

A Simple Crop Phenology Algorithm in the Land Surface Model CN-CLASS

Kuo-Hsien Chang,* Jon S. Warland, Paul A. Bartlett, Altaf M. Arain, and Fengming Yuan

ABSTRACT

Land surface models are useful tools for estimating the contribution and response to climate change of C dynamics in various terrestrial ecosystems. In many land surface models, plant phenological algorithms are incorporated based on field studies in forests. However, to simulate adequately the C cycle over a large area, there is a need to include and validate algorithms for other ecosystems. The Carbon and Nitrogen-coupled Canadian Land Surface Scheme (CN-CLASS) is a land surface model that has been applied successfully to the study of C stocks in forest ecosystems. The objective of this study is to incorporate a simple crop phenology algorithm into CN-CLASS and validate its ability to simulate C cycles at an agricultural site in southern Ontario, Canada. The model was validated on a corn crop (*Zea mays* L.) in 2005 and 2008 based on measurements of aboveground biomass and net ecosystem productivity (NEP), as well as a well-tested agricultural model, DayCENT (the daily time-step version of the CENTURY model). The modified CN-CLASS showed similar dynamics of biomass allocation compared with field measurements and DayCENT simulations. Regression analysis indicated that the modifications improved the NEP simulation for a cornfield, with the coefficient of determination (R^2) relating simulated and observed NEP increasing from 0.51 in the original CN-CLASS to 0.78 in the modified model. Other crop species could be further validated to expand the model application to crop rotation studies and large areas covered by forests and crop fields in consideration of land management practices.

Process-based land surface models represent

physical and biogeochemical processes for simulating energy exchange, hydrology, phenology, C allocation, and respiration on a wide spatial scale (Medlyn et al., 2002a, 2002b; Raupach et al., 2005). Such models often adopt a forest phenology scheme for simulating crop growth in agricultural ecosystems (Chmielewski and Rotzer, 2001; Krinner et al., 2005; Lei et al., 2010; Van den Hoof et al., 2011), but when accurate C accounting is required for regional or global simulations, the influence of crop phenological development and agricultural management practices needs to be considered (Chmielewski and Rotzer, 2001).

A model-data comparison of gross primary productivity of the North American Carbon Program sites showed that the models generally performed best for forest sites and worst for croplands due to either a lack of model structure for agricultural ecosystems or the complex interactions of physical and biological processes (Schwalm et al., 2010). This result indicated that the appropriate

representation of phenology and C allocation for crops is not well established in these land surface models (Arora and Boer, 2005; Hansen et al., 2006; Osborne et al., 2007). Thus, it is imperative that model developers focus first on the vegetation growth mechanism for croplands, which cover nearly 40% of the Earth's land surface (Ramankutty and Foley, 1999; Foley et al., 2005) and are subject to changes in climate and atmospheric CO₂ concentrations.

Improved land surface models for agricultural ecosystems might consider the aspects of C allocation, agricultural management practices, and the linkage between phenological development and C allocation. The simulation of C allocation among plant organs is one of the weakest features of crop growth models, but it is clearly of great importance in crop growth, yield, and the terrestrial C budget (Marcelis and Heuvelink, 2007; Schaefer et al., 2012). The regulation of C allocation varies with different crop species and is different from that of perennial plants. Due to a lack of field measurements for the detailed internal regulation of partitioning among plant organs, crop model parameterizations in surface schemes require further examination to ensure accurate crop development simulations.

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Abbreviations: CN-CLASS, Carbon and Nitrogen-coupled Canadian Land Surface Scheme; CGCM, Canadian global climate model; CLM, Community Land Model; DayCENT, the daily time-step version of the CENTURY model; DOY, day of year; GDD, growing degree-days; GI, growth index; ERS, Elora Research Station; LAI, leaf area index, LPJmL, Lund-Postsdam-Jena managed Land model; NEP, net ecosystem productivity; NPP, net primary productivity; RMSE, root mean square error; SiBcrop, Simple Biosphere Crop-specific phenology model; SOC, soil organic carbon; ST, soil temperature; SC, soil water content; WOY, week of the year.

Agricultural management strongly influences the exchanges of energy, water, and C throughout the growing and non-growing season (Tsvetsinskaya et al., 2001; Challinor et al., 2004). To illustrate the impacts of agricultural management practices on the C cycle, we usually consider residue management practices, fertilization application, and the schedule of planting/harvesting procedures. As there are no reliable regional data for agricultural management practices, the model parameterization has in the past relied on aggregated data from agricultural censuses or was simply based on geographically referenced data of the climate zone for crop growth.

Particularly in the areas of crop phenology and development, the concept of growing degree-days (GDD) has been widely applied to describe and predict phenological events (McMaster and Wilhelm, 1997). The GDD approach has been used as the phenological scheme in most land surface models, such as the agricultural version of the Integrated Biosphere Simulator (Agro-IBIS, Kucharik and Brye, 2003), the Community Land Model (CLM, Oleson et al., 2008), the Lund-Postdam-Jena managed Land model (LPJmL, Bondeau et al., 2007), and the Simple Biosphere Crop-specific phenology model (SiBcrop, Lokupitiya et al., 2009). The C allocation to plant organs in these models was dependent on the accumulated GDD for phenological development. Since C assimilation via the process of photosynthesis varied throughout the stages of phenological development, the leaf area index (LAI) was updated according to the C allocation to leaves. Therefore, the parameters and functions used in the phenology algorithms could be specific to different crops, growth stages, and plant pools.

In this study, we examined and improved the current model mechanism in the Carbon and Nitrogen version of the Canadian Land Surface Scheme (CN-CLASS, Arain et al., 2002, 2006) to simulate crop growth. CN-CLASS evolved from the CLASS land surface model (Verseghy, 1991; Verseghy et al., 1993) developed at Environment Canada for use in the Canadian global climate model (CGCM), which is used to study climate change and variability and to understand the various processes that govern the climate system. CN-CLASS has been found to perform well in simulating CO₂ exchange and evaporation in both deciduous and coniferous forests (Arain et al., 2002, 2006; Yuan et al., 2007, 2008). However, since CN-CLASS was developed using datasets from mature forests (Arain et al., 2002), its phenological algorithm requires modification to represent crop growth. As described by Kothavala et al. (2005), CN-CLASS requires a crop-specific phenological algorithm associated with C allocation, agricultural management practices (i.e., tillage and the schedule of sowing, fertilization, and harvest) and a linkage between phenological development and C allocation to refine its ability to simulate the C cycle in agricultural ecosystems.

To improve the functionality of CN-CLASS for cropland ecosystems, we first examined the current model mechanism to build a crop-specific phenology scheme on top of the original model framework without changing the existing modules for forest ecosystems. We created an index to specify the type of ecosystem in the simulated grid cell, and the crop-specific phenology scheme was applied when the crop plant functional type was specified. The GDD-driven dynamic phenology scheme within the modified CN-CLASS describes crop

phenological stages and events during the crop growth cycle such as sowing, emergence, juvenile, stem elongation and leaf growth, LAI plateau, maturity, and net-senescence, based on the studies of Tsvetsinskaya et al. (2001), Gervois et al. (2004), and McMaster et al. (2005). The phenology scheme simulates biomass in different plant pools, LAI, and net ecosystem productivity (NEP) in half-hourly time steps. We evaluated the performance of the modified CN-CLASS for a corn crop by using field measurements at an agricultural site, the Elora Research Station (ERS) in southern Ontario, Canada. We also evaluated the performance of the modified CN-CLASS with a pre-validated agricultural model, DayCENT (Parton et al., 1998), which showed a fairly good C productivity simulation for the ERS (Chang et al., 2013). Half-hourly NEP data over the course of two corn years were also obtained from flux tower eddy covariance measurements at the ERS for model validation.

The main objective of this study was to focus on the simulations of corn crop phenology and C allocation in CN-CLASS by applying a simple crop phenology algorithm within the current modeling structure. This study expands the ability to evaluate the effects of crop rotations and land use/land cover (vegetation shift) on the C budget under different climate scenarios.

MATERIALS AND METHODS

Site Description

The Elora Research Station is located 20 km north of Guelph, Ontario (43°39' N 80°25' W). The monthly average daily air temperature at this site ranges from −8.0°C in January to 19.7°C in July. The accumulated monthly precipitation for the growing season (May–September) is 44 cm, with 50 cm for the remaining months (October–April). The soil texture is Conestoga (fine-loamy, mixed, active, mesic Typic Hapludalfs) silt loam consisting of 29% sand, 52% silt, and 19% clay. According to Mueller et al. (2009), soil taxonomic types are Brunisolic Gray Brown Luvisol in the Canadian System of Soil Classification and Typic Hapludalf in the U.S. Soil Taxonomy. Total organic C is 18.4 g kg^{−1} soil, total N is 1.7 g kg^{−1} soil and the soil pH (1:2 soil/H₂O ratio) is 7.1 in the surface soils (0–20 cm) (Wanniarachchi et al., 1999).

The agricultural experiment at the ERS was established in 2000 and included two replicates of two tillage treatments (conventional tillage and no-tillage) and four plots in total. The size of each plot was 150 by 100 m (1.5 ha). The site followed a crop rotation sequence of corn, soybean [*Glycine max* (L.) Merr.], and winter wheat (*Triticum aestivum* L.). Two recent corn years (2005 and 2008) at the ERS were selected for testing the crop phenology algorithms in CN-CLASS. The maize varieties planted in 2005 (DK355) and 2008 (SRIL-TC/IRIL-TC) were derived from the same parent material. Whole-plot assessments, representing approximately 50% of the plants provided dates of sowing, emergence, full crop cover, beginning of leaf senescence, end of the growing season, and harvest dates of 10 May [day of year (DOY) 130], 28 May (148), 4 August (216), 12 September (255), 1 October (274), and 28 October (301), respectively. Granular urea was applied at a rate of 150 kg N ha^{−1} during the sowing (Jayasundara et al., 2007; Wagner-Riddle et al., 2007).

Aboveground biomass measurements for model validation were taken by Wilton (2010) at the ERS in week of the year (WOY) 32, 34, 39, and 42 in 2008. Three corn plants were

randomly sampled across the entire field and all biomass of each plant was clipped to the soil surface. Each sample was reported in dry weight after oven drying at 60°C for 24 to 48 h. The NEP data were measured by an eddy covariance flux tower within an aerodynamically homogeneous region to represent the average of the fluxes from the entire four-plot area of the ERS. An open-path infrared gas analyzer (LI-7500; Li-Cor, Lincoln, NE, USA) and a 3-dimensional sonic anemometer (CSAT3; Campbell Scientific, Logan, UT, USA) were installed on the flux tower at a height of 2 m to measure CO₂ and H₂O fluxes. The flux tower operated in the field throughout the year, except for periods of agricultural management (sowing, plowing, fertilization, and harvest) and equipment maintenance. The raw NEP data were filtered to exclude times of low turbulence, unsuitable wind direction, and periods of instrument malfunction and calibration. A gap-filling method (Falge et al., 2001) was applied when missing data occurred, and ~25% raw data ($n = 7786$) were gap-filled in this study.

Model Parameters and Modifications

The model forcing variables for CN-CLASS included incoming short-wave and long-wave radiation, precipitation, air temperature, specific humidity, wind speed, atmospheric pressure, and air specific humidity at 30-min time steps. These model inputs were measured at the ERS in 2005 and 2008. The initial plant and soil C and N pools, canopy temperature, soil temperature (ST), and soil water content (SWC) were based on measurements in early 2005. The crop-specific, N/C, photosynthesis, and respiration parameters are listed in Table 1. These parameters were either measured directly or adapted from Kothavala et al. (2005).

The original and modified modeling frameworks are illustrated in Fig. 1. There are six modifications: (i) plant functional types for crops; (ii) C allocation; (iii) C partitioning; (iv) phenological stage; (v) leaf growth condition; and (vi) agricultural management schedule. The model results are compared with NEP, aboveground biomass (i.e., leaf and stem) measurements, and DayCENT simulations. The DayCENT model (Parton et al., 1998; Li et al., 2006; Stehfest et al., 2007; Del Grosso et al., 2008) has already been validated with 9 yr of field measurements of SWC, ST, biomass, grain yield, NEP, and soil organic carbon (SOC) at the ERS (Chang et al., 2013). Details of modifications to CN-CLASS are described below.

Carbon Allocation

In the original CN-CLASS, the biomass components were based on the C allocation for forest structures, including leaf, sapwood, heartwood, fine root, coarse root, and non-structural reservoir (Cannell and Dewar, 1994; Arain et al., 2006). However, crops have a different biomass structure from forests. Thus, modeling C allocation for crops requires proper allometry pools to initialize the plant growth (Reich et al., 1997). When adapting CN-CLASS for crop simulations, the woody components were considered as the stem structure and as a fraction of total aboveground biomass (Gower et al., 1997; Turner et al., 2000; Litton et al., 2003). The storage organ (i.e., grain yield) was regarded as a part of the aboveground biomass. Initial values for stem and roots have been set to zero; the reserved C for seeds was set to 0.002 kg C m⁻² (Krinner et al.,

2005). The C allocations to the biomass components for crops were computed as:

$$\begin{aligned} C_{\text{leaf}} &= \frac{(1 - f_{\text{pool}}) A_{\text{net}}}{1 + f_{\text{resp}}} \\ C_{\text{stem}} &= X_{\text{stem,stage}} \frac{C_{\text{post}}}{1 + f_{\text{resp}}} \\ C_{\text{root}} &= X_{\text{root,stage}} \frac{C_{\text{pool}}}{1 + f_{\text{resp}}} \end{aligned} \quad [1]$$

where f_{pool} is a partitioning function of the reservoir of assimilated C for leaf growth, A_{net} is the net C assimilation via photosynthesis, and f_{resp} is a fraction of respiratory loss during plant growth. The leaf component is mainly controlled by LAI (Eq. [6]) and the leaf C assimilation from photosynthesis (C_{pool} shown in Eq. [2]).

Stem development was determined by the available C pool (C_{post} shown in Eq. [3]) and was calculated after the deduction of the root, leaf growth, and respiratory losses; $X_{\text{stem,stage}}$ and $X_{\text{root,stage}}$ (Table 2) are prescribed constants for partitioning C going to stem and root for each phenological stage, respectively. Crops are assumed to use carbohydrate reserves to grow a minimum amount of leaves and roots in the initial growing season; the C allocation for leaves and roots is linked with the crop phenological scheme. The C_{pool} and C_{post} are the C available for leaf growth and for C allocation to roots and stem after leaf growth, respectively.

The initial biomass compartments start to accumulate C in C_{pool} for leaf growth and respiration. C_{pool} is regulated by the photosynthetic mechanism as:

$$C_{\text{pool}} = f_{\text{pool}} A_{\text{net}} - k_{\text{leaf}} (1 - f_{\text{pool}}) \times \exp(-\text{LAI}) C_{\text{pool}} - R_{\text{m}} \quad [2]$$

where k_{leaf} is the transformation rate from C reservoir to leaf structure, LAI is the leaf area index, and R_{m} is the total maintenance respiration for leaves, stem, and roots. Leaf growth is determined by the transformation rate (k_{leaf}) of C reservoir to leaf structure and LAI. Since the total respiratory loss from the nonstructural reservoir, leaves, stem, and roots influences plant growth, R_{m} acts to reduce the reservoir of assimilated C.

Carbon allocation to the stem requires accounting for the respiratory loss from maintenance respiration, growth respiration, leaf growth, and root growth. The rest of the available C (C_{post}) is allocated to stem and roots by the prescribed allocation ratios.

$$C_{\text{post}} = (1 - f_{\text{pool}}) C_{\text{pool}} - (C_{\text{root}} + R_{\text{root}} + C_{\text{leaf}} + R_{\text{leaf}}) \quad [3]$$

where f_{pool} is a function for partitioning the assimilate reservoir for leaf growth. C_{pool} is in increments by allocations (f_{pool}) from the available C from A_{net} after the C allocation of leaf structure. R_{leaf} and R_{root} are leaf respiration and root respiration,

Table 1. The parameters for crop simulations are related to field description, N/C ratios, and photosynthesis. Most of the values were adopted from measurements at ERS. The parameters related to photosynthesis were adopted from other ecosystem model studies.

Key parameter	Symbol	Unit	Value	Reference
<u>Site parameter</u>				
Sowing time		DOY	125–130	measured at ERS
Harvest time		DOY	246	measured at ERS
Max. standing biomass		kg m ⁻²	1.5	Fallow et al. (2003)
Plant density		unit m ⁻²	6.0	Liu and Tollenaar (2009)
Max./Min. LAI	LAI	m ² m ⁻²	6.0/0.0	Kothavala et al. (2005)
Specific leaf area	SLA	m ² kg ⁻¹	30.0	Schulze et al. (1994)
Base temperature	T _{base}	°C	10.0	McMaster (2005)
Transit. of linear growth	D _{ln}	°d	30	Ishag and Dennett (1998)
Coeff. of light extinction	k _{rad}	-	0.7	Ishag and Dennett (1998)
Max. leaf growth rate	k _{grow}	°d ⁻¹	0.15	Ishag and Dennett (1998)
<u>SOC pool parameter</u>				
C in surface litter		kg C m ⁻²	0.15	measured at ERS
C in root litter		kg C m ⁻²	0.15	measured at ERS
C in short-lived SOC		kg C m ⁻²	0.25	measured at ERS
C in stable SOC		kg C m ⁻²	4.5	measured at ERS
<u>Nitrogen parameter</u>				
N bio-fixation		g N m ⁻² s ⁻¹	3.5 × 10 ⁻⁷	Smil (1999)
N deposition		g N m ⁻² s ⁻¹	1.5 × 10 ⁻⁸	Smil (1999)
N fertilization		g N m ⁻² yr ⁻¹	18.8	adapted from ERS
N/C in reservoir		-	0.015	Anderson (1988)
N/C in leaf		-	0.022	Anderson (1988)
N/C in stem		-	0.001	Anderson (1988)
N/C in root		-	0.015	Anderson (1988)
N/C in surface litter		-	0.013	Anderson (1988)
N/C in root litter		-	0.013	Anderson (1988)
N/C in short-lived SOC		-	0.10	Anderson (1988)
N/C in stable SOC		-	0.10	Anderson (1988)
<u>Photosynthesis</u>				
Max. carboxylation rate		mol CO ₂ m ⁻² s ⁻¹	5.4 × 10 ⁻⁵	Kothavala et al. (2005)
Coeff. of intercellular CO ₂		-	6.0	Kothavala et al. (2005)
Stomatal sensitivity		Pa Pa ⁻¹	2000.0	Kothavala et al. (2005)
Canopy N extinction		-	0.14	Kothavala et al. (2005)
Quantum use efficiency		mol e ⁻ mol ⁻¹ quanta	0.2	Kothavala et al. (2005)
<u>Respiration</u>				
Resp. rate of leaf at 15°	K _{leaf}	μmol CO ₂ m ⁻² s ⁻¹	0.5	Lokupitiya et al. (2009)
Resp. rate of stem at 25°	K _{stem}	μmol CO ₂ kg ⁻² s ⁻¹	0.0	Kothavala et al. (2005)
Resp. rate of root at 25°	K _{root}	μmol CO ₂ kg ⁻² s ⁻¹	0.59	Kothavala et al. (2005)

respectively. Leaf structure is described as a function of LAI. f_{pool} approaches 1 for small LAI, referring to a higher transfer fraction for C_{pool} , and approaches 0 for greater LAI or with a decreasing C_{pool} as shown by:

$$f_{\text{pool}} = \left[1 - \exp\left(-\left(C_{\text{leaf}} + C_{\text{froot}}\right)\right) \right] \exp\left(-\frac{C_{\text{pool}}}{0.1}\right) \quad [4]$$

where C_{leaf} and C_{froot} are C in leaves and fine roots, respectively. Because the respiratory losses influence C allocation, C_{pool} for stem and roots is regulated by all of the component maintenance respiration values (Bonan, 1996). These respiratory losses are linearly related to individual pool size and governed by a Q_{10} form of temperature function at a reference temperature

and base rate of respiration (Arain et al., 2002). These parameterizations are shown in Table 1.

Crop Phenology and Agricultural Practices

Phenological response to GDD and agricultural practices are necessary modifications in CN-CLASS for agriculture. Equation [5] calculates the sum of the average daily maximum and minimum temperatures (e.g., T_{max} , T_{min}) compared to a base temperature at 10°C (T_{base}). The crop thermal accumulation ($\text{GDD}_{\text{accu,stage}}$) is constrained by the GDD thresholds for each stage. Six phenological stages and GDD thresholds were categorized as listed in Table 3.

$$\text{GDD}_{\text{accu,stage}} = \sum_{\text{stage}_{\text{begin}}}^{\text{stage}_{\text{end}}} \left(\frac{T_{\text{max}} + T_{\text{min}}}{2} - T_{\text{base}} \right) \quad [5]$$

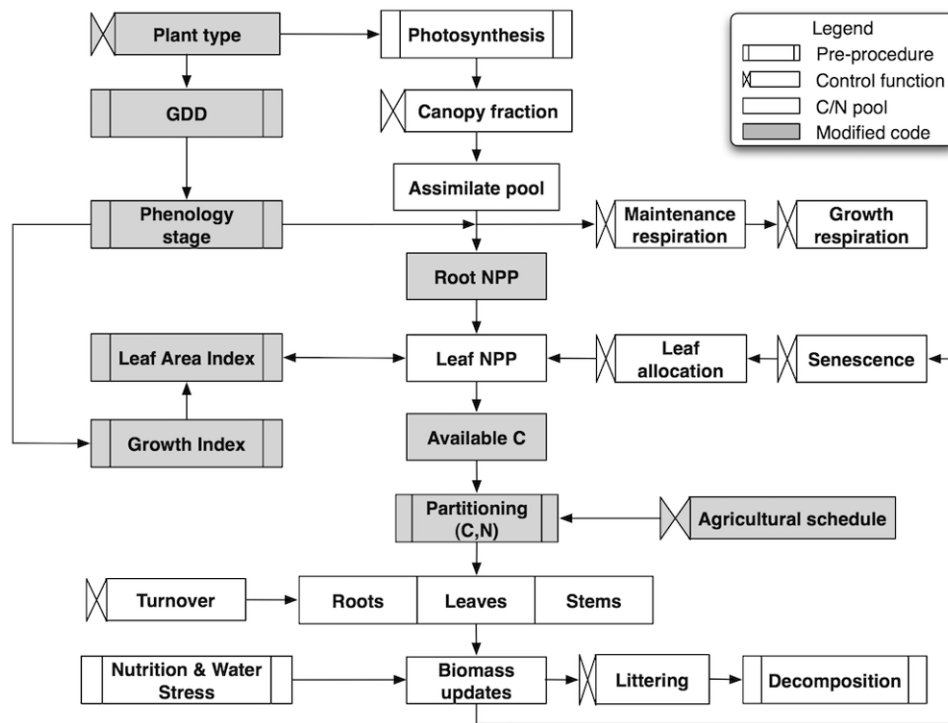


Fig. 1. The modeling framework of CN-CLASS for crops. The gray color indicates the new modification for crop simulation. The plant type is a flag to indicate the new crop module. The phenological stage and agricultural schedule are two main schemes in this study. The allocation module is linked with these two main schemes.

The crop phenological stages follow a sequence of fallow, sowing to emergence, juvenile, LAI plateau, maturity, and net-senescence. Emergence is defined as the coleoptile reaching the surface of the soil following germination. During the juvenile phase the leaves unfold and start to grow; the end of the juvenile phase is marked by tassel initiation followed by stem elongation. Rapid leaf growth occurs during the elongation phase and ends when the flag leaf has collared. Once new leaf growth has stopped, LAI is at a plateau, the tassel emerges and silking occurs, followed by rapid grain filling (maturity phase). Based on Brisson et al. (1998), grain filling continues through the point where senescence starts to cause a decrease in LAI (net senescence phase) and ends at physiological maturity. The LAI is computed as the net balance between leaf growth and senescence, therefore LAI starts to drop when insufficient C is added to maintain the LAI. Physiological maturity is assumed to be reached when the degree days reaches the input value for total GDD.

The crop phenological stages were numbered from 1 to 6. Negative values of GDD are not accumulated. The mean values from the GDD references were used to represent the required and accumulated GDD for each corn crop phenological stage in the modified CN-CLASS. In general, leaf emergence for corn was initiated when $GDD_{accu,stage}$ reached 120°d, though it may vary by 30 to 50°d (McMaster and Wilhelm, 1997). The juvenile stage and maturity required 400°d and 100 to 150°d. It takes 2300 to 2600 $GDD_{accu,stage}$ to reach full-canopy development for corn grown in southern Ontario, depending on its genotype. Senescence was activated after canopy maturity (2400–2750°d). However, the GDD approach alone is not sufficient for managed croplands. The $GDD_{accu,stage}$ onset requires a given agricultural management schedule. Table 1 lists the dates of sowing, fertilization, and harvest at the ERS. Therefore, the GDD calculation is initialized based on user-defined plant functional type and the date of sowing. The date of harvest also regulates the timing of crop residues incorporated into the litter and SOC pools.

Table 2. The initial values for each plant component and the values for C allocation based on the phenological stages. These values were adopted from the related field estimation and further adjusted for this study.

Key parameter	Symbol	Unit	Value	Reference
Initial C pool				
C in reserved pool	C_{pool}	kg C m ⁻²	0.002	Krinner et al. (2005)
C in stem	C_{stem}	kg C m ⁻²	0	adapted from ERS
C in root	C_{root}	kg C m ⁻²	0	adapted from ERS
C in fine root	C_{froot}	kg C m ⁻²	0	adapted from ERS
C allocation				
Rate of C for leaf	K_{leaf}	kg C m ⁻² s ⁻¹	5.0×10^{-6}	Arain et al. (2006)
Fraction of C for stem	$X_{stem,stage}$	–	0.45–0.75	Buyanovsky and Wagner (1986)
Fraction of C for root	$X_{root,stage}$	–	0.25–0.55	Gregory et al. (1996)
				Johnson and Thornley (1987)

Table 3. Growth stages of corn in CN-CLASS and organ growth, required growing degree-days (GDD), and its accumulation during those stages. These thresholds were modified based on the studies of Buyanovsky and Wagner (1986), Ritchie et al. (1986), McMaster and Wilhelm (1997), Brisson et al. (1998), Tsvetinskaya et al. (2001), McMaster et al. (2005), and Gervois et al. (2004).

Stage	Phenology	Components	Required GDD (°d)	Accumulated GDD (°d)
1	fallow	—	—	—
2	sowing to emergence	root	90–120	90–120
3	juvenile	root, leaf	400	490–520
4	LAI plateau	root, leaf, stem	1780–2080	2300–2600
5	maturity	root, stem	100–150	2400–2750
6	net-senescence	—	—	—

The LAI in CN-CLASS is calculated as a function (Eq. [6]) of SLA, net leaf biomass, and senescence (Ishag and Dennett, 1998; Arain et al., 2002). In this study, LAI calculation is initialized based on $GDD_{accu,stage}$ to leaf emergence and is constrained by the prescribed LAI thresholds for each phenological stage. No more biomass is allocated to leaves above the maximum prescribed LAI. At the end of each time-step, C pools were updated by subtracting the growth and maintenance respiration from the biomass C allocation.

$$LAI = (C_{leaf} + K_{leaf} f_{leaf} C_{pool} - C_{sens}) SLA \quad [6]$$

where K_{leaf} is the transformation rate of C going to leaf structure, f_{leaf} is a partitioning function from the non-structural reservoir to leaf pool, C_{sens} is the decay of vegetation tissues, and SLA is specific leaf area, a prescribed parameter based on the specific plant type, with lower SLA for longer leaf life span and thicker leaves as observed in nature (Arora and Boer, 2005).

The LAI is linked with crop phenology through the leaf growth index (GI). The GI describes the potential leaf growth and expansion according to several empirical parameters (Table 1), such as radiation extinction, leaf growth rate, and the duration of leaf expansion, shown by:

$$GI = \frac{1}{k_{rad}} \ln \left\{ \frac{1 + \exp[k_{grow} (D_{ac} - D_{ln})]}{1 + \exp[k_{grow} (D_{ac} - D_{ln}) - k_{rad} LAI_{max}]} \right\} \quad [7]$$

where k_{rad} is the light extinction coefficient, k_{grow} is maximum leaf relative growth rate, D_{ac} is GDD after leaf emergence, D_{ln} is GDD until leaf growth reaches a linear phase, and LAI_{max} is the maximum LAI. More detailed information about GI can be found in Ishag and Dennett (1998), Arain et al. (2002), and Yuan and Bland (2004).

RESULTS

Model Parameter Calibration

The modeling workflow was divided into two phases: pre-validation for the original CN-CLASS model with a set of fundamental parameters followed by examination of the modified CN-CLASS model. The model fundamental parameters (Table 1) are calibrated against observed latent heat flux (λE) and sensible heat flux (H), hourly ST at 10 cm and SWC in the 0- to 25-cm soil layer. Linear regression between observed and simulated hourly average and daily average values

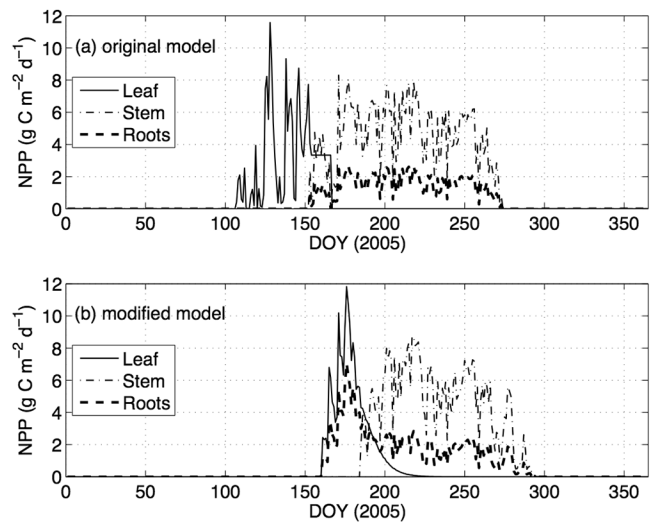


Fig. 2. The comparison of C allocation between the simulations of corn growth in 2005 from (a) the original CN-CLASS model and (b) the modified CN-CLASS model. The corresponding model parameters in the original CN-CLASS were identical to those in the modified CN-CLASS. The unit for component NPP is $g\ C\ m^{-2}\ d^{-1}$.

was used to calculate the coefficient of determination (R^2), intercept (INT), slope (S), and root mean square error (RMSE), which were used as relative indices of model performance.

In the pre-validation phase, the model showed a reasonable agreement with observed ST throughout 2005 and 2008 (RMSE = $1.99^\circ C$, $S = 0.95$, INT = $1.49^\circ C$, $R^2 = 0.96$, $p < 0.001$, $n = 35,040$). The model also captured the year-round tendency of SWC in the surface layer (RMSE = $0.10\ m^3\ m^{-3}$, $S = 0.64$, INT = $0.16\ m^3\ m^{-3}$, $R^2 = 0.51$, $p < 0.001$, $n = 35,040$). The model showed better agreement in corn simulations with observed latent heat flux (RMSE = $38.58\ W\ m^{-2}$, $S = 0.78$, INT = $22.23\ W\ m^{-2}$, $R^2 = 0.66$, $p < 0.001$, $n = 791$) than sensible heat flux (RMSE = $31.62\ W\ m^{-2}$, $S = 0.45$, INT = $3.51\ W\ m^{-2}$, $R^2 = 0.48$, $p < 0.001$, $n = 791$). The underestimated λE might be due to overestimation of ground heat flux (Arain et al., 2002; Kothavala et al., 2005) or to overestimation of the canopy resistance (Arora, 2003). The prescribed parameters were tested to ensure the ability to simulate the water and energy balance. The parameters were held constant during testing of the agricultural scheme for CN-CLASS.

Although the grain yields for the corn in 2005 and 2008 were overestimated by $\sim 200\ g\ C\ m^{-2}$, the long-term simulations showed a similar tendency to grain yield observations in most years. In the comparison between simulated and measured NEP, the simulated NEP had a fairly good agreement over a 9-yr simulation ($R^2 = 0.71$, RMSE = $1.9\ g\ C\ m^{-2}$, 0.64 , INT = $0.39\ g\ C\ m^{-2}$, $n = 2458$). The model results of aboveground and belowground biomass in 2005 and 2008 provided a reference for verifying the crop phenology scheme in CN-CLASS.

Crop Phenology

Figure 2a and 2b show the net primary productivity (NPP) allocation dynamics for leaves, stem, and roots in 2005 using the original and modified CN-CLASS, respectively. Figure 2a shows that the C fixation was initialized on 15 April (DOY 105) in the original CN-CLASS, which was about 30 d earlier than that of the modified CN-CLASS. The original model simulated a forest-type C allocation rather than crop phenology

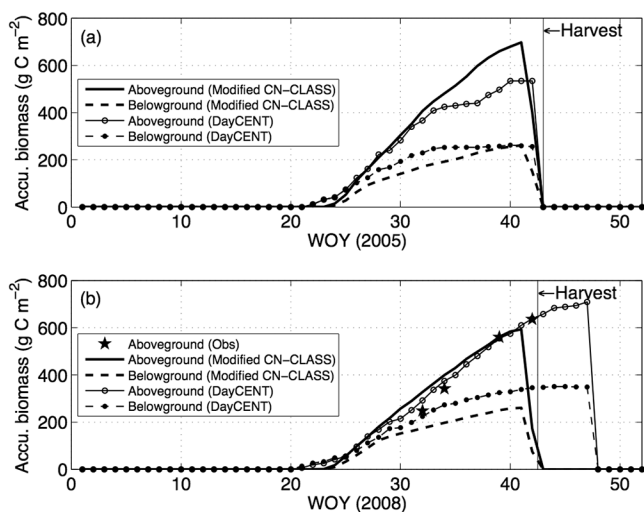


Fig. 3. The simulations of accumulated aboveground and belowground biomass using modified CN-CLASS and DayCENT for 2005 and 2008, respectively. The biomass output in CN-CLASS was accumulated to a weekly time-step to compare with DayCENT. The periodic aboveground biomass harvest measurements are shown in the 2008 simulation. The unit for accumulated biomass is g C m^{-2} .

development. With a given planting day and a simple crop phenology algorithm, the modified model shows the precise timing for crop development and a reasonable C allocation for crops, with assimilation going to roots and/or leaves at the same time (Fig. 2b).

Figure 3a and 3b show comparisons of accumulated aboveground and belowground NPP between DayCENT and the modified CN-CLASS for 2005 and 2008, respectively. The harvesting day was given to reflect the actual field condition and agricultural management practices (Table 1). Another

modeling study (Chang et al., 2013) at the ERS indicated that the validated DayCENT captured the dynamics of grain yield, heterotrophic respiration and NEP, which suggested that DayCENT can be used to simulate crop productivity as a reference to examine the simple crop phenology algorithm applied within CN-CLASS. Both models show a similar crop growth pattern in C allocation. The modified CN-CLASS captured the duration of crop growth, particularly in the period of harvest. The model underestimated the aboveground biomass at the end of the growing season of 2008 by only 5% based on the biomass measurements (Fig. 3b). The linear regression analysis indicated that the modified CN-CLASS model is capable of allocating C to aboveground biomass production ($R^2 = 0.98$, $\text{RMSE} = 34.4 \text{ g C m}^{-2}$, $S = 0.82$, $\text{INT} = 92.1 \text{ g C m}^{-2}$, $p < 0.001$, $n = 6$) in 2008.

To examine the performance of the crop phenology algorithm in the modified CN-CLASS with respect to allocation of assimilated C over the course of a year, we compared the aboveground and belowground NPP dynamics in 2005 and 2008, respectively (Fig. 4). In general, the modified CN-CLASS and DayCENT models display similar NPP tendencies throughout the growing season, and several periods with low C productivity were also present in both models. For example, lower NPP occurred after WOY 30 in 2005 and 2008, respectively. DayCENT shows that the onset of emergence began right after the sowing date, but it usually takes 3 wk for emergence at the ERS (Paul Voroney, personal communication, 2011). In the modified CN-CLASS, the model represented reasonable emergence timing around WOY 23 because a given GDD threshold for emergence and the accumulated GDD initialization is based on the planting date rather than the accumulation from the beginning of each year.

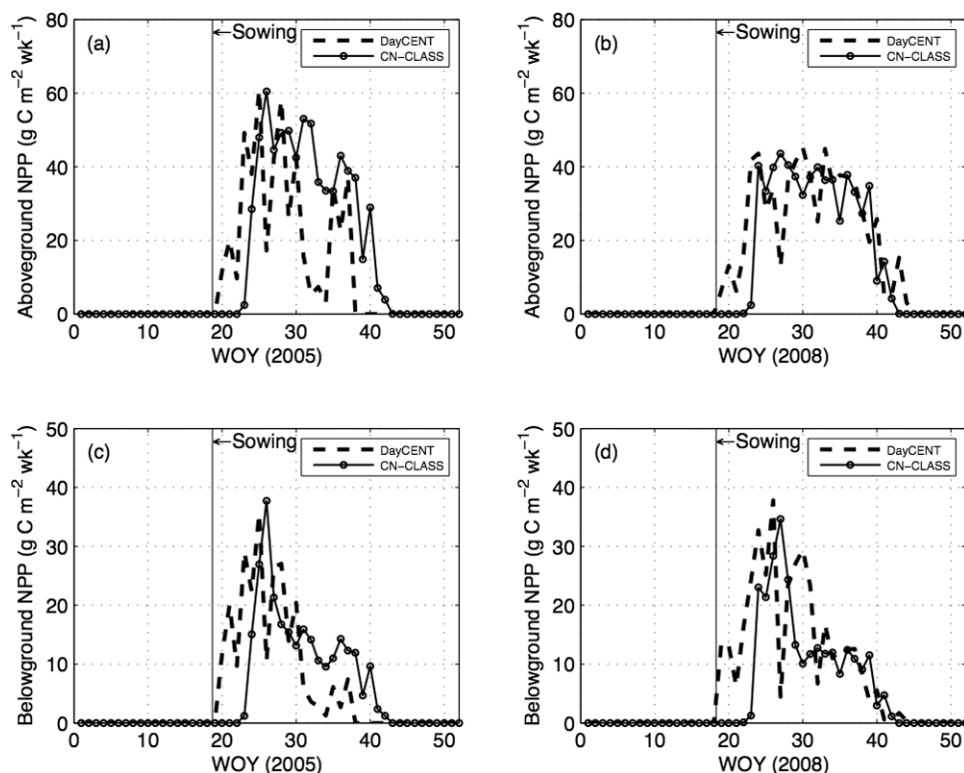


Fig. 4. The weekly dynamics of modeled aboveground and belowground biomass using DayCENT and modified CN-CLASS for 2005 and 2008, respectively. The vertical line indicates the date of sowing. The unit for weekly biomass is $\text{g C m}^{-2} \text{ wk}^{-1}$.

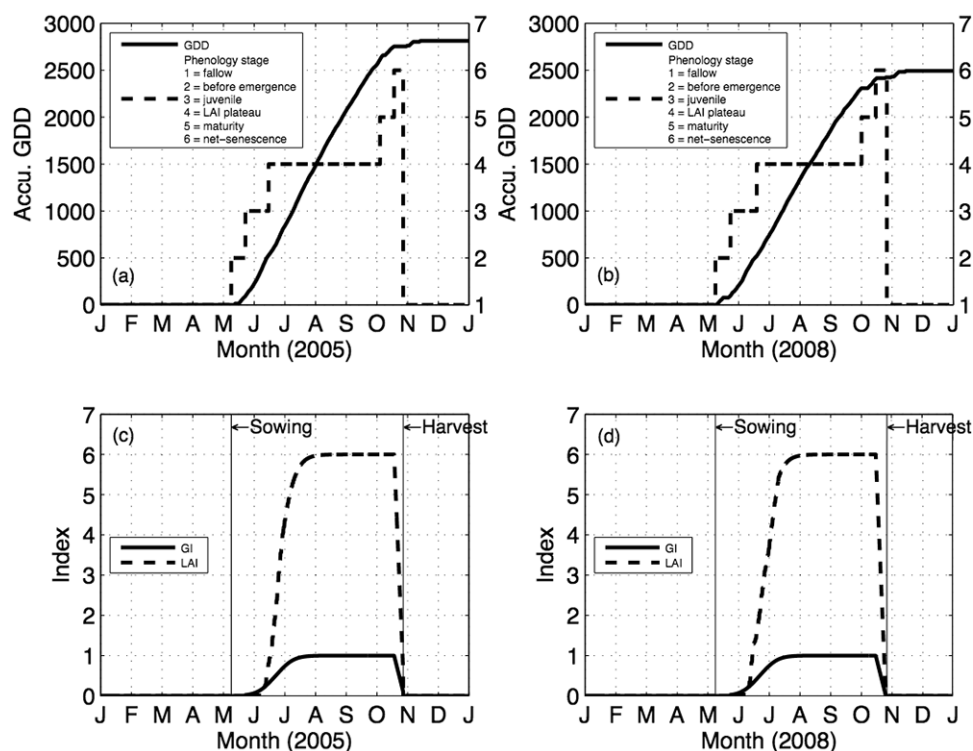


Fig. 5. The dynamics of (a–b) accumulated growing degree-day and phenology stage, and (c–d) growth index and leaf area index for 2005 and 2008, respectively. The vertical lines indicate the date of sowing and harvest, respectively.

Figure 5a and 5b show the accumulated GDD and its associated phenological stage for 2005 and 2008, respectively. The threshold for each phenological stage is based on the average accumulated GDD listed in Table 3. For corn crops, on average, the required GDDs for the juvenile stage and leaf canopy development are ~ 400 and 1780 to 2080°C d , respectively. Based on the general field assessment at the ERS, the juvenile period occurred from mid-May to mid-June followed by the period of canopy development (elongation) approaching maturity in October. The major period of GDD accumulation is during the middle of the growing season and lasts longer than other phenological stages as the stage index 4 occurred from June to September. A short period of senescence happened after mid-October before harvest. The modified CN-CLASS with crop-specific GDD thresholds simulated reasonably the seasonality of phenological development as shown in Fig. 2, 5a, and 5b.

As Fig. 1 showed, crop canopy development is related to LAI (Eq. [6]), and the relationship between crop phenology algorithms and LAI is controlled by GI (Eq. [7]). To see the tendencies over the period of leaf development, the LAI and GI for 2005 and 2008 are shown in Fig. 5c and 5d, respectively. The aboveground biomass was larger in the modified CN-CLASS until 14 October (DOY 287) and then tails off with the decrease in LAI; the conversion of senescent leaves to standing dead biomass occurred after canopy maturity. The growth pattern at the end of the growing season was regulated by the GDD threshold (Fig. 5a and 5b) because the timing and duration of senescence were linked with the GDD-associated crop phenology.

Carbon Exchanges

Figure 6a shows the modeled NEP ranging from 0.5×10^{-3} to $-0.1 \times 10^{-3} \text{ g C m}^{-2} \text{ s}^{-1}$, which followed the diurnal NEP patterns. Days with underestimated NEP (12–14 and

19–20 August) might be related to an underestimation of photosynthesis under low-light conditions (i.e., weaker short-wave radiation, stronger long-wave radiation, and higher specific humidity). Figure 6b demonstrates that the new crop phenological scheme in CN-CLASS provides an effective method to reshape the seasonal NEP tendency in a cornfield. The simulation suggests that our cornfield acted as a net sink of atmospheric CO_2 during June and July with 497.5 g C m^{-2} stored, and as a net source during the post-harvest period (October) with 5.2 g C m^{-2} released. At the time of harvest (DOY 301), there was an observed peak of CO_2 released to the atmosphere $\sim 2.5 \text{ g C m}^{-2} \text{ d}^{-1}$, which was also captured by the model. Figure 6c shows that the best-fit line for the modified CN-CLASS (RMSE = $2.3 \text{ g C m}^{-2} \text{ d}^{-1}$, $S = 0.90$, INT = -0.33) was closer to the 1:1 line than the original model (RMSE = $3.6 \text{ g C m}^{-2} \text{ d}^{-1}$, $S = 0.50$, INT = -0.54). In addition, the coefficient of determination (R^2) of 0.78 in the modified model was higher than 0.51 in the original CN-CLASS.

DISCUSSION

Predetermining vegetation phenology in terms of known values (e.g., dominant plant functional type, LAI and C allocation) is the most common approach used by land surface models (Lokupitiya et al., 2009; Schaefer et al., 2012). In agroecosystems, having a specific phenology algorithm for each crop species is particularly important to estimate the C cycles as well as interactions and feedback among vegetation, climate, and water more accurately. This study obtained results from the pre-validated DayCENT model and field measurements at ERS to modify CN-CLASS for use with corn crops. Once the crop-specific phenology scheme is verified, the parameters in the crop scheme can be refined for other crop species. Other researchers can adopt this new modification for crop phenology to

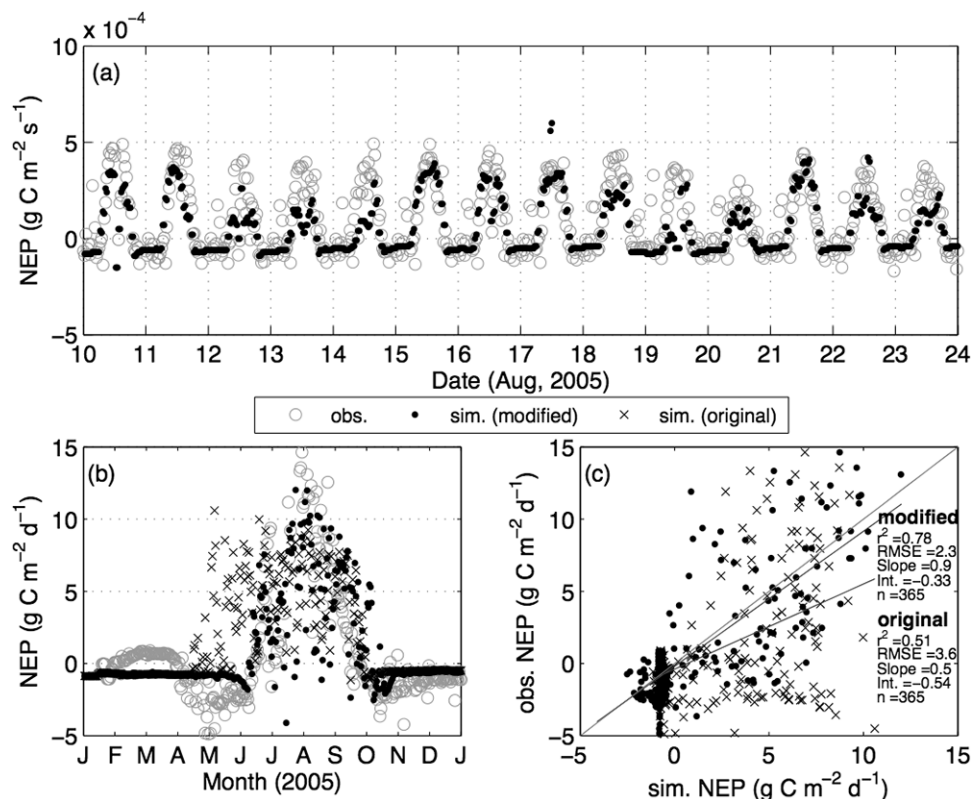


Fig. 6. The NEP from eddy covariance C flux measurements, modified and original CN-CLASS; (a) half-hourly time-step during the period of 10–24 Aug. 2005; (b) daily time-step in 2005; and (c) the comparison between daily observed and simulated NEP in 2005. The straight lines indicate the regression lines for 1:1 line, modified model and original model, respectively. The unit for half-hourly and daily is $\text{g C m}^{-2} \text{s}^{-1}$ and $\text{g C m}^{-2} \text{d}^{-1}$, respectively.

investigate topics such as the impact of changing environmental variables on C productivity.

Schwalm et al. (2010) compared NEP model performance at various biome levels and found that most of the land surface models were generally poor or the modeling architectures (parameterization and initialization) were not established for the C exchange simulations for croplands. This study demonstrated a simple modification in CN-CLASS that could lead to a better simulation and application of the model for agriculture. This crop phenology architecture in CN-CLASS can be further verified for other crops by modifying the C allocation fractions and the GDD thresholds for the phenological stages. In this study, crop phenology is composed of six life-cycle phases throughout a year for corn crops. The response of crop phenology development to temperature is a linear function of the mean daily temperature above an effective threshold temperature. Transitions between the phenological stages occur at prescribed thresholds of accumulated GDD. Based on this concept, crop emergence and subsequent growth stages were set based on the accumulated GDD. Based on several referenced GDD thresholds (Buyanovsky and Wagner, 1986; Tsvetinskaya et al., 2001; Gervois et al., 2004; McMaster et al., 2005), the GDD thresholds for corn crops in this study were averaged for each phenology stage (see Table 3). The GDD accumulation in the crop module was initially based on the prescribed crop planting dates, which differed from the GDD accumulation from the beginning of each year for forest ecosystems in the original CN-CLASS. An accurate planting date is particularly important to simulations of crop yields or of the effects of croplands on energy and water balances in the land surface

models. The harvest date was also given based on field records and used to determine the end of GDD accumulation (if earlier than when the GDD accumulation for maturity would be reached) and decomposition of post-harvest biomass. Since the planting and harvesting dates may vary depending on the year and on field conditions, crop development could be sensitive to the thresholds of GDD accumulation and planting date. Sacks et al. (2010) pointed out that precise planting date information (i.e., datasets) ensures proper crop development estimations. However, simulations at a single location require specifying the planting and harvesting dates. For simulations over a larger area, the initialization of GDD accumulation could benefit from a data set of crop planting and harvesting dates for major crops (Sacks et al., 2010). The availability of GDD statistics for each phenological stage allows process-based models to estimate the crop life cycle and thus, the C source/sink status more precisely. In this study, six phenology stages were modeled based on the thresholds of GDD accumulations. These stage categories can be further modified for other crop species.

Another essential modification in CN-CLASS for agriculture was to apply a modeling mechanism of anthropogenic influences (Gervois et al., 2004): a crop index for initializing the crop module and agricultural management practices for regulating C/N dynamics and GDD calculation. We created a vegetation index for crop-type species for the original CN-CLASS, which only has a forest-type module. This vegetation index in the modified model initializes the crop module (model architecture and parameters), which allows us to adopt crop phenology algorithms and parameters in the model architecture and also apply the model for both forests and agriculture. The agricultural

practices included the planting/harvest dates as well as the type and amount of fertilizer and its application date. These agricultural practices modulated the timing and duration of the growth cycle, and C/N pool development. The indices and parameters (see Table 1) used in the C/N allocation can be adjusted for different crops, growth stages, and plant pools based on the architecture in this study. In CN-CLASS, LAI was used to calculate photosynthesis to constrain leaf growth (Eq. [1]) and was further shaped by GI (Eq. [7]) during leaf emergence and after full canopy development (Fig. 5c and 5d). We found that the architecture of the LAI function could be different from other crop models. For example, in the SiBcrop (Lokupitiya et al., 2009), LAI was derived from remote sensing and particularly useful for regional simulations. In the modified CN-CLASS model, the LAI approach was derived from process-based functions with prescribed parameters (Eq. [6]), which might be easily calibrated on a small scale.

By following the photosynthetic pathway in the original CN-CLASS model, the C allocation is initialized by the assimilated C pool for a crop. In the original model, the sequence of allocation to various pools followed a mature forest growth pattern that prescribes root growth following leaf growth (Dickinson et al., 1998). For crops, as Abrahamsen and Hansen (2000) suggested, the C assimilation partitioning to roots is regulated by the phenological stage and the partitioning factors associated with each stage. As Fig. 2 showed, the original model simulated typical forest growth and dynamics of assimilated C pools; the modified model was implemented to simulate reasonable C pool dynamics for crops as opposed to forests.

In particular, the growth rate during the initial emergence phase was determined by the amount of C stored in the seeds in the modified model. The reserved C for corn crops was set to $0.002 \text{ kg C m}^{-2}$ (Krinner et al., 2005) and the assimilated C was allocated to the C pools (Table 3). Chevalier and Schrader (1977), Nakaseko et al. (1978) and Anderson (1988) indicated that the proportion of C allocation varied throughout phenological development and between specific species. In this study, the partitioning factors, X_{root} , X_{leaf} , and X_{stem} , control the proportion of C allocation from assimilated photosynthate to the three biomass pools. The root/shoot ratios can decrease during growth from 0.45 to 0.10, depending on the corn plant age, hybrid and soil volume. Three major vegetation components were calculated sequentially by the different partitioning factors. The reserve C pool goes to the roots during the period between sowing and emergence (Stage 2). Based on Johnson and Thornley (1987) and Gregory et al. (1995), the partitioning factor for roots ($X_{\text{root,stage}}$) decreases from 0.55 (Stage 3) to 0.25 (Stage 4). The fraction of C partitioning to stem ($X_{\text{stem,stage}}$) increases from 0.45 to 0.75 (Buyanovsky and Wagner, 1986) as listed in Table 2.

The seasonal dynamics and diurnal changes of NEP were better simulated using the modified CN-CLASS (RMSE = $2.3 \text{ g C m}^{-2} \text{ d}^{-1}$, $R^2 = 0.78$, $S = 0.90$, INT = -0.33) compared with the original model (RMSE = $3.6 \text{ g C m}^{-2} \text{ d}^{-1}$, $R^2 = 0.51$, $S = 0.50$, INT = -0.54). The C exchange prediction capability (R^2) has been improved from 0.51 to 0.78 and RMSE decreased from 3.6 to $2.3 \text{ g C m}^{-2} \text{ d}^{-1}$. In particular, due to the ability to have more precise control over crop phenology in the model rather than applying a forest model for a corn field, the modified model captured the onset of C sink and the C sink/source

transition after harvest (Fig. 6b). The total C sink during the growing season (i.e., June–September) was estimated as 641 and 478 g C m^{-2} by using the original and modified CN-CLASS model, respectively. The modified model estimated a cumulative NEP close to the observed 437 g C m^{-2} ; the original model overestimated annual NEP by 204 g C m^{-2} . The estimated C source was 5.2 and 50.3 g C m^{-2} from the effect of post-harvest in October and the effect of thaw during April and May, respectively. These results are consistent with our field measurements at ERS. The modified CN-CLASS constrained most of the larger simulated NEP (i.e., large obs./sim. NEP differences) in the original model (Fig. 6c). The modified model may not simulate well some large eddy covariance C fluxes. These larger overestimated or underestimated NEP in the modified model may be caused by other factors that the model was not designed for, such as water stress, insects, and other disturbances. In addition, the C uptake by weed growth and the decomposition of crop residues from previous years were not considered in this study. Therefore, the C exchange was not well simulated in the pre-emergence period. Further improvements can be made by including dynamic litter and SOC pools from a multi-year agroecosystem simulation.

A simple crop phenology algorithm in CN-CLASS was verified to simulate the overall C allocation, productivity, and C exchange. Due to the minimal dataset available at ERS over the two corn years of this study, further testing of the algorithms at different locations, with multiple crops and genotypes should be undertaken before the model is employed within a climate change scenario. The current modeling approach falls within the accepted practices of parameterization for surface schemes, but it is acknowledged that many of the finer details of crop development are not explicitly represented. Modellers employing surface schemes (off-line or within GCMs) for climate-C-balance studies need to be aware of the limitations of such parameterizations for representing the responses to variability and extremes, and of progress made with more detailed models.

CONCLUSION

This study demonstrated that a simple modification in the Carbon Nitrogen coupled Canadian Land Surface Scheme (CN-CLASS) has the capability to simulate C dynamics in a crop field. The modifications to CN-CLASS included the thresholds of crop-specific GDD for each phenological stage, allocation functions that linked with the phenological algorithm, and an agricultural schedule that regulated the growth duration.

Overall, compared with the original CN-CLASS, the C allocation simulation in our modified model agreed with the aboveground biomass measurements and with the DayCENT agricultural model. By adopting an agricultural scheme, the model suggested that 5.2 and 50.3 g C m^{-2} were released during the period of post-harvest and thaw, respectively. The total C sink during the growing season from June to September was estimated at 477.5 g C m^{-2} , which was close to the observed NEP at 436.7 g C m^{-2} . The coefficient of determination (R^2) of annual NEP simulation was increased from 0.51 to 0.78, and root mean square error (RMSE) was decreased from 3.6 to $2.3 \text{ g C m}^{-2} \text{ d}^{-1}$. The overall C exchange simulations were largely improved to capture the onset of C sink and the C sink/source transition after harvest.

The advantage of the new phenology scheme within CN-CLASS includes a plant functional type index, which can be evaluated against the C cycles in forests and crop fields, heterogeneity of ecosystems, and realistic C fluxes. The crop phenology scheme was tested in only two individual years in a corn field; therefore, future improvements can be made by providing the dynamic litter and SOC pools and replicating the results using other crop species in a multi-year agroecosystem simulation.

REFERENCES

- Abrahamsen, P., and S. Hansen. 2000. Daisy: An open soil-crop-atmosphere system model. *Environ. Model. Softw.* 15:313–330. doi:10.1016/S1364-8152(00)00003-7
- Anderson, E.L. 1988. Tillage and N-fertilization effects on maize root growth and and root:shoot ratio. *Plant Soil* 108:245–251. doi:10.1007/BF02375655
- Arain, M.A., T.A. Black, A.G. Barr, P.G. Jarvis, J.M. Massheder, D.L. Verseghy, and Z. Nescic. 2002. Effects of seasonal and interannual climate variability on net ecosystem productivity of boreal deciduous and conifer forests. *Can. J. For. Res.* 32:878–891. doi:10.1139/x01-228
- Arain, M.A., F.M. Yuan, and T.A. Black. 2006. Soil-plant nitrogen cycling modulated carbon exchanges in a western temperate conifer forest in Canada. *Agric. For. Meteorol.* 140:171–192. doi:10.1016/j.agrformet.2006.03.021
- Arora, V.K. 2003. Simulating energy and carbon fluxes over winter wheat using coupled land surface and terrestrial ecosystem models. *Agric. For. Meteorol.* 118:21–47. doi:10.1016/S0168-1923(03)00073-X
- Arora, V.K., and G.J. Boer. 2005. A parameterization of leaf phenology for the terrestrial ecosystem component of climate models. *Glob. Change Biol.* 11:39–59. doi:10.1111/j.1365-2486.2004.00890.x
- Bondeau, A., P.C. Smith, S. Zaehle, S. Schaphoff, W. Lucht, and W. Cramer. 2007. Modelling the role of agriculture for the 20th century global terrestrial carbon balance. *Glob. Change Biol.* 13(3):679–706. doi:10.1111/j.1365-2486.2006.01305.x
- Bonan, G. 1996. A land surface model (LSM v 1.0) for ecological, hydrological and atmospheric studies: Technical description and user guide. NCAR/TN-417+STR. National Center for Atmospheric Research, Boulder, CO.
- Buyanovsky, G.A., and G.H. Wagner. 1986. Postharvest residue input to cropland. *Plant Soil* 93:57–65. doi:10.1007/BF02377145
- Brisson, N., B. Mary, D. Ripoche, M.H. Jeuffroy, F. Ruget, B. Nicoulaud, P. Gate, F. Devienne-Barret, R. Antonioletti, C. Durr, G. Richard, N. Beaudoin, S. Recous, X. Tayot, D. Plenet, P. Cellier, J.M. Machet, J.M. Meynard, and R. Delecolle. 1998. STICS: A generic model for the simulation of crops and their water and nitrogen balances. I. Theory and parameterization applied to wheat and corn. *Agronomie* 18:311–346. doi:10.1051/agro:19980501
- Cannell, M.G.R., and R.C. Dewar. 1994. Carbon allocation in trees: A review of concepts for modeling. *Adv. Ecol. Res.* 25:59–104. doi:10.1016/S0065-2504(08)60213-5
- Challinor, A.J., T.R. Wheeler, P.Q. Craufurd, J.M. Slingo, and D.I.F. Grimes. 2004. Design and optimisation of a large-area process-based model for annual crops. *Agric. For. Meteorol.* 124:99–120. doi:10.1016/j.agrformet.2004.01.002
- Chang, K.H., J. Warland, P. Voroney, P. Bartlett, and C. Wagner-Riddle. 2013. Using DayCENT to simulate carbon dynamics in conventional and no-till agriculture. *Soil Sci. Soc. Am. J.* 77(3):941–950. doi:10.2136/sssaj2012.0354
- Chevalier, P., and L.E. Schrader. 1977. Genotypic differences in nitrate absorption and partitioning of N among plant parts in maize. *Crop Sci.* 17:897–901. doi:10.2135/cropsci1977.0011183X0017000600020x
- Chmielewski, F.M., and T. Rotzer. 2001. Response of tree phenology to climate change across Europe. *Agric. For. Meteorol.* 108:101–112. doi:10.1016/S0168-1923(01)00233-7
- Del Grosso, S.J., A.D. Halvorson, and W.J. Parton. 2008. Testing DayCENT model simulations of corn yields and nitrous oxide emissions in irrigated tillage systems in Colorado. *J. Environ. Qual.* 37:1383–1389. doi:10.2134/jeq2007.0292
- Dickinson, R.E., M. Shaikh, R. Bryant, and L. Graumlich. 1998. Interactive canopies for a climate model. *J. Clim.* 11:2823–2836. doi:10.1175/1520-0442(1998)0112.0.CO;2
- Falge, E., D. Baldocchi, R. Olson, P. Anthoni, M. Aubinet, C. Bernhofer, G. Burba, R. Ceulemans, R. Clement, H. Dolman, A. Granier, P. Gross, T. Grunwald, D. Hollinger, N.O. Jensen, G. Katul, P. Keronen, A. Kowalski, C.T. Lai, B.E. Law, T. Meyers, H. Moncrieff, E. Moors, J.W. Munger, K. Pilegaard, U. Rannik, C. Rebmann, A. Suyker, J. Tenhunen, K. Tu, S. Verma, T. Vesala, K. Wilson, and S. Wofsy. 2001. Gap filling strategies for defensible annual sums of net ecosystem exchange. *Agric. For. Meteorol.* 107:43–69. doi:10.1016/S0168-1923(00)00225-2
- Fallow, D.J., D.M. Brown, G.W. Parkin, J.D. Lauzon, and C. Wagner-Riddle. 2003. Identification of critical regions for water quality monitoring with respect to seasonal and annual water surplus. Technical Report 1. Dep. of Land Resource Science, University of Guelph, ON, Canada.
- Foley, J.A., R. DeFries, G.P. Asner, C. Barford, G. Bonan, and S.R. Carpenter. 2005. Global consequences of land use. *Science* 309(5734):570–574. doi:10.1126/science.1111772
- Gervois, S., N. de Noblet-Ducoudré, N. Viovy, P. Ciais, N. Brisson, B. Seguin, and A. Perrier. 2004. Including croplands in a global biosphere model: Methodology and evaluation at specific sites. *Earth Interact.* 8:1–25. doi:10.1175/1087-3562(2004)82.0.CO;2
- Gower, S.T., J.G. Vogel, J.M. Norman, C.J. Kucharik, S.J. Steele, and T.K. Stow. 1997. Carbon distribution and aboveground net primary production in aspen, jack pine, and black spruce stands in Saskatchewan and Manitoba, Canada. *J. Geophys. Res. Atmospheres* 102:29029–29041. doi:10.1029/97JD02317
- Gregory, P.J., J.A. Palta, and G.R. Batts. 1995. Root systems and root:mass ratio—carbon allocation under current and projected atmospheric conditions in arable crops. *Plant Soil* 187:221–228. doi:10.1007/BF00017089
- Hansen, J.W., A. Challinor, A. Ines, T. Wheeler, and V. Moron. 2006. Translating climate forecasts into agricultural terms: Advances and challenges. *Clim. Res.* 33:27–41. doi:10.3354/cr033027
- Ishag, K.H.M., and M.D. Dennett. 1998. Use of the expolinear growth model to analyse the growth of faba bean, peas and lentils at three densities: Fitting the model. *Ann. Bot. (London)* 82:497–505. doi:10.1006/anbo.1998.0708
- Jayasundara, S., C. Wagner-Riddle, G. Parkin, P. von Bertoldi, J. Warland, B. Kay, and P. Voroney. 2007. Minimizing nitrogen losses from a corn-soybean-winter wheat rotation with best management practices. *Nutr. Cycl. Agroecosyst.* 79:141–159. doi:10.1007/s10705-007-9103-9
- Johnson, I.R., and J.H.M. Thornley. 1987. A model of shoot–root partitioning with optimal growth. *Ann. Bot. (London)* 60:133–142.
- Kothavala, Z., M.A. Arain, T.A. Black, and D. Verseghy. 2005. The simulation of energy, water vapor and carbon dioxide fluxes over common crops by the Canadian Land Surface Scheme (CLASS). *Agric. For. Meteorol.* 133:89–108. doi:10.1016/j.agrformet.2005.08.007
- Krinner, G., N. Viovy, N. de Noblet-Ducoudré, J. Ogee, J. Polcher, P. Friedlingstein, P. Ciais, S. Sitch, and I.C. Prentice. 2005. A dynamic global vegetation model for studies of the coupled atmosphere-biosphere system. *Global Biogeochem. Cycles* 19:1015. doi:10.1029/2003GB002199
- Kucharik, C.J., and K.R. Brye. 2003. Integrated Biosphere Simulator (IBIS) yield and nitrate loss predictions for Wisconsin maize receiving varied amounts of nitrogen fertilizer. *J. Environ. Qual.* 32:247–268.
- Lei, H., D. Yang, E. Lokupitiya, and Y. Shen. 2010. Coupling land surface and crop growth models for predicting evapotranspiration and carbon exchange in wheat-maize rotation croplands. *Biogeosciences* 7:3363–3375. doi:10.5194/bg-7-3363-2010
- Li, X.Y., T. Meixner, J.O. Sickman, A.E. Miller, J.P. Schimel, and J.M. Melack. 2006. Decadal-scale dynamics of water, carbon and nitrogen in a California chaparral ecosystem: DayCENT modeling results. *Biogeochemistry* 77:217–245. doi:10.1007/s10533-005-1391-z
- Litton, C.M., M.G. Ryan, D.B. Tinker, and D.H. Knight. 2003. Below-ground and above-ground biomass in young postfire lodgepole pine forests of contrasting tree density. *Can. J. For. Res.* 33:351–363. doi:10.1139/x02-181
- Liu, W.D., and M. Tollenaar. 2009. Response of yield heterosis to increasing plant density in maize. *Crop Sci.* 49:1807–1816. doi:10.2135/cropsci2008.07.0422
- Lokupitiya, E., S. Denning, K. Paustian, I. Baker, K. Schaefer, S. Verma, T. Meyers, C.J. Bernacchi, A. Suyker, and M. Fischer. 2009. Incorporation of crop phenology in simple biosphere model (SiBcrop) to improve land-atmosphere carbon exchanges from croplands. *Biogeosciences* 6:969–986. doi:10.5194/bg-6-969-2009
- Marcelis, L.F.M., and E. Heuvelink. 2007. Concepts of modelling carbon allocation among plant organs. *Wageningen Frontiers Ser.* 22:103–111.

- McMaster, G.S. 2005. Phytomers, phyllochrons, phenology and temperate cereal development. *J. Agric. Sci.* 143:137–150. doi:10.1017/S0021859605005083
- McMaster, G.S., and W.W. Wilhelm. 1997. Growing degree-days: One equation, two interpretations. *Agric. For. Meteorol.* 87:291–300. doi:10.1016/S0168-1923(97)00027-0
- McMaster, G.S., W.W. Wilhelm, and A.B. Frank. 2005. Developmental sequences for simulating crop phenology for water-limiting conditions. *Aust. J. Agric. Res.* 56:1277–1288. doi:10.1071/AR05068
- Medlyn, B.E., E. Dreyer, D. Ellsworth, M. Forstreuter, P.C. Harley, M.U.F. Kirschbaum, X. Le Roux, P. Montpied, J. Strassmeyer, A. Walcroft, K. Wang, and D. Loustau. 2002a. Temperature response of parameters of a biochemically based model of photosynthesis. II. A review of experimental data. *Plant Cell Environ.* 25:1167–1179. doi:10.1046/j.1365-3040.2002.00891.x
- Medlyn, B.E., D. Loustau, and S. Delzon. 2002b. Temperature response of parameters of a biochemically based model of photosynthesis. I. Seasonal changes in mature maritime pine (*Pinus pinaster* Ait.). *Plant Cell Environ.* 25:1155–1165. doi:10.1046/j.1365-3040.2002.00890.x
- Mueller, L., B.D. Kay, C. Hu, Y. Li, U. Schindler, A. Behrendt, T.G. Shepherd, and B.C. Ball. 2009. Visual assessment of soil structure: Evaluation of methodologies on sites in Canada, China and Germany. Part I: Comparing visual methods and linking them with soil physical data and grain yield of cereals. *Soil Tillage Res.* 103:178–187. doi:10.1016/j.still.2008.12.015
- Nakaseko, K., K. Gotoh, and H. Sato. 1978. Physio-ecological studies of prolificacy in maize. III. The relationships between expression of second ear and some physico-ecological characteristics. *Jpn. J. Crop. Sci.* 47:212–220. doi:10.1626/jcs.47.212
- Oleson, K.W., G.Y. Niu, Z.L. Yang, D.M. Lawrence, P.E. Thornton, and P.J. Lawrence. 2008. Improvements to the Community Land Model and their impact on the hydrological cycle. *J. Geophys. Res.* 113:G01021. doi:10.1029/2007JG000563
- Osborne, T.M., D.M. Lawrence, A.J. Challinor, J.M. Slingo, and T.R. Wheeler. 2007. Development and assessment of a coupled crop-climate model. *Glob. Change Biol.* 13:169–183. doi:10.1111/j.1365-2486.2006.01274.x
- Parton, W.J., M. Hartman, D. Ojima, and D. Schimel. 1998. DayCENT and its land surface submodel: Description and testing. *Global Planet. Change* 19:35–48. doi:10.1016/S0921-8181(98)00040-X
- Ramankutty, N., and J.A. Foley. 1999. Estimating historical changes in global land cover: Croplands from 1700 to 1992. *Global Biogeochem. Cycles* 13(4):997–1027. doi:10.1029/1999GB900046
- Raupach, M.R., P.J. Rayner, D.J. Barrett, R.S. DeFries, M. Heimann, D.S. Ojima, S. Quegan, and C.C. Schmullius. 2005. Model-data synthesis in terrestrial carbon observation: Methods, data requirements and data uncertainty specifications. *Glob. Change Biol.* 11:378–397. doi:10.1111/j.1365-2486.2005.00917.x
- Reich, P.B., M.B. Walters, and D.S. Ellsworth. 1997. From tropics to tundra: Global convergence in plant functioning. *Proc. Natl. Acad. Sci. USA* 94:13730–13734. doi:10.1073/pnas.94.25.13730
- Ritchie, S.W., J.J. Hanway, and G.O. Benson. 1986. How a corn plant develops. Special report 48. Iowa State University of Science and Technology, Cooperative Extension Service, Ames, IA.
- Sacks, W.J., D. Deryng, J.A. Foley, and N.A. Ramankutty. 2010. Crop planting dates: An analysis of global patterns. *Glob. Ecol. Biogeogr.* 19:607–620.
- Schaefer, K., C.R. Schwalm, C. Williams, M.A. Arain, A. Barr, and J.M. Chen. 2012. A model-data comparison of gross primary productivity: Results from the North American Carbon Program site synthesis. *J. Geophys. Res.* 117:G03010. doi:10.1029/2012JG001960
- Schulze, E.D., F.M. Kelliher, C. Korner, J. Lloyd, and R. Leuning. 1994. Relationships among maximum stomatal conductance, ecosystem surface conductance, carbon assimilation rate, and plant nitrogen nutrition—a global ecology scaling exercise. *Annu. Rev. Ecol. Syst.* 25:629–660. doi:10.1146/annurev.es.25.110194.003213
- Schwalm, C.R., C.A. Williams, K. Schaefer, R. Anderson, M.A. Arain, and I. Baker. 2010. A model-data intercomparison of CO₂ exchange across North America: Results from the North American Carbon Program site synthesis. *J. Geophys. Res.* 115:G00H05. doi:10.1029/2009JG001229
- Smil, V. 1999. Nitrogen in crop production: An account of global flows. *Global Biogeochem. Cycles* 13:647–662. doi:10.1029/1999GB900015
- Stehfest, E., M. Heistermann, J.A. Priess, D.S. Ojima, and J. Alcamo. 2007. Simulation of global crop production with the ecosystem model DayCENT. *Ecol. Modell.* 209:203–219. doi:10.1016/j.ecolmodel.2007.06.028
- Tsvetinskaya, E.A., L.O. Mearns, and W.E. Easterling. 2001. Investigating the effect of seasonal plant growth and development in three-dimensional atmospheric simulations. Part I: Simulation of surface fluxes over the growing season. *J. Clim.* 14:692–709. doi:10.1175/1520-0442(2001)0142.0.CO;2
- Turner, D.P., S.A. Acker, J.E. Means, and S.L. Garman. 2000. Assessing alternative allometric algorithms for estimating leaf area of Douglas-fir trees and stands. *For. Ecol. Manage.* 126:61–76. doi:10.1016/S0378-1127(99)00083-3
- Van den Hoof, C., E. Hanert, and P.L. Vidale. 2011. Simulating dynamic crop growth with an adapted land surface model—JULES-SUCROS: Model development and validation. *Agric. For. Meteorol.* 151(2):137–153. doi:10.1016/j.agrformet.2010.09.011
- Verseghy, D. 1991. CLASS—a Canadian land surface scheme for GCMs. 1. Soil model. *Int. J. Climatol.* 11:111–133. doi:10.1002/joc.3370110202
- Verseghy, D., N. McFarlane, and M. Lazare. 1993. CLASS—a Canadian land-surface scheme for GCMs. 2. Vegetation model and coupled runs. *Int. J. Climatol.* 13:347–370. doi:10.1002/joc.3370130402
- Wagner-Riddle, C., A. Furon, N.L. McLaughlin, I. Lee, J. Barbeau, S. Jayasundara, G. Parkin, P. Von Bertoldi, and J. Warland. 2007. Intensive measurement of nitrous oxide emissions from a corn-soybean-wheat rotation under two contrasting management systems over 5 years. *Glob. Change Biol.* 13:1722–1736. doi:10.1111/j.1365-2486.2007.01388.x
- Wanniarachchi, S.D., R.P. Voroney, T.J. Vyn, R.P. Beyaert, and A.F. MacKenzie. 1999. Tillage effects on the dynamics of total and corn-residue-derived soil organic matter in two southern Ontario soils. *Can. J. Soil Sci.* 79:473–480. doi:10.4141/S97-096
- Wilton, M. 2010. The use of natural abundance carbon-13 to identify and quantify sources of emitted carbon dioxide in a calcareous southern Ontario Luvisolic soil. M.S. diss. University of Guelph, ON, Canada.
- Yuan, F.M., M.A. Arain, A.G. Barr, T.A. Black, C.P.A. Bourque, C. Coursolle, H.A. Margolis, J.H. McCaughey, and S.C. Wofsy. 2008. Modeling analysis of primary controls on net ecosystem productivity of seven boreal and temperate coniferous forests across a continental transect. *Glob. Change Biol.* 14:1765–1784. doi:10.1111/j.1365-2486.2008.01612.x
- Yuan, F.M., M.A. Arain, T.A. Black, and K. Morgenstern. 2007. Energy and water exchanges modulated by soil-plant nitrogen cycling in a temperate pacific northwest conifer forest. *Ecol. Modell.* 201:331–347. doi:10.1016/j.ecolmodel.2006.10.023
- Yuan, F.M., and W.L. Bland. 2004. Light and temperature modulated exponential growth model for potato (*Solanum tuberosum* L.). *Agric. For. Meteorol.* 121:141–151. doi:10.1016/j.agrformet.2003.08.032