Using DayCENT to Simulate Carbon Dynamics in Conventional and No-Till Agriculture

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The DayCENT model was employed to simulate the effects of conventional tillage (CT) and no-till (NT) practices on the dynamics of soil organic carbon (SOC) over 9 yr in a rotational cropping system in Southern Ontario, Canada. Observations of site properties and eddy covariance measurements were used to assess crop productivity, net ecosystem productivity (NEP), and SOC changes. The validated model captured the dynamics of grain yield and net primary production, which indicated that DayCENT can be used to simulate crop productivity for evaluating the effects of tillage on crop residues and heterotrophic respiration (R_h) dynamics. The simulation suggested that CT enhanced the annual R_h relative to NT by 38.4, 93.7 and 64.2 g C m^{-2} yr^{-1} for corn (*Zea mays* L.), soybean [*Glycine max* (L.) Merr], and winter wheat (*Triticum aestivum L.*), respectively. The combined effect of incorporating crop residues and increased cultivation factors enhanced R_h in CT by 35% relative to NT after disk cultivation in the spring. The simulated NEP varied with crop species, tillage practices, and timing/length of the growing season. The seasonal variation of the total SOC pool was greater in CT than NT because of tillage effects on C transfer from the active surface SOC pool to the active soil SOC pool at a rate of 50 to 100 g C m^{-2} yr^{-1}. The NT method practiced during the study period accounted for a 10.7 g C m^{-2} yr^{-1} increase in the slow SOC pool. The validated DayCENT model may be applied for longer-term simulations in similar ecosystems for a variety of climate change experiment.

Abbreviations: CT, conventional tillage; DOY, day of year; ERS, Elora Research Station; GDD, growing degree days; NEP, net ecosystem productivity; NPP, net primary production; NT, no-till; PPT, accumulated monthly precipitation; R_H, heterotrophic respiration; SOC, soil organic carbon; ST, soil temperature; SWC, soil water content.

The C budget in agriculture has been studied in association with strategies for mitigating climate warming (Freibauer et al., 2004; Lal, 2004; Paustian et al., 2000; West and Post, 2002), so it is important to ensure the reliability of estimates of C cycle components from C flux measurements and process-based models. This study uses the daily version of the CENTURY model (DayCENT, Version 4.5) to simulate the effects of agricultural management practices on long-term R_h, NEP, and SOC dynamics at a rotational crop field in Elora, Southern Ontario, Canada.

Estimates of R_h are crucial for describing soil biological activity and biogeochemical processes (Rochette et al., 1999). They account for a considerable amount of total global CO_2 emissions at 77 to 98 ± 12 Pg C yr^{-1} (Bond-Lamberty and Thomson, 2010; Davidson and Janssens, 2006; Jenkinson et al., 1991). In agriculture, tillage practices influence the process of SOC decomposition, and thus can modify R_h. However, there are still open questions regarding differences in SOC levels and R_h rates between CT and NT practices.

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Contrasting effects of tillage on SOC dynamics have been reported in various regions. VandenBygaart et al. (2003) reported an increased storage of SOC in western Canada using NT practices; however, NT has not always been shown to increase SOC in central and eastern Canada (Angers et al., 1997). In addition, Aslam et al. (2000), Fortin et al. (1996) and Oorts et al. (2007) pointed out that NT enhanced R_h, while Alvarez et al. (2001), Curtin et al. (1998) and Vinten et al. (2002) found NT reduced C emissions. Since the behavior of C cycle components varies by region, an intensive model validation based on field measurements becomes a key step to strengthen modeling capability for national-level C accounting (Ogle et al., 2003; Sanderman and Baldock, 2010).

This study presents a validation of the DayCENT model and a 9-yr simulation of the effects of agricultural management practices on C cycle components at the field scale. The objectives are:

1. To parameterize and validate DayCENT for a SOC equilibrium simulation based on long-term field measurements of soil water content (SWC), soil temperature (ST), aboveground biomass production and grain yields;
2. To examine the dynamics of net primary production (NPP), R_h and NEP, and their differences over 9 yr, under two different tillage practices using the growing degree day (GDD) option; and
3. To evaluate the multi-year transformation of crop residues and SOC pools.

MATERIALS AND METHODS

Site Description

The measurements were conducted at the Elora Research Station (ERS), located 20 km north of Guelph, ON (43°39′ N 80°25′ W). The monthly average of daily air temperature at this site ranged from −8.0°C in January to 19.7°C in July; the accumulated monthly precipitation (PPT) for the growing season (May–Sep.) was 44.1 cm, and 49.8 cm for the remaining months (Oct.–Apr.). 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 and Typic Hapludalf in the Canadian and American soil classification, respectively. 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/H_2O ratio) is 7.1 in the surface soils (0–20 cm) (Wanniarachchi et al., 1999).

For comparing the effects of two contrasting agricultural management practices (CT verse NT) on the C cycle, the treatment comparisons studied at the ERS were established in 2000, included two replicates of two treatments and four plots in total (Plots 1 and 4 for CT; 2 and 3 for NT). The size of each plot was 150 m ×100 m. Tillage was conducted in the autumn using moldboard ploughing to a depth of 15 to 20 cm after harvest and was followed by a spring secondary tillage with a field cultivator and packer. The crops were grown for grain production and all of the residues were returned to the soil in both systems after harvest. The residues were incorporated by tillage in CT plots and left on the soil surface in NT plots.

The rotation crops were corn (2000, 2003, 2005, 2007, and 2008), soybean (2001, 2004, and 2006), and winter wheat (2002). Corn and soybean were planted in mid-May or early June and harvested in October and September, respectively. Winter wheat was planted after the soybean harvest, and was harvested the following August. For CT, granular urea, at a rate of 150 kg N ha^{-1} for the corn and 90 kg N ha^{-1} for the winter wheat, was incorporated by disk harrowing before planting, based on the recommendations of the Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA). For NT, a side-dress application of liquid fertilizer 28% NH_4–N was applied for the corn at a rate of 50 to 60 and 60 kg N ha^{-1} of urea for the winter wheat, based on soil tests. Soybean did not receive any fertilizer applications. The purpose of these fertilizer treatments was to examine the combined effects of several best management practices versus conventional practices. An additional description of the management practices for the ERS is given in Jayasundara et al. (2007) and Wagner-Riddle et al. (2007).

Soil water content (SWC) and soil temperature (ST) were monitored using water content reflectometers (CS615, Campbell Scientific Inc., Logan, UT) and thermistors (Model 107, Campbell Scientific Inc.) at depths of 5, 25, 50, and 85 cm for the period 2000 to 2007. An open-path infrared gas analyzer (LI-7500; Li-Cor, Lincoln, NE) and a three-dimensional sonic anemometer (CSAT3; Campbell Scientific) were installed on the flux tower at a height of 2 m to measure CO_2 and H_2O fluxes since 2001. The flux tower was surrounded by crop fields within an aerodynamically homogeneous region. The flux footprint covered both CT and NT treatments, and so NEP derived using the eddy covariance method was assumed to represent the average of the fluxes from the entire four-plot area. The raw NEP measurements 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 measurements were missing. This gap-filling method searches the time of day for missing data and then replaces them with the average value for that same time of day within a 14-d window. For the half-hourly C flux measurements (n = 140256) at the ERS, 22% of raw data was gap-filled in this study. The grain yields were weighted during the harvest period from 2000 to 2007. The oven-dry weight of above-ground corn biomass was measured in the week of year (WOY) of 32, 34, 39, and 42 in 2008. The initial total SOC at 0- to 20-cm soil depth was sampled in 1999 at 5205.2 g C m^{-2} (Jayasundara et al., 2007; Wagner-Riddle et al., 2007).

Model Description

The DayCENT model has been evaluated in a wide range of ecosystems for SOC and R_h simulations (Del Grosso et al., 2008; Kelly et al., 2000; Schimel et al., 1997; Parton et al., 1998). In this study, DayCENT was adopted for a 5000-yr equilibrium simulation, including a 75-yr deforestation (1865–1939), a

60-yr low intensity agriculture (1940–1999), and followed by a 9-yr CT/NT field experiment (2000–2008) at the ERS. The land-use history for the equilibrium simulation at the ERS was described in studies by Larson et al. (1999) and Wanniarachchi et al. (1999). The site parameters of interest are listed in Table 1. The major submodels related to the process of SOC decomposition and plant growth are described below.

The purpose of the SOC submodel is to calculate the decomposition of the dead plant material and the SOC pools (i.e., active, slow, and passive) with different turnover times (Parton et al., 1988). The active pool consists of live microbes and microbial products, and has a short (1–5 yr) turnover time. The slow pool contains physically protected forms of plant material and soil stabilized microbial products; this pool has an intermediate turnover time of 20 to 50 yr. The passive pool includes physically and chemically stabilized SOC with a turnover time of 400 to 2000 yr.

The R_h includes the CO_2 emission by rhizosphere microorganisms and the SOC decomposition by the microorganisms in the bulk soil. The process of decomposition is governed by soil properties, soil environment and factors that describe the effect of decomposition efficiency and cultivation. The general form of the C flow (C_{flow}) function in decomposition is expressed as

$$C_{flow} = \mathrm{SOM}\ r_{dec}\ k_{clt}\ f(deco)\ f(soil)\ f(anbic)\ f(acid) \quad [1]$$

where SOM is the quantity of soil organic matter, r_{dec} is an intrinsic soil microbial decomposition rate, k_{clt} is a cultivation factor to describe the effect of cultivation on decomposition of the active, slow and passive SOC pool and soil structural material; f(deco), f(soil), f(anbic), and f(acid) are functions to describe the effect of ST/SWC, soil texture, soil anaerobic condition, and pH on microbial decomposition, respectively. The R_h function in the model is the CO_2 loss associated with C_{flow} and climatic factors. The general form of the R_h function is

$$R_h = C_{flow}\ f(r_{resp}) \quad [2]$$

where $f(r_{resp})$ is the intercept parameter which controls C flow from SOC pools to CO_2. The $f(r_{resp})$ is also regulated by soil texture. The daily dynamics of ST/SWC were simulated based on a 13-layer soil structure using the Fourier Heat Flow Equation (De Vries, 1963) and Darcy's Law, respectively. The soil CO_2 emission for each C flow is calculated by the R_h function, except for the active SOC pool, which varies with the soil silt plus clay content.

The plant growth submodel in DayCENT is used to describe the production of crop residues and further regulate the SOC decomposition. Since temperature influences plant phenology, the GDD option was used in the plant growth simulation to regulate the duration of the growing season (Del Grosso et al., 2005). Moreover, grain yield is determined by the harvest index, which is calculated based on a genetic maximum and moisture stress in the months corresponding to anthesis and grain fill. After harvest, the grain is removed from the system and live shoots can either be removed or transferred to standing dead and surface residues. A detailed description of the plant growth submodel can be found in the studies of Stehfest et al. (2007) and Del Grosso et al. (2008).

Parameterization for Cultivation

The cropping and cultivation practices were parameterized based on the field management schedule. The No-Till Drill, Offset and Tandem Disks, and Moldboard Plow functions in DayCENT were applied for this study. In general, 95% of aboveground live, standing dead, and surface litter in CT were parameterized to be transferred to the top soil layer. The cultivation factors (k_{clt}, Eq. [1]) in CT were set 1.5 to 3 times higher than the values in the NT simulation depending on the turnover time of the C pools. The values of the cultivation factors for CT and NT are listed in Table 2.

The GDD option was adopted to determine the duration of the plant growth season. The GDD parameters were modified based on the studies of Buyanovsky and Wagner (1986), Gervois et al. (2004), McMaster and Wilhelm (1997), McMaster et al. (2005), Ritchie et al. (1986), and Tsvetsinskaya et al. (2001). The parameters related to biomass accumulation are listed in Table 3. The measured grain yield values were manually converted from the measurement of field grain to C biomass based on an assumed C to dry weight biomass ratio of 0.45 (Monje and Bugbee, 1998; Law et al., 2000). DayCENT calculated R_h at a daily time-step; however, modeled NPP was provided at a weekly time-step. Therefore, weekly NPP was resolved to daily NPP (i.e., same daily NPP during its associated 1-wk period) for the purpose of calculating daily NEP.

Table 1. The major site properties and model parameters describing the study site at the Elora Research Station.

Site parameter	Unit	Value
Latitude, Longitude	°	43.39 N, 80.25 W
Elevation	m	376.0
Treatment (CT; NT)	plot	1,4; 2,3
Crop rotation		
– corn	year	2000, 2003, 2005, 2007, 2008
– soybean	year	2001, 2004, 2006
– winter wheat	year	2002
Soil texture (sand, silt, clay)	%	35, 52, 13
Total organic carbon	g kg^{-1} soil	18.4
Total organic nitrogen	g kg^{-1} soil	1.7
Soil pH	–	7.1
Damping value for water submodel	–	0.0005
Max./Min. soil temp. for bottom soil layer	°C	15.0/4.0
Damping factor for calculating soil temp.	–	0.0047
Coolest soil temp. for bottom soil layer from Jan. 1	d	30

Table 2. Cultivation parameters for conventional tillage (CT) and no-till (NT) plots were adopted from the original model settings.

Cultivation parameter	Unit	CT	NT
Above-ground live biomass transferred to standing dead	%	0	5
Above-ground live biomass transferred to surface litter	%	5	5
Above-ground live biomass transferred to top soil layer	%	95	0
Standing dead biomass transferred to surface litter	%	5	5
Standing dead biomass transferred to top soil layer	%	95	5
Surface litter biomass transferred to top soil layer	%	95	5
Roots transferred to top soil layer	%	100	5
Cultivation factor for active soil organic carbon	–	1	1
Cultivation factor for slow soil organic carbon	–	3	1
Cultivation factor for passive soil organic carbon	–	3	1
Cultivation factor for soil structural material	–	1.5	1

Model Validation

A 5000-yr equilibrium simulation was conducted before the CT/NT simulations. The equilibrium simulation suggested that the SOC pools decreased during the 65-yr transition from cold temperate mixed forests (8300 g C m^{-2}) to conventional, low intensity agriculture (3400 g C m^{-2}) by 1940 (Fig. 1). The SOC level at 0- to 20-cm soil depth was at a steady-state by the end of the low intensity agricultural simulation in 2000 with the total SOC pool size in the range of 5200 to 5400 g C m^{-2}, which was similar to the initial SOC, 5205.2 g C m^{-2}, obtained from field measurements in 1999. The equilibrium simulation was consistent with the literature, indicating up to a loss of ~30% of SOC during the transition from forest to agriculture in 62 long-term field studies in Canada (VandenBygaart et al., 2003). Others have reported the projected SOC level of agricultural soils in Canada to be at steady-state for the period 1970 to 2010 using the CENTURY model (Smith et al., 2000).

The evaluation of the simulation was based on the linear regression method (Janssen and Heuberger, 1995), and included coefficient of determination (R^2), root mean squared error (RMSE), slope (S), and intercept (INT). A comparison of daily SWC/ST between measurements and simulations (simulated versus measured data during the period of 2000 to 2007) indicated that DayCENT gave an effective simulation for SWC (R^2 = 0.71, RMSE = 0.07 m^3 m^{-3}, S = 0.45, INT = 0.13 m^3 m^{-3}, p < 0.001, n = 6576) and ST (R^2 = 0.98, RMSE = 2.158°C, S = 0.98,

Table 3. The growing degree day (GDD) submodel parameters for corn, soybean, and winter wheat at the Elora Research Station. GDD for the anthesis stage is number of degree days required to reach anthesis (flowering) for a grain-filling annual crop. A grain-filling stage ranges from anthesis to harvest.

Plant growth parameter	Unit	Corn	Soybean	Winter wheat
Maximum harvest index	–	0.6	0.39	0.5
Germination temperature	°C	10	7.8	8
Non-growing temperature	°C	−2.0	−2.0	−5.0
Base temperature for crop growth	°C	10	10	4
GDD for a anthesis stage	d°C	600	400	450
Max./Min. GDD for a grain-filling stage	d°C	750/600	600/450	450/400

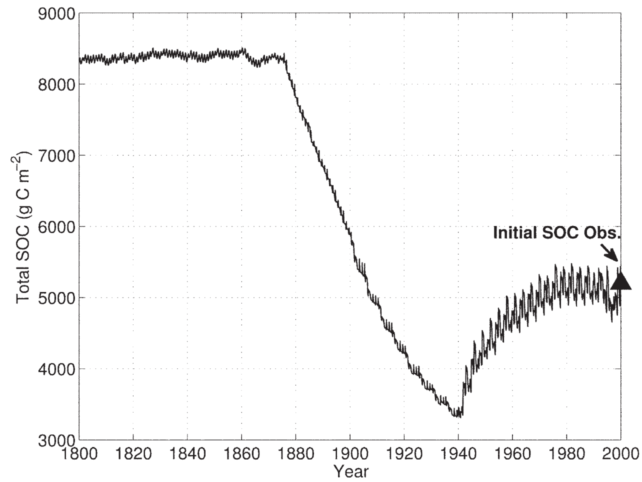

Fig. 1. The total soil organic carbon (SOC) at the 0- to 20-cm soil depth at the Elora Research Station from 1800 to 2000 in a 5000-yr SOC equilibrium simulation. The triangle symbol indicates the initial SOC observation in 1999, 5205.2 g C m^{-2}.

INT = 0.20°C, p < 0.001, n = 26304) in the top 0- to 30-cm soil depth. To test the C allocation in DayCENT, a comparison of grain yield and above-ground biomass between measurements and simulations was shown in Fig. 2a and 2b), respectively. The 8-yr grain yield simulations were compared with field observations in CT and NT. Regression analysis of the simulated versus measured grain yield and above-ground biomass production in 2001–2008, indicates DayCENT is capable of allocating C to grain yield (R^2 = 0.93, RMSE = 75.1 g C m^{-2}, S = 1.24, INT = −11.34 g C m^{-2}, p < 0.001, n = 16) and above-ground biomass production (R^2 = 0.98, RMSE = 34.4 g C m^{-2}, S = 0.84, INT = 91.5 g C m^{-2}, p < 0.001, n = 8). Although the grain yields for the corn in 2003 and 2008 were overestimated by ~200 g C m^{-2}, the long-term simulations showed a similar tendency to observation in most years. The GDD model was set up based on climate and vegetation data, rather than planting and harvest schedules, and some crops will grow or be permitted to grow for longer or shorter periods than this.

RESULTS

Relationship of Tillage-Soil Climate-Heterotrophic Respiration

Figure 3 shows daily PPT, modeled SWC/ST and R_h in 2008. Several heavy rainfall events (>2.3 cm d^{-1}) occurred on day of year (DOY) 180, 193, 202, 204, 218, 222, and 257; some of these rainfall events significantly increased the SWC. Because the silt loam soil at the ERS has a high water-holding capacity, the tendency of SWC in the 0- to 30-cm soil layer was to stay in a stable range of ~0.3 m^3 m^{-3}. The pattern of ST reflected a typical annual pattern of soil thermal response which showed increasing ST from 0°C on DOY 99 to 20°C on DOY 200, and thereafter decreasing gradually until the end of the year.

Figure 3c shows the modeled R_h fluctuated early in the season and decreased gradually from 3.3 to 1.3 g C m^{-2} d^{-1} during the growing season (DOY 122–294). A relatively higher R_h in both CT and NT was simulated during spring thaw, cultivation and harvest compared with that during the growing season. The R_h peaks correspond to the heavy rainfall events (Fig. 3a).

Net Carbon Exchange in Cropfield

Figure 4 presents the 9-yr dynamics of simulated NPP, R_h, and NEP for CT and NT at the ERS. The annual totals are summarized in Table 4. Figure 4a shows a slightly higher NPP at the beginning of the growing season for CT in the corn years. The tillage effects on NPP are not obvious in the simulation. The differences in NPP between CT and NT (CT–NT, Table 4) are 56.6, 34.7 and 24.3 g C m^{-2} yr^{-1} for corn, soybean, and winter wheat years, respectively.

The differences in R_h between CT and NT are 38.4, 93.7, and 64.2 g C m^{-2} yr^{-1} for the corn, soybean, and winter wheat years, respectively. Larger values of R_h were also found at the beginning of the growing season for CT (Fig. 4c and 4d). The differences between CT and NT in R_h during the middle of growing season were ~2 g C m^{-2} d^{-1} for the corn and winter wheat and ~4 g C m^{-2} d^{-1} for the soybean years. Consequently, CT produced greater R_h in the soybean years as compared with the corn and winter wheat years. The ranges of R_h during the growing season were 2.9 to 3.9, 3.6 to 3.9, and 3.8 g C m^{-2} d^{-1} for corn, soybean, and winter wheat, respectively (Fig. 4c). Figure 4f shows the NEP difference between CT and NT simulation. NEP in NT is generally greater than that of in CT at the beginning of the growing season due to a smaller R_h in NT. After the middle of growing season, a larger NEP in CT occurred due to a greater NPP.

In the comparison between simulated and measured NEP (Fig. 5), overall, the simulated NEP dynamics followed a general seasonal pattern of C source/sink as shown in observed NEP. However, the simulated NEP had a closer agreement (R^2 = 0.71, RMSE = 1.9 g C m^{-2}, S = 0.56, INT = 0.28 g C m^{-2}, n = 728) with observation in the first 3 yr (2001–2003) of agricultural experiment, compared with that in 2001–2008 (R^2 = 0.55, RMSE = 3.1 g C m^{-2}, S =

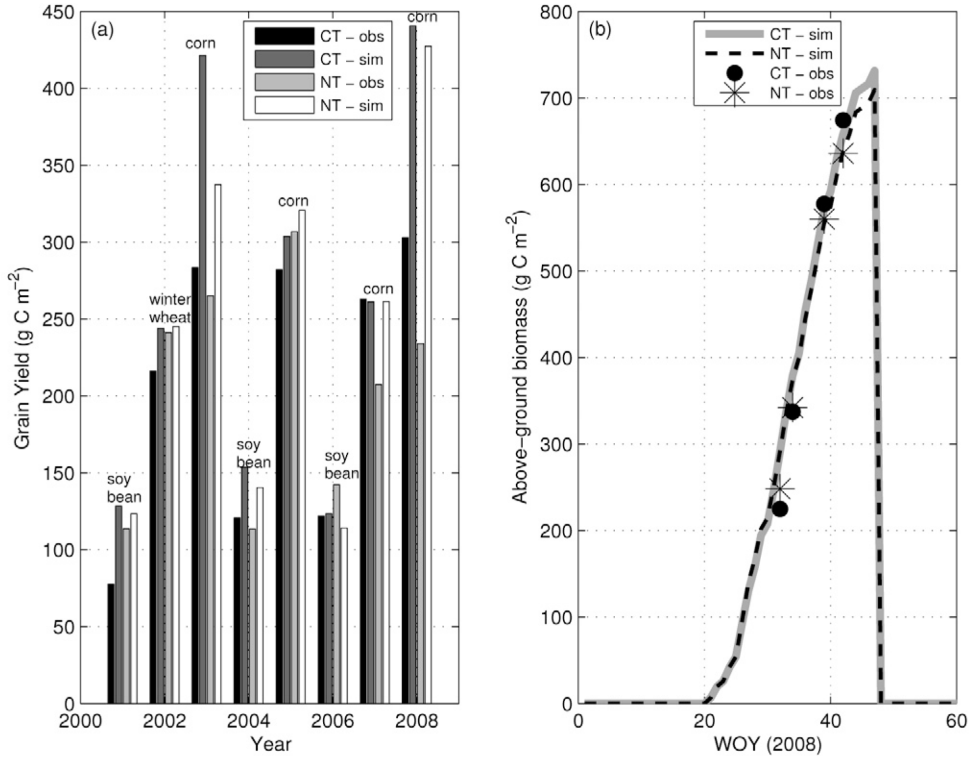

Fig. 2. The model validation on (a) grain yield; observations were obtained from the yield measurements at the Elora Research Station from 2001 to 2008; (b) above-ground dry weight corn biomass.

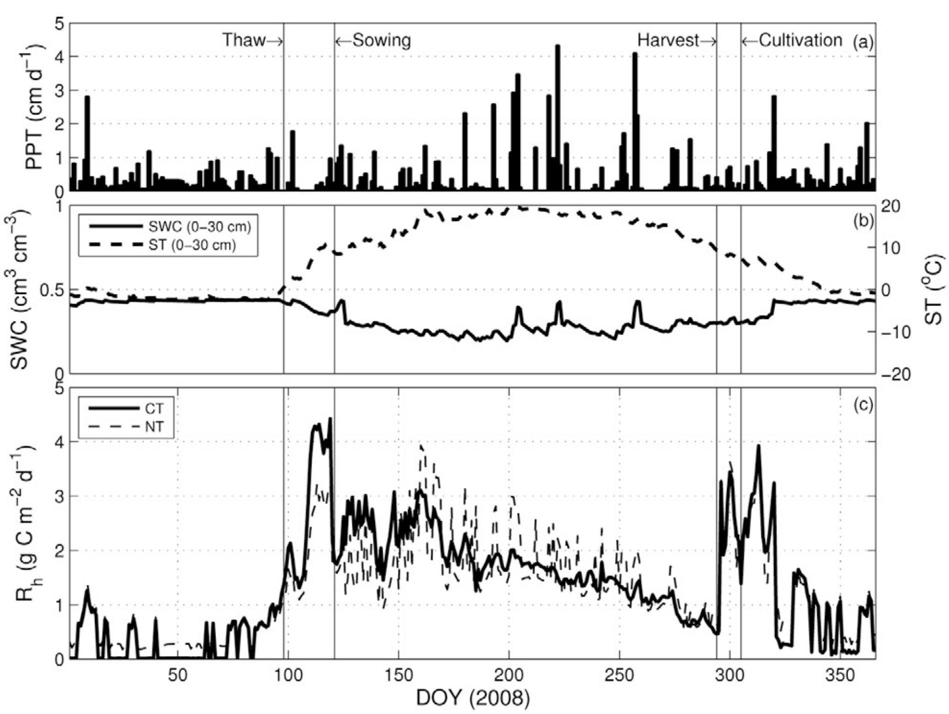

Fig. 3. Seasonal variation of environmental factors (i.e., precipitation, soil temperature, and soil water content) and heterotrophic respiration in 2008: (a) daily precipitation; (b) average modeled soil water content and soil temperature to a depth of 0 to 30 cm; a thaw period was defined as a period with an average soil temperature greater than 0°C to the sowing date; (c) modeled heterotrophic respiration for conventional tillage (CT) and no-till (NT) plots. The vertical lines indicate DOY 70, 121, 258, and 305 in 2008 for the date of thaw, sowing, harvest and cultivation, respectively.

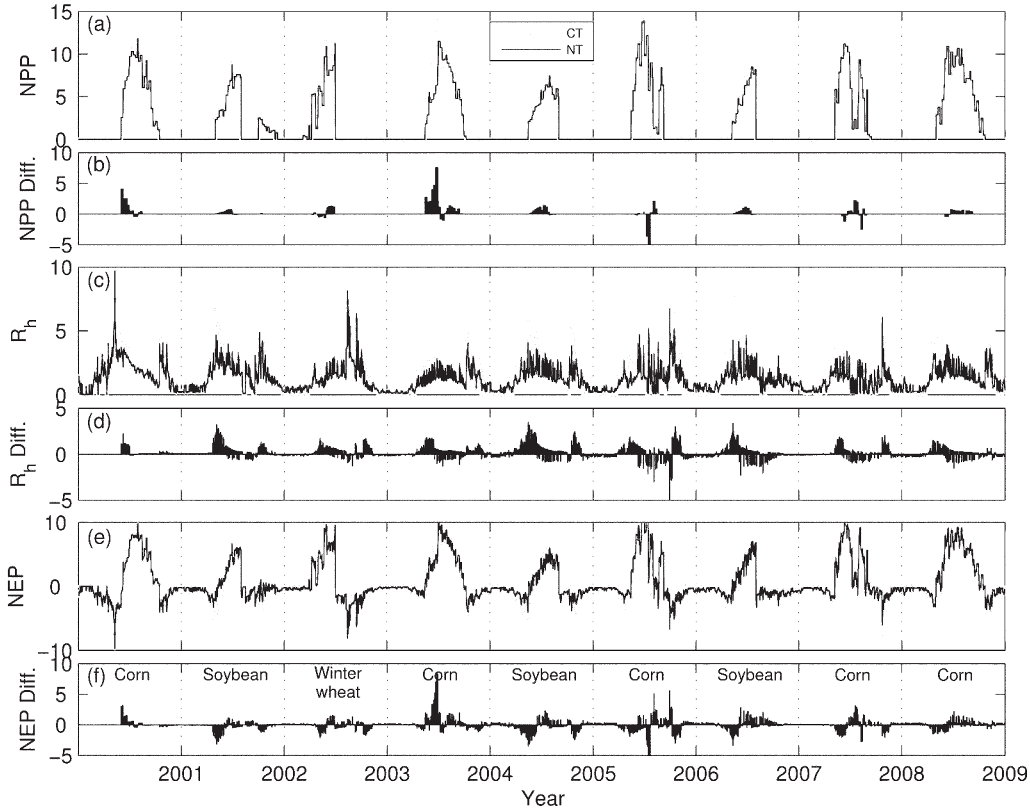

Fig. 4. Simulation of (a) net primary production, (c) heterotrophic respiration, and (e) net ecosystem productivity (all in units of g C m^{-2} d^{-1}). Differences (CT−NT) in simulations between the conventional tillage (CT) and no-till (NT) are shown in (b), (d) and (f) for net primary production, heterotrophic respiration and net ecosystem productivity, respectively. Based on mass conservation, the daily net ecosystem productivity is equal to the daily-integrated C flux. Positive net ecosystem productivity values represent a C sink.

0.64, INT = 0.39 g C m^{-2}, n = 2458). The model underestimated NEP in 2005 and 2006, particularly during the middle of the growing season. The simulated NEP for corn in 2005 during the fast growing stage was underestimated by 39% (~5 g C m^{-2} d^{-1}); the model only presented 50% of observed NEP for soybean in 2006. The underestimated NEP simulation for 2004–2008 might be caused by the more complex agricultural management practices (e.g., seeding red clover and fertilization) that were not parameterized into the model. Additionally, NEP measurements might be interrupted and influenced by the installation of field equipment and maintenance.

Table 4. The average annual C totals of net primary production, heterotrophic respiration and net ecosystem productivity for the corn, soybean, and winter wheat years. The Diff. (CT-NT) indicates the difference in annual C totals between the conventional tillage (CT) and no-till (NT). The units of these annual C totals are g C m^{-2} yr^{-1}.

Variable	Tillage practice	Corn	Soybean	Winter wheat
			g C m^{-2} yr^{-1}	
NPP	CT	946.7	546.0	583.1
	NT	890.1	511.3	558.8
	Diff. (CT − NT)	56.6	34.7	24.3
R_h	CT	495.0	565.7	513.1
	NT	456.6	472.0	448.9
	Diff. (CT − NT)	38.4	93.7	64.2
NEP	CT	452.0	−19.7	70.0
	NT	434.0	39.4	110.0
	Diff. (CT − NT)	18.0	−59.1	−40.0

Soil Organic Carbon Dynamics

The effects of tillage practices on soil C pool sizes are presented in Fig. 6 and Fig. 7. Figure 6 indicates that the active surface pool in CT maintained a low C level due to the effect of cultivation. About 50 to 100 g C m^{-2} of crop residues were incorporated into the active soil pool annually. Conventional tillage had larger annual changes of SOC in the active soil pool than NT as a result of the incorporation of plant residues in the CT soils every year. Following the spin-up simulation, the active soil pool decreased in both CT and NT during the first 4 yr, and then appeared to stabilize on an annual basis, with CT showing 50 to 100 g C m^{-2} of additional C in the active pool relative to NT. The annual cultivation and crop rotation caused the seasonal variation of SOC in the active soil pool.

Figure 7 shows the SOC dynamics in the slow, passive, and total SOC pools for CT and NT. As a result of a longer turnover time in the passive pool, the mount of SOC in the passive pool for both CT and NT is very stable, at ~2000 g C m^{-2}. The equilibrium simulation produced the initial total SOC values for the agricultural simulation in the range of 5200–5400 g C m^{-2}, which is close to field measurements of ~5200 g C m^{-2} in 2000. In addition, the agricultural simulation estimated the total SOC in the range of 4900 to 5100 g C m^{-2} at the end of 2005 (Fig. 7a). A field measurement in the fall of 2005 at the ERS showed that the total SOC was 5600 to 5700 g C m^{-2} (Ramnarine, 2010). This indicates a good agreement between the simulation and measurements, given the large uncertainties in total SOC estimations.

The field study of Ramnarine (2010) also indicated that the quantity of slow SOC in the 0- to 10-cm layer was significantly higher in the NT soils at 2890 versus 2550 g C m^{-2} for CT. In this study, the tendency of the slow SOC pool was simulated at approximately 2400 and 2600 g C m^{-2} for CT and NT, respectively (Fig. 7b). The tillage effects on SOC in DayCENT were consistent with the measurements. In general, the SOC tendencies in the slow SOC pool were estimated at a rate of +10.7 g C m^{-2} yr^{-1} for NT and −11.5 g C m^{-2} yr^{-1} for CT.

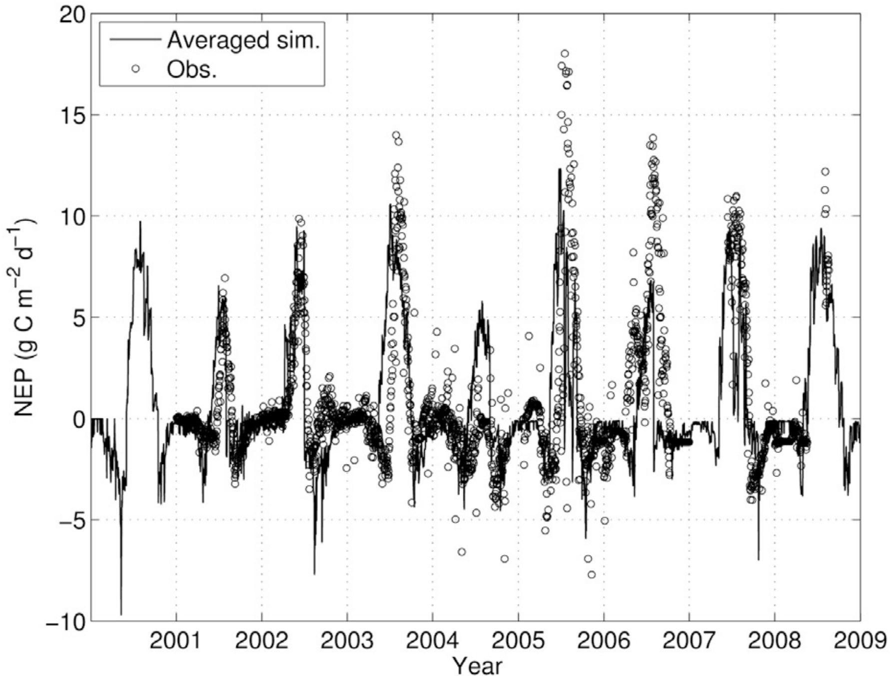

Fig. 5. The dynamics of measured and simulated net ecosystem productivity. The measured net ecosystem productivity was obtained from an eddy covariance C tower in the middle of the field that represented the well-mixed fluxes from the conventional tillage (CT) and no-till (NT). The simulated net ecosystem productivity in CT and NT was averaged to represent the overall C sink/source in the field.

DISCUSSION

Tillage Effects on the SOC Decomposition

The model was validated to ensure that the plant growth submodel and soil physical submodel can be used to identify crop residue input and to evaluate the decomposition of SOC. The combined effect of incorporating crop residues and associated cultivation factors (Table 2) enhanced R_h in CT by 35% relative to NT after disk cultivation in the spring (Fig. 3). The general tendency and magnitude of simulated R_h is in agreement with the studies of Lal (2004), Oorts et al. (2007), and Rochette et al. (1999) indicating that the enhancement in R_h by CT over NT was in the range of 1.50 to 2.45 g C m^{-2} d^{-1} throughout the whole growing season for the corn years. In particular, larger values of R_h in CT occurred in the spring potentially due to the faster crop growth and higher ST, while NT emissions were enhanced in the middle of the growing season under a favorable soil environment (i.e., ST/SWC) for decomposition. This phenomenon resulted in a small difference (i.e., 38.4 g C m^{-2} yr^{-1}) in annual R_h between CT and NT as listed 495.0 and 456.6 g C m^{-2} yr^{-1} for CT and NT, respectively in Table 5.

Tillage practices modify water interception by standing above-ground crop, crop residues, and the soil water holding capacity, and in turn, influence the dynamics of SWC and SOC decomposition (Franzluebbers et al., 1995). Soil water content regulates the water-filled pore space which controls soil CO_2 levels. During the period of thaw–cultivation (DOY 99–121), CT produced a significantly higher R_h than NT by 16.8 g C m^{-2}. The accumulated R_h in this period contributed to 10 to 13.3% of the annual total. In addition to the nature of greater R_h due to a higher ST and SWC, the modeled R_h was influenced by the distribution of organic matter and transformation of crop residues. Regarding two contrasting tillage practices, the parameterization (Table 2) of the distribution of organic matter and cultivation

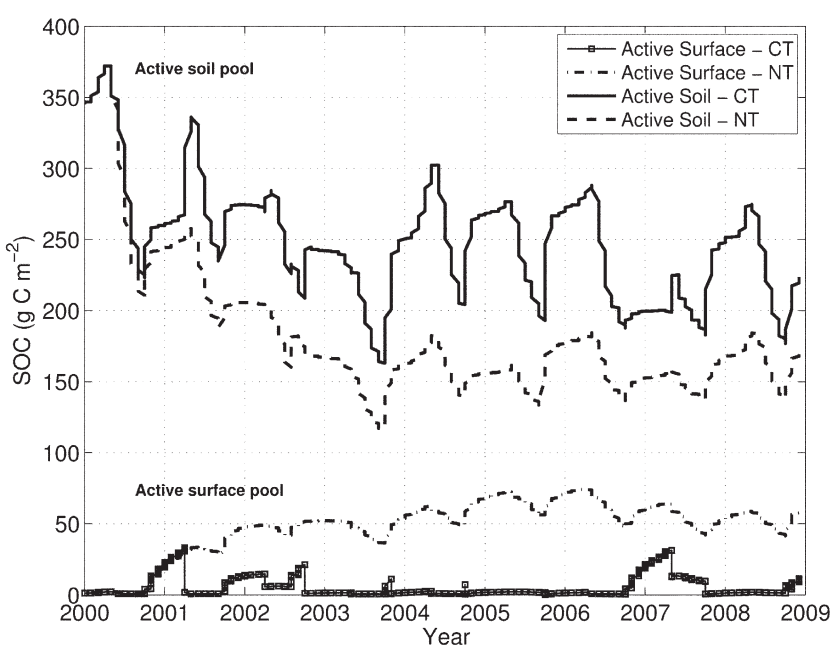

Fig. 6. Simulation of soil organic C changes for the conventional tillage (CT) and no-till (NT) in the active surface soil organic C pool and active soil organic C pool during the period 2000 to 2009.

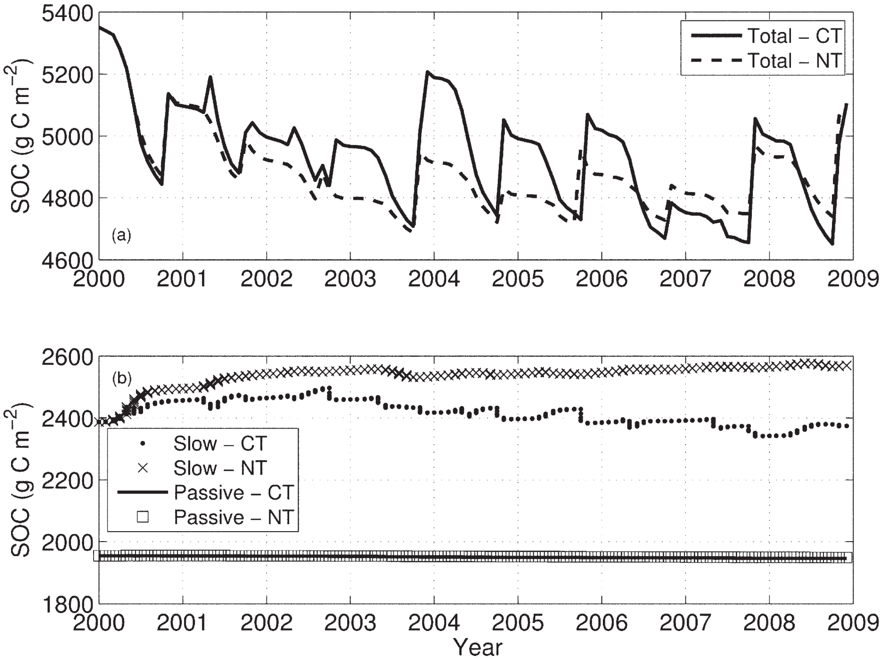

Fig. 7. Simulation of soil organic C changes for the conventional tillage (CT) and no-till (NT) in (a) the total soil organic C pool; and (b) the slow soil organic C pool and the passive soil organic C pool during the period 2000 to 2009.

can significantly influence the modeled R_h. The transfer rates of live and dead biomass and surface litter to the top soil layer are much greater in CT than that of in NT. The cultivation factor (i.e., multiplier) for slow, passive and soil structural material pools are also greater in CT than NT by 1.5 to 3.0 times. The greater transfer rates of crop residues and cultivation factors in CT could lead to a large modeled R_h.

Tillage Effects on Net Carbon Exchange

On an annual basis, the modeled NEP differences (CT–NT) are 18, −58.1, and −40.0 g C m^{-2} yr^{-1} for corn, soybean, and winter wheat, respectively. The NEP differences are determined by the differences between NPP and R_h, therefore a positive NEP difference may be caused by either a relatively larger NPP or smaller R_h. This study suggests that tillage has a positive effect on C accumulation for corn years; and a negative effect for soybean and winter wheat years due to a stimulated R_h under CT. At a daily time-step, NEP for corn, soybean, and winter wheat were simulated at 10.6 to 12.3, 5.8 to 6.7, and 7.1 g C m^{-2} d^{-1}, respectively, during the growing season. The maximum NEP in soybean and winter wheat years was smaller by ~45% of maximum NEP in corn years in the middle of the growing season.

The fact that the largest variation in NPP and R_h occurred at the beginning of the growing season in the corn years indicates a greater uncertainty in representing NEP. The uncertainty might be caused by the sensitivity of GDD parameters. Currently, GDD is one of the most common methods to describe the interaction between phenology and carbon exchange (Chuine et al., 2003; Arora and Boer, 2005). In this study, the GDD submodel was applied instead of specifying the harvest date in the schedule file of DayCENT. The onset of each crop phenological stage was regulated by the GDD accumulation counting from sowing day and the GDD thresholds. The timing and length of carbon fixation can be influenced by the sensitivity of the GDD thresholds. A further validation on the optimum temperature in the GDD submodel might improve the timing of modeled C uptake and thus influence seasonal and annual NEP totals.

Carbon Sequestration in Agriculture

The SOC tendency in the slow pool suggested the rate of sequestration at +10.7 and −11.5 g C m^{-2} yr^{-1} for NT and CT, respectively. NT can be regarded as a soil management practice to enhance C sequestration. However, Angers et al. (1997) and VandenBygaart et al. (2003) reported that NT has not always been shown to increase SOC in Ontario, Canada. Our modeling result is for the first 9 yr of SOC dynamics after switching to NT, and therefore a long-term agricultural management simulation is required to determine the long-term tillage effects on SOC. According to a field study at the ERS (Ramnarine, 2010), CT contributed to the seasonal variation of SOC mainly in labile organic matter fractions of active and slow SOC pools and not from the passive SOC pool. Tilling the soil caused a greater annual fluctuation of C inflow in the active pools so that it mitigated the magnitude of total SOC changes in CT.

The SOC dynamics are associated with vertical variability of soil texture, bulk density, and equivalent soil mass. An inadequate sampling depth might lead to a result showing a difference in the distribution of SOC (Campbell et al., 2000; Deen and Kataki, 2003; Ramnarine, 2010). For instance, NT resulted in an increase in SOC in the 0- to 10-cm sampling layer; however, the effect of C sequestration was not significantly different for the 0- to 30-cm sampling layer between CT and NT (Ramnarine, 2010). The soil depth (0–20 cm) represented in the DayCENT model and in the different depth of soil sampling might cause the uncertainty in SOC validation and comparison.

CONCLUSION

This study used the daily version of the process-based CENTURY model (DayCENT, Version 4.5) to simulate the effects of two contrasting agricultural management practices (CT versus NT) on NPP, R_h, NEP, and SOC over 9 yr at the Elora Research Station, Southern Ontario, Canada. The major findings and perspectives of this study are as follows:

- The GDD submodel was adopted to simulate grain yield and NPP. The results indicated that the model captured the dynamics of crop productivity for evaluating the effects of tillage on R_h dynamics. The model estimated that the differences in NPP (CT– NT) were 56.6, 34.7 and 24.3 g C m^{-2} yr^{-1} for corn, soybean, and winter wheat years, respectively.

- The differences in R_h (CT– NT) were 38.4, 93.7, and 64.2 g C m^{-2} yr^{-1} for corn, soybean, and winter wheat years, respectively. Conventional tillage enhanced R_h in the period of thaw-cultivation relative to NT by 16.8 g C m^{-2}. In this period, the combined effect of incorporating crop residues and increased cultivation factors enhanced R_h in CT by 35% relative to NT after disk cultivation.
- The 9-yr NEP simulation indicated that DayCENT is able to present the dynamics of ecosystem C exchange. The annual NEP differences (CT– NT) were 18, −58.1, and −40.0 g C m^{-2} yr^{-1} for corn, soybean, and winter wheat, respectively. Improvement in the modeled NEP simulation may be achieved by validating crop phenology at the daily time-step.
- The total SOC pools decreased during the 65-yr transition from cold temperate mixed forests (8300 g C m^{-2}) to low intensity agriculture (3400 g C m^{-2}) in 1940, and then approached a steady state by 2000 CE (5200–5400 g C m^{-2}). The CT/NT simulation during the period of 2000 to 2008 indicated that about 50–100 g C m^{-2} of crop residues were incorporated into the active soil pool annually. The SOC tendencies in the slow SOC pool were estimated at +10.7 g C m^{-2} yr^{-1} for the NT and −11.5 g C m^{-2} yr^{-1} for CT. The capacity for C sequestration in the SOC slow pool was enhanced by adopting NT practices. A longer simulation period (i.e., >10 yr) might be required to better reflect the SOC dynamics and the climate effects in an agricultural management system.

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