The Community Land Model underestimates land-use CO_2 emissions by neglecting soil disturbance from cultivation

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Abstract

The Community Land Model (CLM) can simulate planting and harvesting of crops but does not include effects of cultivation on soil carbon decomposition. The biogeochemistry model DayCent does account for cultivation and provides a baseline for evaluating the CLM. With the goal of representing cultivation effects on soil carbon decomposition, we implemented the DayCent cultivation parameterization in the CLM and compared CLM and DayCent simulations at eight Midwestern United States sites with and without the cultivation parameterization. Cultivation decreases soil carbon by about 1350 gC m^{-2} in the CLM and 1660 gC m^{-2} in DayCent across the eight sites from first cultivation (early 1900s) to 2010. CLM crop simulations without cultivation have soil carbon gain, not loss, over this period, in contrast to the expected declining trends in agricultural soil carbon. A global cultivation simulation for 1973-2004 reduces ecosystem carbon by 0.4 Pg yr^{-1} over temperate corn, soybean, and cereal crop areas, which occupy approximately 1/3 of global crop area. Earth System Models may improve their atmospheric CO_2 and soil carbon simulations by accounting for enhanced decomposition from cultivation.

1. Introduction

Earth System Models (ESMs) include carbon (C) cycle calculations to assess the biogeochemical effects of changes in the global environment, including changes in the land cover due to land use (Brovkin et al., 2013). The Community Land Model (CLM) underestimates the global land use and land management (LULM) C flux to the atmosphere in large parts of the 19th and 20th centuries in simulations coupled to the Community Earth System Model (CESM), when compared to the Houghton (2003) bookkeeping estimates (Lawrence et al., 2012).

The Houghton (2003) estimates of the LULM flux are based on a bookkeeping model that assesses the cumulative C flux to the atmosphere from LULM relative to no LULM. The bookkeeping model performs detailed accounting of carbon pools and fluxes in areas of LULM based on meticulous usage of data combined with an empirical age-class ecosystem model. In contrast, mechanistic land biogeochemistry models like the CLM compute an instantaneous C flux to the atmosphere from the conversion of unmanaged to managed (and vice versa) land; they do not include cumulative C effects of land cover change in the calculated flux for the years following the change (Lawrence et al., 2012). This difference in definition accounts for part of CLM's underestimation of the LULM flux. Similarly the CLM estimate is low relative to estimates from an intercomparison of ESM simulations that replicate the bookkeeping approach by comparing simulations with and without LULM (Brovkin et al., 2013).

There are other inconsistencies in the ESM and bookkeeping communities' definitions and usage of the LULM flux (Pongratz et al., 2013; Houghton, 2013; Gasser and Ciais, 2013). As just one example, the Houghton (2003) estimates also include more of the

LULM activities that contribute to the land use C flux. For example, Houghton (2003) reports contributions from deforestation, afforestation, agricultural abandonment, wood harvest, fire suppression, woody encroachment, and cultivation. CLM accounts for the first four by prescribing annual changes in land cover type and harvesting. Woody encroachment may be implicit in such data, and CLM's latest fire model accounts for fire suppression (Li et al., 2013). Loss of soil C from cultivation is definitely a missing process in the CLM and, as far as we know, in other land biogeochemical models used in ESM simulations.

In simulations with the DayCent biogeochemical model at twenty-one sites around the American Midwest, Hartman et al. (2011) account for the loss of soil C from cultivation. Extrapolating to the Great Plains region and accounting for N_2O and CH_4 in their greenhouse gas calculations, Hartman et al. calculate 1.73×10^{15} g CO_2-C equivalents emitted from 1860 to 2003 (1×10^{15} g = 1 petagram = 1 Pg). This number includes processes that partly mitigate the loss of soil C (irrigation, fertilization, grassland restoration), so cultivation alone results in a larger number.

Here we investigate the feasibility of accounting for the direct loss of soil C from cultivation in the CLM, which would reduce the current underestimation in land use emissions shown by Lawrence et al. (2012). CESM's existing land use emission term only accounts for the removal of C from replacing unmanaged vegetation with crops and has no direct effect on the soil C.

2. Methods

We use the models DayCent (Parton et al., 1998; Del Grosso et al., 2006) and CLM4.5bgc, the most recent version of the CLM with biogeochemistry (Oleson et al., 2013; Koven et al., 2013). We perform simulations at eight sites distributed across the Great Plains of the American Midwest that span much of the region's climate variations:

Cherry and Hamilton Counties in Nebraska; Dewey County, Oklahoma; Dunn County, North Dakota; Hutchinson County, Texas; Kingsbury and Lyman Counties in South Dakota; and Yuma County in Colorado (see Hartman et al. (2011) Fig. 1 for map). At each site we drive the models with nearest neighbor 0.5° in latitude and longitude CRU-NCEP version 4 atmosphere data (Climate Research Unit-National Centers for Environmental Prediction) (http://dods.extra.cea.fr/store/p529viov/cruncep/V4_1901_2012), available for years 1901-2010. We also drive the models with transient atmospheric CO_2 concentration and transient nitrogen (N) deposition data as done by Bonan and Levis (2010), available for years 1860-2010. We prescribe soil texture per site with percent sand/silt/clay values from Hartman et al. (2011). Grass is the native vegetation at all sites (Hartman et al., 2011) (Table 1).

We spin up the models at each site with boundary conditions for the year 1860, 100% grass cover, and repeating atmospheric conditions for 1901-1920. We continue with transient simulations that cycle the 1901-1920 atmospheric conditions from 1861 to 1920 and proceed with the remaining time series from 1921 to 2010. We perform three such 1861-2010 transient simulations:

1) GRASS with grass cover as in the spin-up but with transient forcings,

2) CROP where grasses switch to rainfed corn on a site-specific conversion year,

3) CLTV same as CROP but with direct effect of cultivation on the decomposition of soil C (Table 2). We expect that the first order effect of cultivation on the soil carbon

decomposition will not depend on the crop type present in the simulations (rainfed corn rather than the more common at these sites rainfed winter wheat and spring grains).

We also perform global CROP and CLTV simulations from 1973 to 2004 to assess large-scale signals of cultivation-enhanced soil C decomposition. As boundary conditions we use transient meteorology (Qian et al., 2006) and transient N deposition and atmospheric CO_2 values as done by Bonan and Levis (2010). We initialize the simulations from a 1972 CROP simulation as a proxy for starting with native soils in 1973. In contrast to the site simulations, here we assume that cultivation begins in 1973 on all temperate corn, soybean, and cereal crop areas. This is a first evaluation of the potential biogeochemical effect of enhanced C decomposition from soils disturbed by agricultural practices.

2.1. DayCent

DayCent is well documented and well tested (Parton et al., 2005; Del Grosso et al., 2008) in simulations of agricultural, grassland, and forest systems and of various cultivation practices. Hence we treat the DayCent model as a baseline for comparisons with the CLM at the eight sites.

Hartman et al. (2011) show that DayCent's crop yields compare very well against observations at the twenty-one sites chosen for their study. Here we select the eight sites where DayCent performs best against observations. We do not expect this selection approach to bias the CLM simulations.

DayCent is designed primarily for local/regional applications, while the CLM is designed mainly for global scale applications. Hence DayCent includes a level of detail in the representation of crop management not included in the CLM (Bonan et al., 2013). For example, the DayCent simulations apply increasing N fertilizer over time beginning in 1950. The CLM site simulations do not apply N fertilizer.

Here we assess the potential biogeochemical effect of adding to the CLM the DayCent representation of agricultural disturbance to soil C by crop cultivation. Cultivation in DayCent refers to a list of plowing or planting events that disturb the soil according to a decomposition enhancement factor (ε) for two litter C pools (metabolic and structural) and three soil C pools (active, slow, and passive) (Table 2). $\varepsilon > 1$ indicates a corresponding increase in the C decomposition rate due to cultivation; 1.0 indicates no effect. A site-specific DayCent schedule file prescribes the timing of cultivation events per simulation year (Table 3). A cultivation event is assumed to have a 30-day effect on soil decomposition and this replaces the effect of previous cultivation events when 30-day periods overlap.

2.2. The Community Land Model (CLM)

The CLM is the land component of the CESM (Hurrell et al., 2012), though used here in offline mode, i.e. not coupled to interactive models of the atmosphere, ocean, and sea-ice. The CLM is a state of the art biogeophysics and biogeochemistry model that simulates interactions among land surface, soil, and canopy processes. The CLM is widely tested and documented in global, regional, and point simulations and is among the most advanced models of its kind for coupling to an ESM for climate change research.

Lawrence et al. (2011, 2012) describe the CLM4.0 and Oleson et al. (2013) describe the CLM4.5 in great detail, including updates relative to the CLM4.0, such as:

1) Revised calculation of canopy conductance, gross primary production, and transpiration, consistent with FLUXNET eddy covariance flux towers (Bonan et al., 2011; Sun et al., 2012).

2) Revised hydrology (Swenson et al., 2012), snow fraction (Swenson and Lawrence, 2012), and representation of lakes (Subin et al., 2012), wetlands, and rivers.

3) Revised soil biogeochemistry that includes DayCent-like litter and soil carbon pools and transfers among pools, vertically-resolved soil carbon dynamics, and N-gaseous emissions (Koven et al., 2013).

4) Updates to the crop model. CLM4.5 crops use the interactive N algorithm instead of prescribed N as in CLM4.0 (Levis et al., 2012). CLM4.5 accounts for N retranslocation during the grain-fill stage of crops by releasing N stored in the leaves and stems for grain development. To support the retranslocation process, CLM4.5 varies C-to-N ratios in crop C pools, prescribing lower ratios in early stages of the crop development. CLM4.5 also includes a simple crop fertilization scheme (Drewniak et al., 2013) that we use here in the global CLTV and CROP simulations but not in the site simulations.

We implement DayCent's enhancement of soil C decomposition due to cultivation in the CLM and prescribe the same site-specific DayCent enhancement factors and schedule files (Tables 2 and 3). The CLM partitions structural litter into cellulose and lignin pools. We apply the DayCent structural litter enhancement factor to both of these pools. The CLM performs biogeophysics and biogeochemistry calculations in 10 soil layers to a depth of 3.8 m. In the comparisons with DayCent simulations, we analyze CLM output in the top five soil layers because they cumulatively reach about 29 cm of depth, closer to the depth of DayCent's soil profile calculations (top 20 cm).

In CLM's global simulations we simplify the effect of cultivation to one that repeats every year rather than changing according to a schedule file. We designate model grid cells as economically more or less developed and assign soil C decomposition enhancement factors (ε) accordingly (Table 4). This protocol was developed for global DayCent simulations (not shown) and the ε values differ from those specified for the site-specific simulations (Table 2).

3. Results and discussion

At all eight sites, GRASS has the smallest 1901-2010 trend in soil C of the three simulations because all eight sites start in equilibrium for the GRASS simulation (e.g., Dunn County shown in Fig. 1). Small trends in soil C in GRASS are due to competing processes, including CO_2 fertilization due to rising CO_2 concentration and increasing soil decomposition by heterotrophic respiration due to warming. Moreover, increased soil decomposition and increased N deposition over time increase the N available to plants and this can increase plant productivity.

At all the sites except for Dewey County, the CLM simulates increasing soil C in the CROP simulations (Fig. 1). This is inconsistent with the expectation that pasture-to-crop conversion should lead to loss of soil C due to biomass removal at harvest, in part because crop biomass is returned to the soil as litter at harvest in the CLM. At all eight sites DayCent simulates a decline of 1000-3000 g C m^{-2} over the 20th century. DayCent's rainfed corn generates less plant litter than the native grass, especially before fertilization begins around 1950, in part because crop biomass is removed at harvest. Even in Dewey County where the CLM simulates a slow decline in soil C, this is an order of magnitude less than the loss simulated in the equivalent DayCent CROP simulation.

At all eight sites the CLM simulates reduced soil C when accounting for the effect of cultivation on the decomposition of soil C (CLTV) relative to when the CLM does not account for this effect (CROP) (Fig. 1). Compared to the DayCent simulations, which were calibrated for each site individually, the CLM performs best in Cherry, Dewey, and Dunn Counties. Here CLM's soil C declines by about 1200, 1500, and 1700 g C m^{-2} from 1901 to 2010 due to enhanced soil decomposition from cultivation.

In Dewey and Dunn Counties the CLM also captures the eventual reduction in soil C loss simulated by DayCent with the adoption of less intensive cultivation practices by farmers (Fig. 1). DayCent shows these declining soil C losses also for Counties where the CLM does not, e.g., Cherry and Hamilton, because DayCent's fertilization effect enhances plant litter inputs. We do not apply fertilizer in these CLM simulations, so we miss the increase in productivity that compensates for increased soil C decomposition from cultivation.

At the four other sites, Hutchinson, Kingsbury, Lyman, and Yuma, the CLM underestimates the cultivation-enhanced decomposition and the resulting soil C decline. We attribute this to higher clay contents at these sites (Table 1), resulting in suppressed soil C decomposition and reduced heterotrophic respiration. The CLM also simulates lower NPP and LAI at these sites because clay inhibits plant access to soil moisture. Reduced productivity at these sites contributes to reduced apparent sensitivity of the soil C to cultivation. In other words, less C produced leads to less decomposed, even under cultivation.

Consistent with the site simulation results, CLM's global CLTV simulation loses more than 120 g C m^{-2} from 1973 to 2004 in the top 29 cm of soil relative to CROP and 800 g

m^{-2} in the central United States (Fig. 2). The global ecosystem C declines by 0.4 Pg C yr^{-1} from 1973 to 2004 in CLTV relative to CROP due to the enhanced soil C decomposition over temperate corn, soybean, and cereal areas.

4. Conclusions

Past work has investigated potential biogeophysical effects from not tilling agricultural soils after harvest. For example, in a version of the CCSM3, Lobell et al. (2006) prescribed increased surface albedo to represent the presence of crop residue after harvest and found cooling as a result. Here we address a potential biogeochemical effect from land cultivation.

We perform CLM simulations at eight sites in the American Midwest to examine whether accounting for the direct effect of cultivation on soil C decomposition may reduce an underestimation in land use emissions simulated by the CLM (Lawrence et al., 2012).

We implement in the CLM the cultivation-enhanced soil C decomposition algorithm used in DayCent (Hartman et al., 2011). According to this algorithm, soil C decomposition responds to farming activities known to disturb the soil and leads to reduced soil C in both the CLM and DayCent relative to simulations without this effect. This simple change brings the CLM closer to simulating the declining trends in agricultural soil C supported by observations (Schlesinger, 1991).

We do not calibrate the CLM against observations or DayCent simulations in this study, so the general agreement between the CLM4.5 and DayCent gives us confidence in the reliability of the CLM4.5 as a biogeochemical and crop model. However, we acknowledge that greater agreement at some of the sites and lesser agreement at others is a function of each model's response to site-specific boundary conditions, e.g. the effect of soil texture as discussed above with regard to clay. More generally we find that CLM productivity (e.g. NPP) tends to be more sensitive to site-specific characteristics than DayCent productivity. As a result CLM's soil decomposition responds to cultivation with more sensitivity to such site-specific characteristics than DayCent's and the same is true of the models' responses to the interannual variability of climate (Fig. 1).

Global CLM simulations put the site results in large-scale perspective. Enhanced soil C decomposition in areas of temperate corn, temperate soybean, and temperate cereals leads to a loss of ecosystem C at a rate of 0.4 Pg yr^{-1}. If all crop areas – the ones that the CLM represents as crops and the ones that the CLM currently represents as grasses – lost C at this rate, the ecosystem C lost could exceed 1.2 Pg yr^{-1}.

This loss rate declines with time as soils affected by the enhanced decomposition gradually approach a new equilibrium. In our global simulations we activate the process of enhanced soil C decomposition in 1973 using present-day crop distributions rather than using transient crop areas and starting from the emergence of agriculture to the present. Given that humans have significantly disturbed present-day crop areas for years to centuries, we assume that true CO_2 emissions from cultivation have been more evenly distributed through time and that soil C losses have declined with time since the initial disturbance.

There are concerns of consistency on multiple levels regarding our community's varying definitions and usage of the LULM C flux (Pongratz et al., 2013; Houghton 2013; Gasser and Ciais, 2013). As just one example, current generation land and biogeochemical models used in assessments of the global C budget (Le Quéré et al.,

2013) are typically compared against bookkeeping models (Houghton 2003) that account for the loss of soil C from cultivation. We propose that land and biogeochemical models have the potential of improving their simulations of soil C and land use emissions by accounting for the loss of C from cultivation. By extension, in this way ESM simulations of atmospheric CO_2 trajectories also have the potential of improving.

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Tables

Table 1. Site Characteristics

County	%sand	%clay	Native grass type
Cherry, NE	65	15	50% C3, 50% C4
Dewey, OK	20	15	25% C3, 75% C4
Dunn, ND	20	15	50% C3, 50% C4
Hamilton, NE	20	15	50% C3, 50% C4
Hutchinson, TX	10	35	25% C3, 75% C4
Kingsbury, SD	10	35	75% C3, 25% C4
Lyman, SD	5	45	75% C3, 25% C4
Yuma, CO	40	20	50% C3, 50% C4

Table 2. Cultivation events and their corresponding decomposition enhancement factors for litter (εL) and soil C (εS). Litter and soil are indexed in order from labile to more recalcitrant C pools for three litter pools (metabolic, cellulose, and lignin) and three soil pools (active, slow, and passive). DayCent combines cellulose and lignin into a single structural litter pool. Site-specific schedule files prescribe the timing of events in each year (Table 3) in CLM and DayCent simulations.

Index	Description	$\varepsilon L1$	$\varepsilon L2$	$\varepsilon L3$	$\varepsilon S1$	$\varepsilon S2$	$\varepsilon S3$
A	RodWeed Row Plant	1.000	1.100	1.100	1.000	2.554	2.554
B	Planters and Cultivators	1.000	1.200	1.200	1.000	2.815	2.815
C	Field Cultivators and Planters	1.000	1.241	1.241	1.041	3.041	3.041
D	Field and Row Cultivators	1.000	1.500	1.500	1.000	3.500	3.500
E	Sweeps and Tandem Disks	1.000	1.600	1.600	1.100	3.691	3.691
F	Field Cultivator and Tandem Disk	1.000	1.649	1.649	1.149	3.849	3.849
G	Multiple Tandem	1.000	1.735	1.735	1.235	4.435	4.435
H	DisksPoint Chisel Tandem Disk	1.000	1.800	1.800	1.200	4.800	4.800
I	Offset and Tandem Disks	1.000	2.034	2.034	1.234	5.434	5.434
J	Pint Chisel Offset Disk	1.000	3.396	3.396	1.396	7.396	7.396
K	Moldboard Plow	1.000	3.500	3.500	8.000	8.000	8.000

Table 3. Example cultivation schedule for Dunn County, North Dakota. Farming activities map by indices (column 3) to 30-day enhancement effects on soil decomposition (Table 2). Farming activities that occur before the 30 days have completed take full effect and replace previous activities. Farming activities do not combine.

Year	Day of year	index	explanations
1917	159	G	
1917	189	G	
1917	220	G	
1918	111	G	
1918	118	K	
1919	136	K	
1919	141	C	
1919	197	C	
1920	159	G	The previous 3-year period of farming activities repeats…
[…]			
1937	197	C	…and this event completes this phase
1938	159	G	
1938	189	G	
1938	220	G	2 years outside of any 3-year cycle
1939	111	G	
1939	118	K	
1940	131	G	Activity added to beginning of the previous 3-year cycle…
[…]			
1954	197	C	…and this event completes this phase
1955	159	G	Original 3-year cycle resumes…
[…]			
1966	197	C	…and this event completes this phase
1967	159	E	
1967	189	E	
1967	220	E	
1968	111	E	New 3-year cycle
1968	118	I	
1969	136	J	
1969	141	C	
1969	197	C	
1970	159	E	3-year cycle repeats…
[…]			
2008	197	C	…and this is the last event of a complete 3-year cycle
[…]			
2010	118	I	Partial 3-year cycle and simulation end in 2010

Table 4. CLM's global annual cultivation events and corresponding decomposition enhancement factors for litter and soil C (pools as in Table 2) in different countries.

Date	Crop	Description	$\varepsilon L2$	$\varepsilon L3$	$\varepsilon S1$	$\varepsilon S2$	$\varepsilon S3$
		More developed country					
15 Apr-14 May	All	Offset & Tandem Disks	6.67	6.67	6.67	6.67	1.00
15 May-13 Jun	All	Drill	3.41	3.41	3.41	3.41	1.00
14 Jun-13 Jul	Corn & Soybean	Row Cultivator	3.41	3.41	3.41	3.41	1.00
		Less developed country					
15 Apr-29 Apr	All	Plowing	10.00	10.00	10.00	10.00	1.00
30 Apr-14 May	All	Cultivator	2.69	2.69	2.69	2.69	1.00
15 May-13 Jun	All	Drill	3.41	3.41	3.41	3.41	1.00
14 Jun-13 Jul	Corn & Soybean	Hand Weeding	1.10	1.10	1.10	1.10	1.10

Figure Captions

Figure 1. Soil carbon (g m^{-2}) from the GRASS, CROP, and CLTV simulations in Dunn County, North Dakota. Showing years 1900-2010 (a) from CLM's top ~29 cm of soil depth; values range $1.70x10^4$ - $1.95x10^4$ gC m^{-2}, (b) from DayCent's ~20-cm soil, and (c) the data from (a) and (b) as the CLTV-CROP difference.

Figure 2. Area averaged soil carbon (g m^{-2}) in CLM's top ~29 cm of soil depth from the global CROP and CLTV simulations for the years 1973-2004. (a) Central United States at 30-45°N 85-105°W and (b) global. Soil carbon increases by about 120 g m^{-2} in both the central U.S. and globally in the CROP simulation. Soil carbon decreases by about 900 g m^{-2} in the central U.S. and by about zero globally in the CLTV simulation. This difference in simulated trends is because the enhanced soil carbon decomposition due to cultivation applies to a much larger fraction of the total land area in the central U.S. than on the global scale.

Figure 1

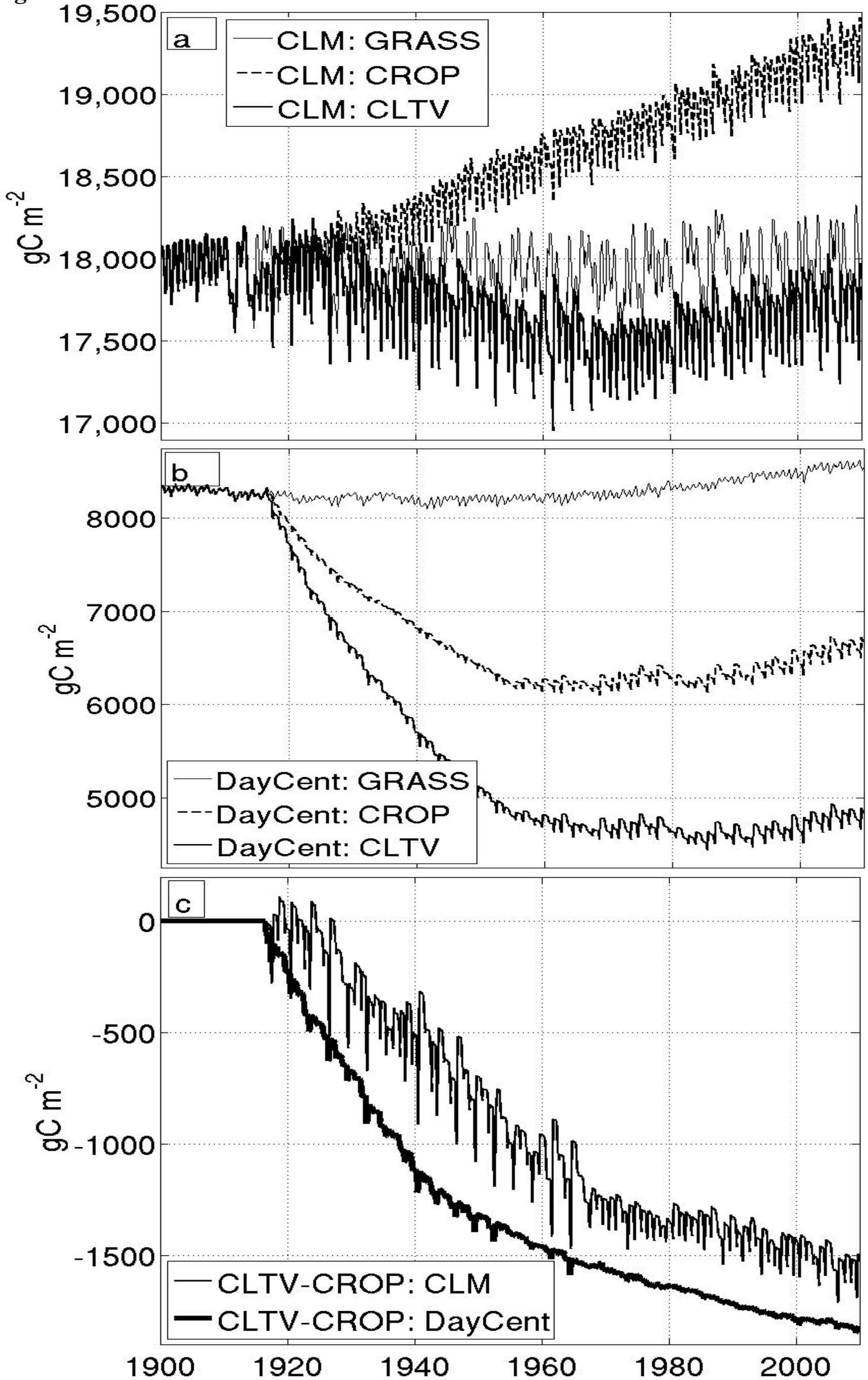
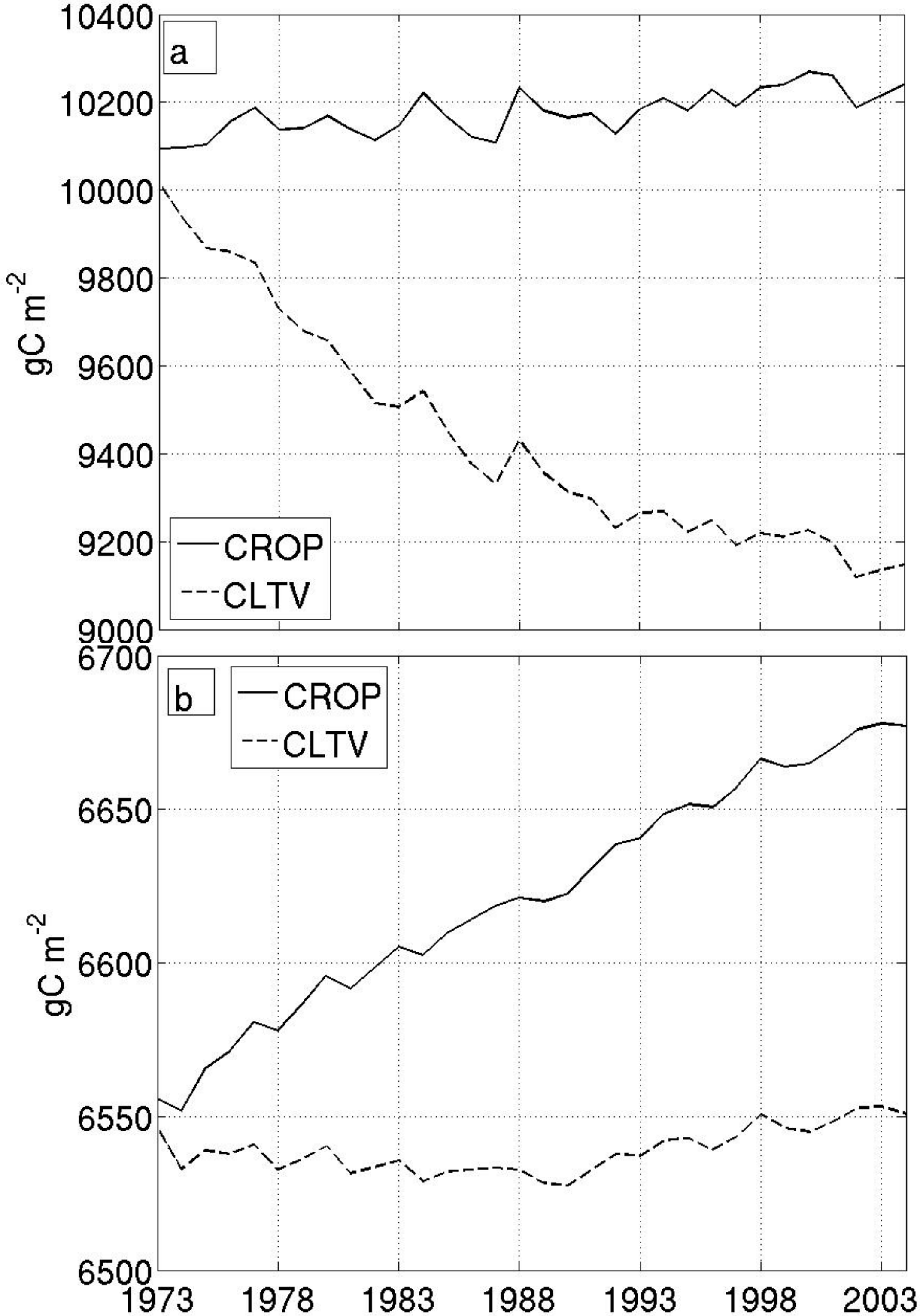

a
CLM: GRASS
CLM: CROP
CLM: CLTV
19,500
19,000
18,500
18,000
17,500
17,000
gC m-2
b
DayCent: GRASS
DayCent: CROP
DayCent: CLTV
8000
7000
6000
5000
gC m-2
c
CLTV-CROP: CLM
CLTV-CROP: DayCent
0
-500
-1000
-1500
gC m-2
1900
1920
1940
1960
1980
2000

Figure 2


a
CROP
CLTV
gC m-2
10400
10200
10000
9800
9600
9400
9200
9000
b
CROP
CLTV
gC m-2
6700
6650
6600
6550
6500
1973
1978
1983
1988
1993
1998
2003