the field, compared to the original SiB model in which LAI (and thus carbon flux estimation) were based on the remotely sensed NDVI. Although the same trend was obvious for the C3 crops, soybean and wheat, the maximum sub hourly NEE predicted for soybean was 20–30% lower than the maximum NEE observed in the field.

Since SiB's complex, process-based equations, parameters, and stress factors, etc., are involved in the derivation of daily carbon and energy fluxes, such a straight forward and relatively simple phenology and physiology scheme seemed to work well in reaching our objective (i.e. to improve the prediction of carbon fluxes from croplands). The overall validity of the phenology scheme was further confirmed by the LAI and biomass data from field observations and past studies.

Overall, compared to the control, SiBcrop better predicted spring onset of growth (i.e. prediction of planting dates and the crop growth following spring onset), which improved the estimate of CO_2 uptake, especially by maize. The advantage of the new phenology scheme within SiBcrop includes the prediction of biomass which can be evaluated against crop yields, realistic treatment of fine-scale heterogeneity of agro ecosystems, and eventual prediction of future fluxes, for which no satellite data are available.

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Table 1. Some important crop relevant parameters in SiBcrop; these parameter values are deviations or additions to the parameter values given for SiB in Sellers et al. (1992, 1996b).

Parameter	Value	Unit	Reference
Maximum Rubisco Carboxilation Velocity (V_{max})		μmol m^{-2} s^{-1}	Harley et al., 1985; Norman and Arkebauer, 1991; Arora, 2003; Morgan et al., 2004, Ainsworth et al., 2004; Bernacchi et al., 2005; Kothavala et al., 2005
Maize	54		
Soybean	100		
Wheat	93		
Height to canopy top		m	Based on observations
Maize	2.5		
Soybean	1.0		
Wheat	0.5, 0.95		
Half point high temperature inhibition function (HHTI)		K	DeVries et al., 1989; Hofstra and Hesketh, 1969; Boote et al., 1998; Law et al., 2001
Maize	318		
Soybean	313		
Wheat	308		
Annual fraction net assimilation C added on soil/litter layers (to account for harvest removal)	0.6–0.65	dimensionless	Based on crop specific harvest indexes.
Maintenance respiration (C) coefficients at 20°C: ($Resp_{maint}$ coeff; derived based on the values given in the references)		g CO_2–C g^{-1} (d.w.C[a]) d^{-1}	Amthor, 1984; de Vries et al., 1989; Norman and Arkebauer, 1991, Goudriaan and Van Laar, 1994
Roots	0.016		
Leaves			
Maize and soybean	0.016		
Wheat	0.009		
Stems	0.005		
Products	0.008		
Growth respiration (C) coefficients: ($Resp_{growth}$ coeff; derived from the values given in the reference)		g CO_2–C g^{-1} (d.w.C) d^{-1}	de Vries et al., 1989
Maize			
Roots	0.221		
Leaves	0.251		
Stems	0.223		
Products	0.209		
Soybean			
Roots	0.293		
Leaves	0.431		
Stems	0.295		
Products	0.675		
Wheat			
Roots	0.221		
Leaves	0.251		
Stems	0.223		
Products	0.189		

[a] d.w.C=dry weight (i.e. biomass) carbon

Table 2. Average predicted biomass.

Crop	site	Biomass carbon g m^{-2}	
		Total	Aboveground
Maize	Bondville	931.3±31.2	790.7±22.4
	Mead	852.1±18.8	727.2±4
Soybean	Bondville	404.2±74	346.1±60
	Mead	435±77.2	360±64.1
Wheat	ARM-SGP	375.3±18.3	292.3±12.4

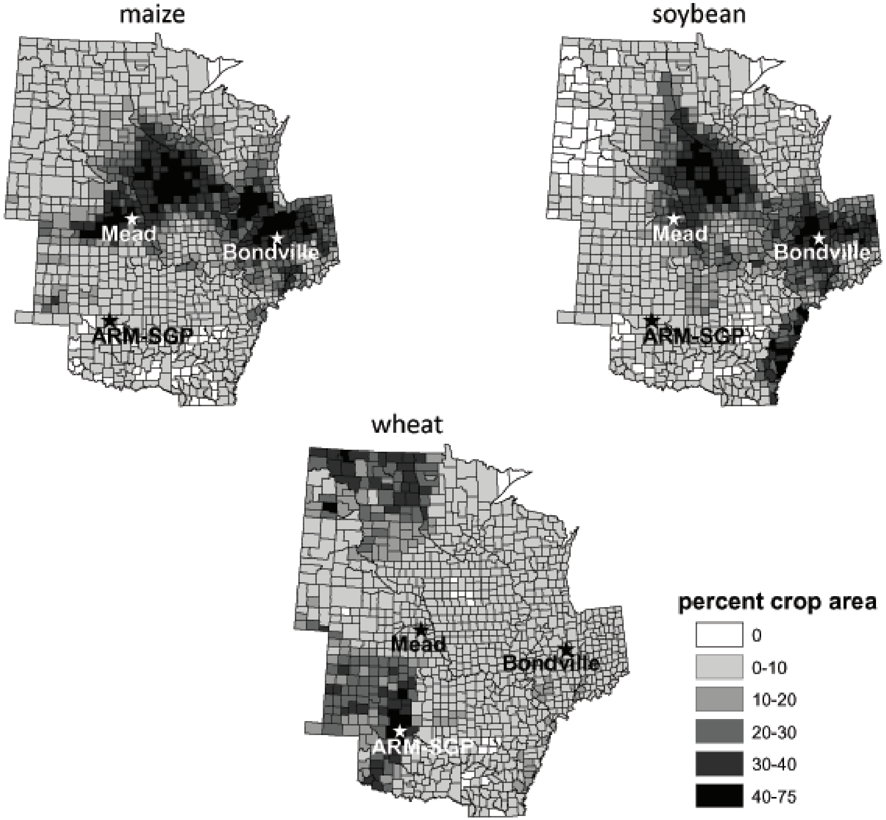

Fig. 1. Distribution of corn, soybean, and wheat in the US mid west region encompassing the eddy covariance flux tower sites used for model testing (i.e. Bondville, IL, Mead, NE, and ARM-SGP, OK; marked with asterisk). Crop areas are presented as a percentage of the county area (Source: NASSus database; Lokupitiya et al., 2007).

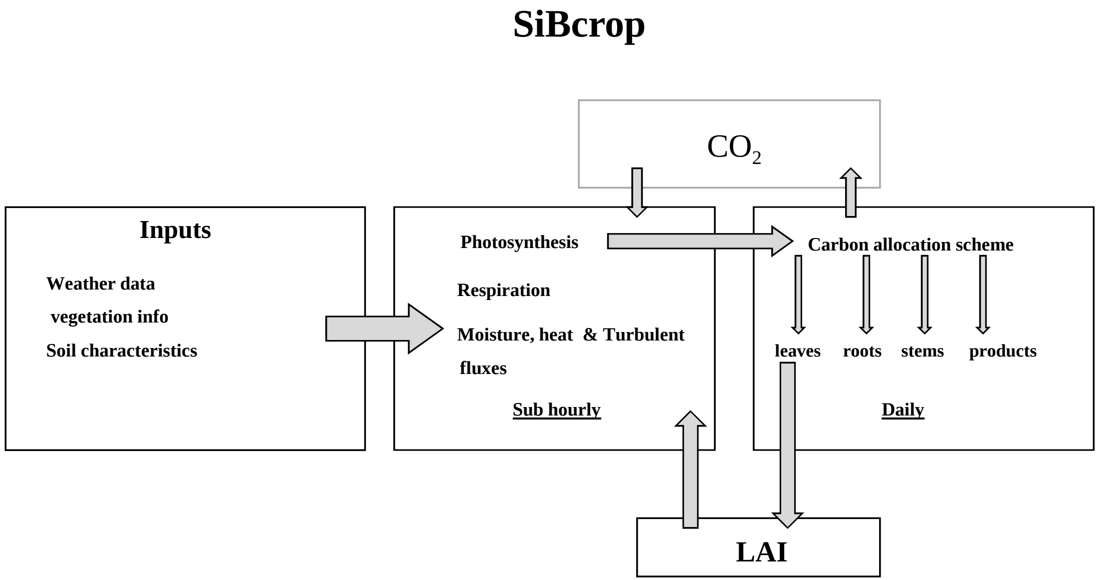

Fig. 2. Methodological framework.

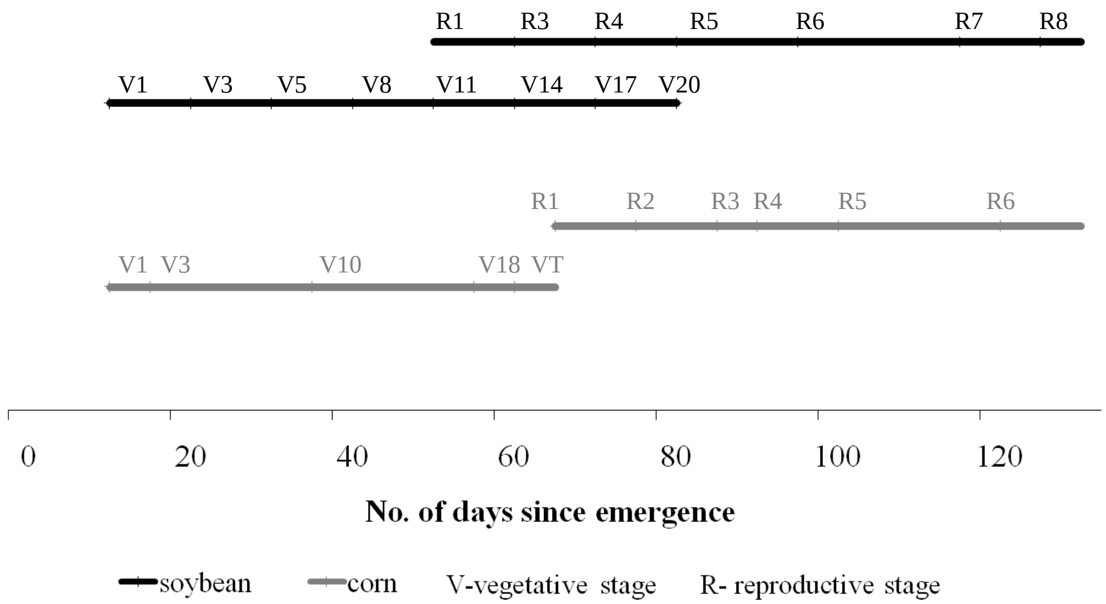

Fig. 3. Growth stages for maize and soybean. Maize: V1–V18=vegetative growth stages from single leaf to 18-leaf stage; VT=tasseling; R1–R6=reproductive growth stages; R1=silking; R2=blister; R3=milk; R4=dough; R5=dent; R6=physiological maturity. Soybean: V1–V20=vegetative stages from single leaf to 20-leaf stage; R1–R7-reproductive growth stages; R1=beginning bloom; R2=full bloom; R3=beginning pod; R4=full pod; R5=beginning seed; R6=full seed; R7=beginning maturity; R8=full maturity.

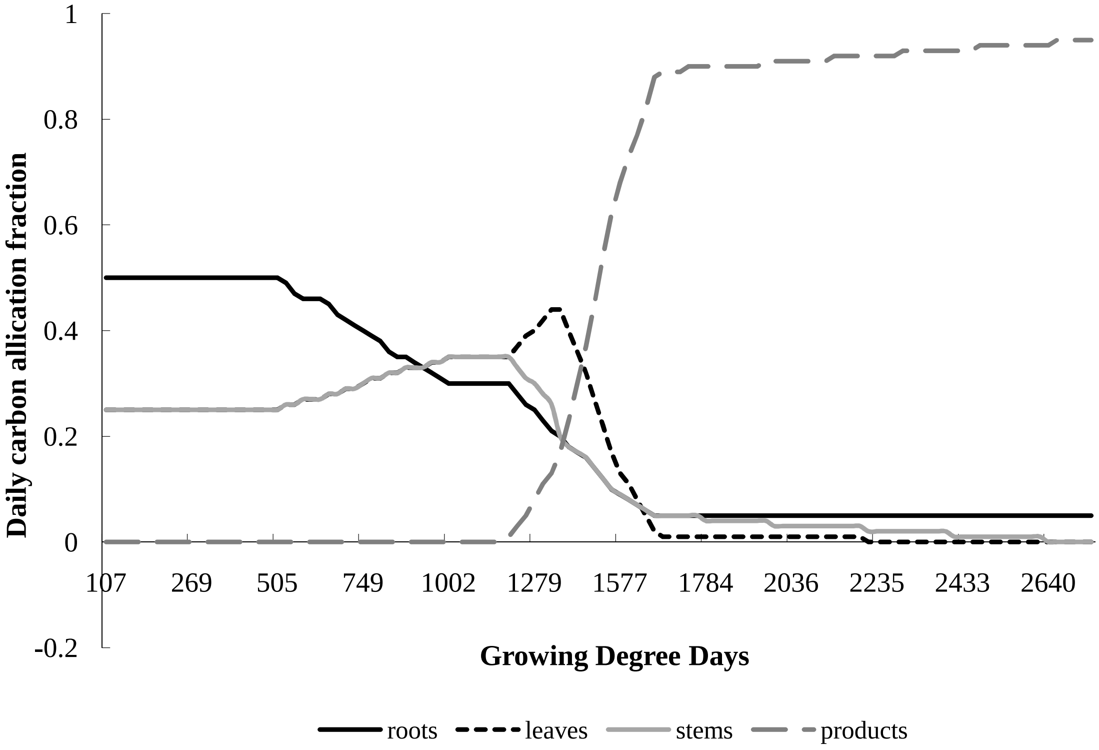

Fig. 4. Carbon allocation scheme for maize.

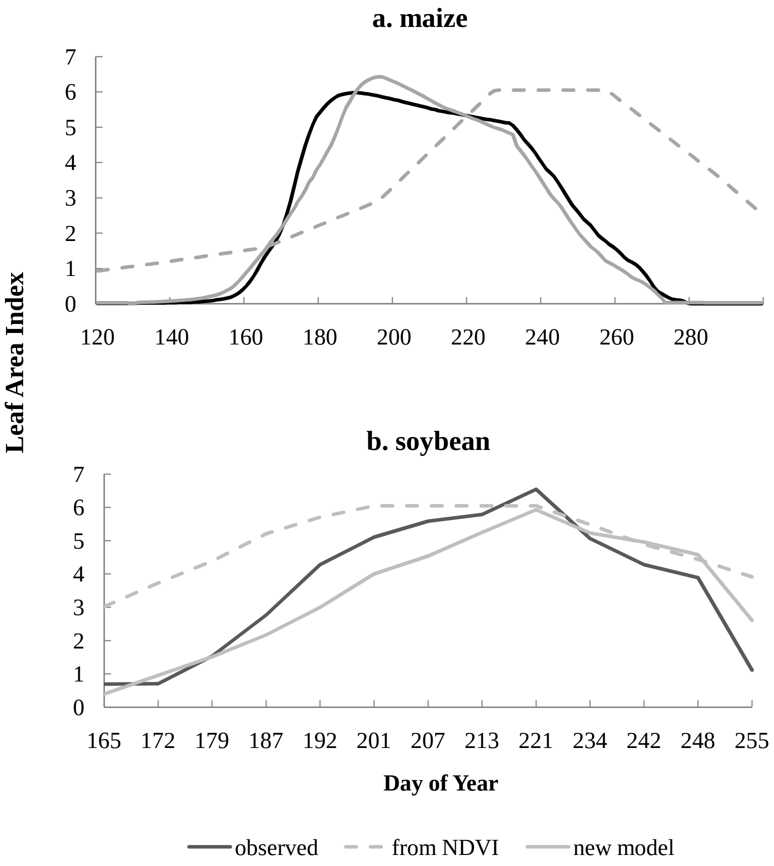

Fig. 5. Leaf Area Index (LAI) of crops in rotation in Bondville. **(a)** Maize in 1999; **(b)** Soybean in 2000. LAI from observed , new model, and NDVI (i.e. original SiB). The drop of LAI towards the end of the growing season represents the field drying and harvest events.

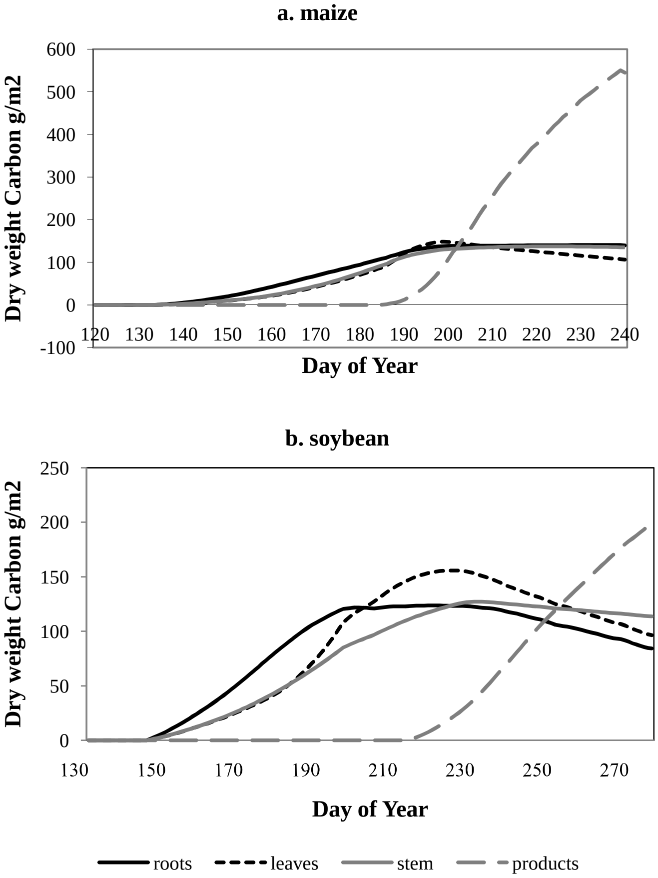

Fig. 6. Biomass carbon predicted for Bondville by the SiB-phenology coupled model (i.e. SiBcrop) for different pools by physiological maturity; **(a)** Maize in 1999, and **(b)** Soybean in 1998.

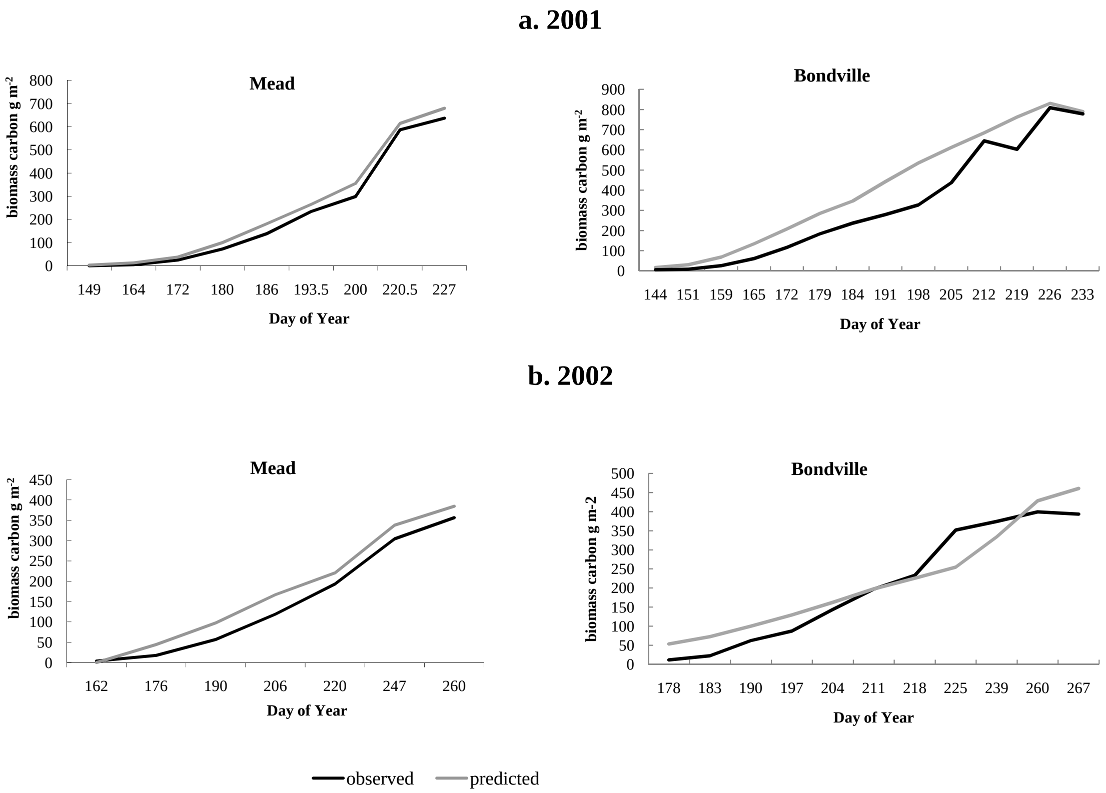

Fig. 7. Observed and predicted total aboveground biomass carbon at Mead and Bondville during a Maize year (2001) **(a)** and a Soybean year (2002) **(b)**.

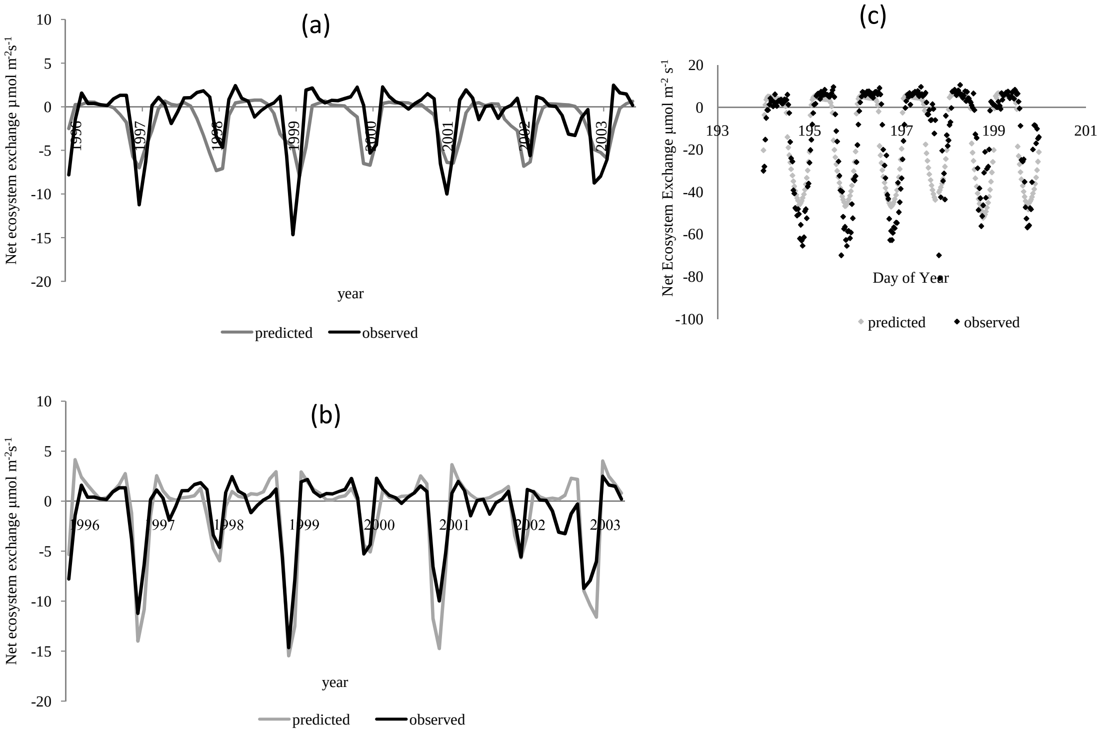

Fig. 8. Monthly means of Net Ecosystem Exchange (NEE) for Bondville site; **(a)** observed and predicted NEE from SiB before any modification (control); **(b)** simulation from the new model (i.e SiB using LAI produced from phenology models for maize (odd years) and soybean (even years); bottom); **(c)** Diurnal pattern of variation of sub hourly NEE at Bondville in mid July 1999.

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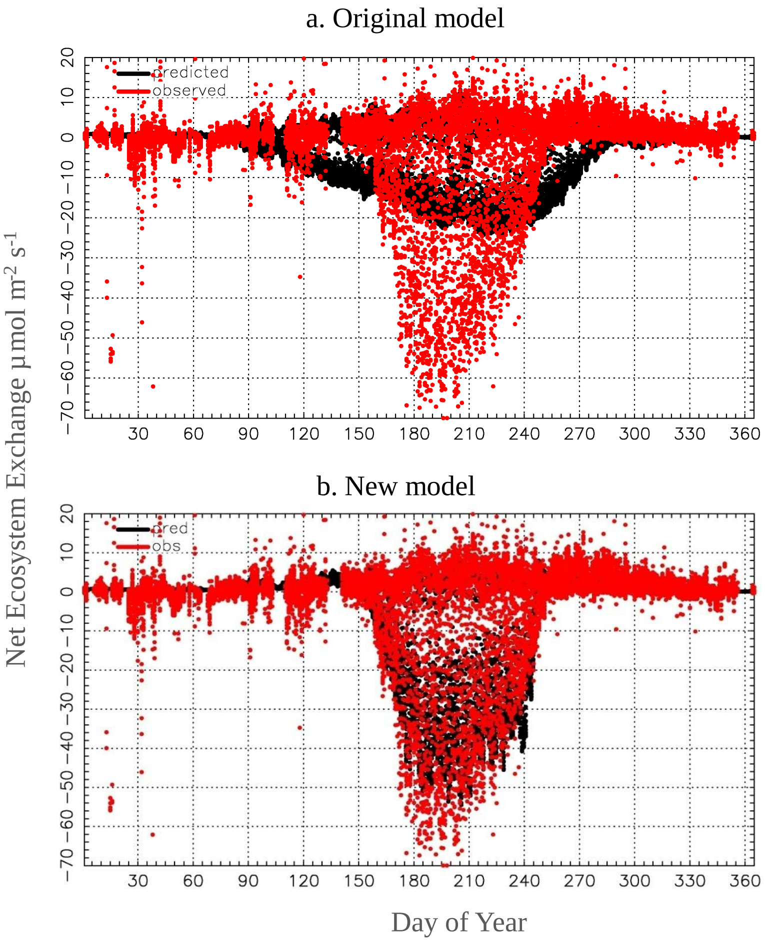

Fig. 9. Predicted and observed sub hourly fluxes for the Bondville site in a maize year (1999).

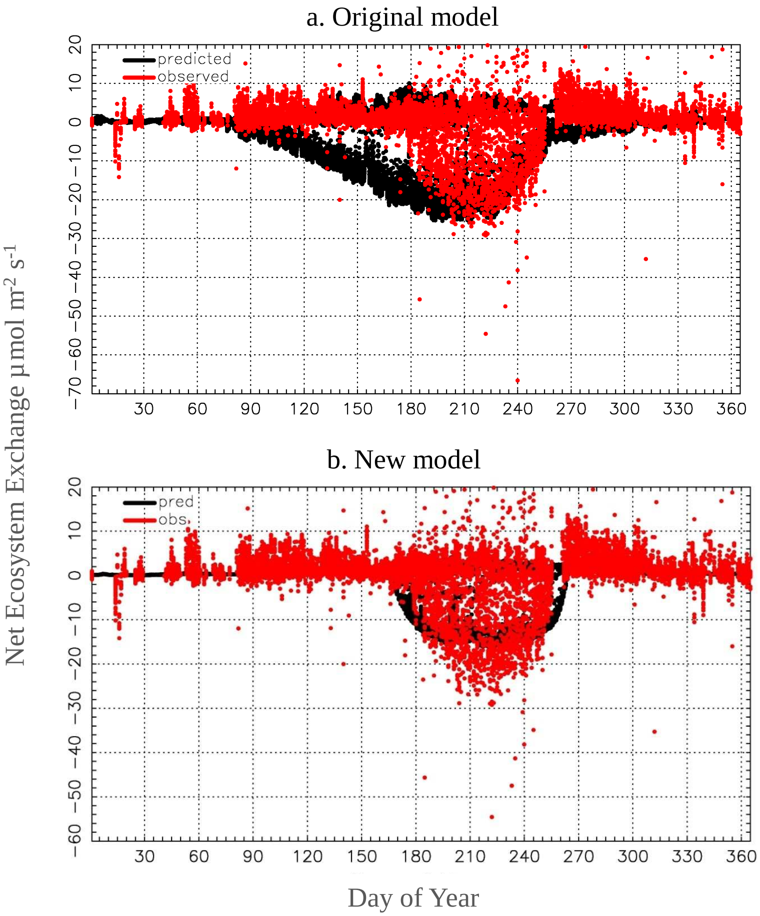

Fig. 10. Predicted and observed sub hourly fluxes for the Bondville site in a soybean year (1998).

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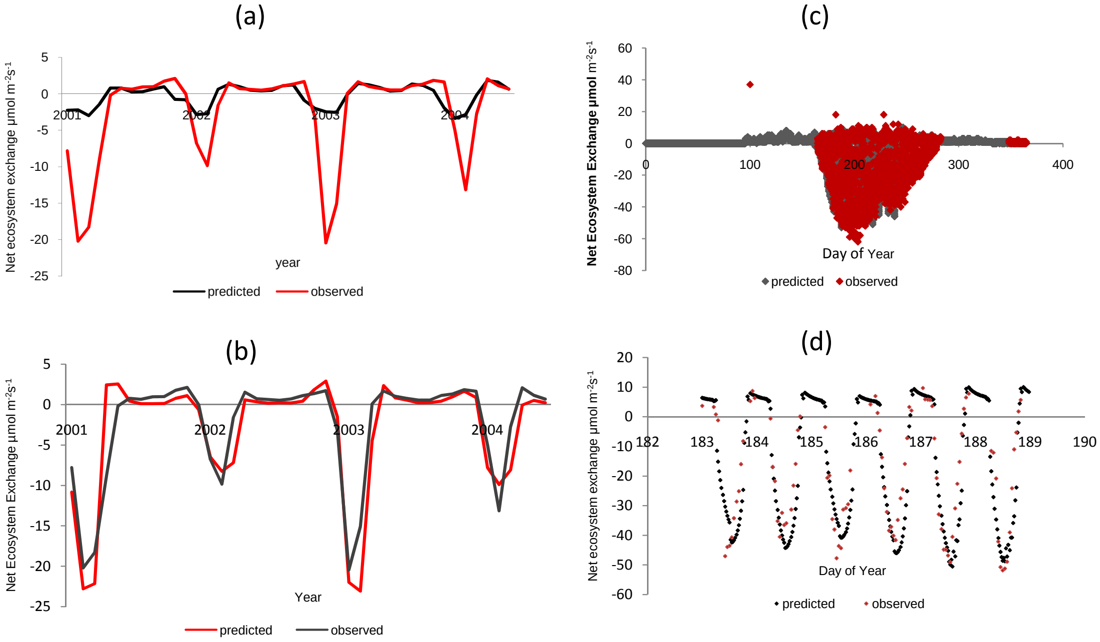

Fig. 11. Evaluation of predicted NEE against the observed data at a rainfed site in Mead, NE with maize and soybean in rotation. **(a)** monthly comparison with original model; **(b)** monthly comparision with new model; **(c)** sub hourly comparison with new model in 2001; **(d)** diurnal variation in the sub hourly NEE in early July in 2001.

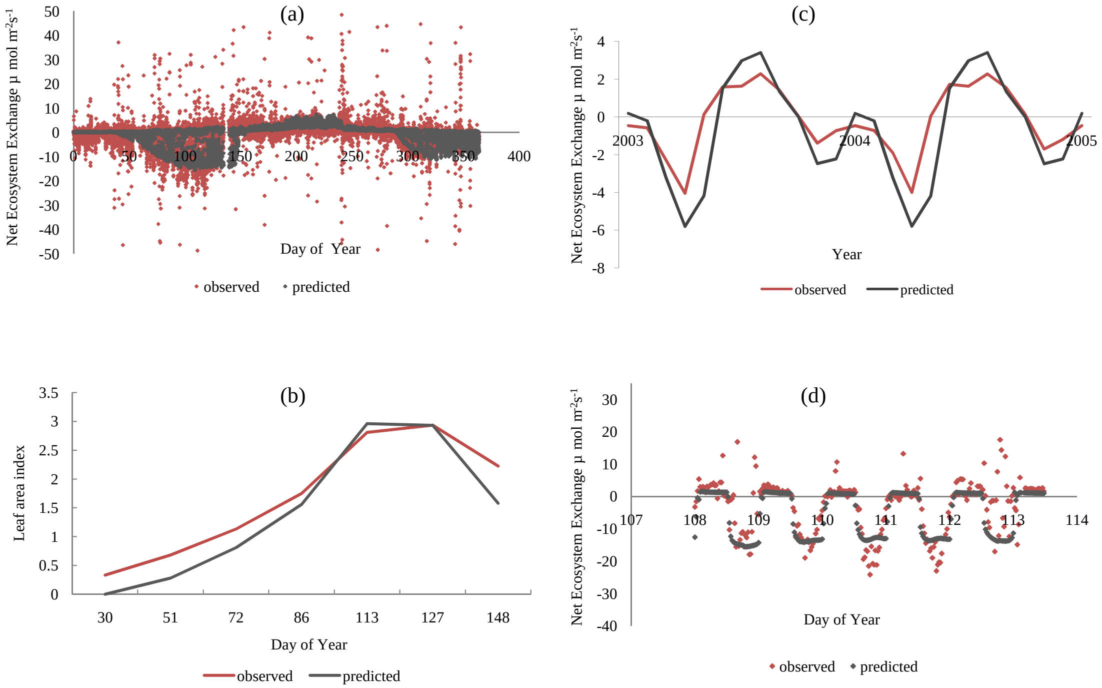

Fig. 12. Evaluation of SiBcrop performance for wheat at ARM-SGP site by comparison of observed and predicted data in 2003: **(a)** subhourly NEE; **(b)** LAI; **(c)** monthly means of NEE; **(d)** diurnal variation of sub hourly NEE from 18–23 April.

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