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Carbon balances in US croplands during the last two decades of the twentieth century

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Abstract Carbon (C) added to soil as organic matter in crop residues and carbon emitted to the atmosphere as CO_2 in soil respiration are key determinants of the C balance in cropland ecosystems. We used complete and comprehensive county-level yields and area data to estimate and analyze the spatial and temporal variability of regional and national scale residue C inputs, net primary productivity (NPP), and C stocks in US croplands from 1982 to 1997. Annual residue C inputs were highest in the North Central and Central and Northern Plains regions that comprise $\sim$70% of US cropland. Average residue C inputs ranged from 1.8 (Delta States) to 3.0 (North Central region) Mg C ha^{-1} year^{-1}, and average NPP ranged from 3.1 (Delta States) to 5.4 (Far West region) Mg C ha^{-1} year^{-1}. Residue C inputs tended to be inversely proportional to the mean growing season temperature. A quadratic relationship incorporating the growing season mean temperature and total precipitation closely predicted the variation in residue C inputs in the North Central region and Central and Northern Plains. We analyzed the soil C balance using the crop residue database and the Introductory Carbon Balance regional Model (ICBMr). Soil C stocks (0–20 cm) on permanent cropland ranged between 3.07 and 3.1 Pg during the study period, with an average increase of $\sim$4 Tg C year^{-1}, during the 1990s. Interannual variability in soil C stocks ranged from 0 to 20 Tg C (across a mean C stock of 3.08 $\pm$ 0.01 Pg) during the study period; interannual variability in residue C inputs varied between 1 and 43 Tg C (across a mean input of 220 $\pm$ 19 Tg). Such interannual variation has implications for national estimates of CO_2 emissions from cropland soils needed for implementation of greenhouse gas (GHG) mitigation strategies involving agriculture.

Keywords Climate change · Cropland carbon cycling · Agriculture · Carbon budgets · Regional and national scale

Abbreviations

AgCensus	Census of Agriculture
AIC	Akaike Information Criterion

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C	Carbon
CPR	Crop Production Region
GHG	Greenhouse gas
NASS	National Agricultural Statistics Service
NEP	Net Ecosystem Productivity
NPP	Net Primary Productivity
P	Precipitation
PET	Potential evapotranspiration

Introduction

The carbon balance in terrestrial ecosystems has large implications on the variation in atmospheric carbon dioxide (CO_2) emissions. Atmospheric CO_2 has increased from 280 ppmv (in 1850) to over 387 ppmv in 2009 (NOAA 2009), due to human perturbations of the global carbon cycle, including land use activities. The agricultural sector is a significant source of anthropogenic greenhouse gas (GHG) emissions, both globally and in the US (IPCC 2007; USEPA 2009). Agriculture is currently responsible for about 7% of US GHG emissions, mostly as CH_4 and N_2O from livestock and soil emissions, while soils are estimated to be a small sink for CO_2 (USEPA 2009). It is believed that agricultural soils can be a significant sink by adopting appropriate improved management practices and therefore contribute to mitigating atmospheric CO_2 emissions (Lal et al. 1998; Paustian et al. 1997a, b, 2002; Follett 2001; Smith et al. 2007).

Long-term trends in productivity and residue inputs to soil, driven by technological and management changes, impact the magnitude and direction of change in soil C storage (Allmaras et al. 1999; Paustian et al. 1997a; Johnson et al. 2006). Because of the high NPP of many agricultural crops, relative to non-cropland vegetation, agricultural systems can substantially increase short-term C exchanges between the land surface and the atmosphere in regions converted to agricultural land use, like the central US. An illustration of this is the large seasonal decreases in atmospheric CO_2 concentrations, of up to ~30 ppm, that are observed over the central Corn Belt region during the mid-summer growth period (Miles 2010). Interannual variability in cropland CO_2 uptake, driven both by weather variability and changes in crop species distribution, as well as interannual variability in net ecosystem C storage, may have significant implications for estimating short-term changes (i.e., over a few years) in terrestrial C balances, for both atmospheric-based estimates of regional C cycling (e.g., Denning et al. 1995; Gurney et al. 2002) and ground-based soil C inventories (e.g., Goidts et al. 2009; Saby et al. 2008).

Spatial and temporal variability of C inputs present significant challenges for estimating the C balance in agricultural ecosystems. Net primary productivity (NPP) represents the total net uptake of atmospheric CO_2 by crop plants during the growing season. Thus, top-down, inverse modeling approaches based on measurements of CO_2 concentration gradients and atmospheric transport (Gurney et al. 2002; Rödenbeck et al. 2003; Michalak et al. 2004; Bruhwiler et al. 2005; Peters et al. 2005; Baker et al. 2006; Lokupitiya et al. 2008) are highly sensitive to the NPP signal in agriculturally dominated regions. However, a large proportion of NPP (about 40–50% of above ground biomass in grain crops) is removed as harvest products and thus the *long-term* C balance of croplands is instead governed by the amount of crop residues that remain in the field. Although there are means of direct estimation of soil C changes (e.g., measurements based on field sampling and lab analyses) and CO_2 emissions (e.g., eddy covariance measurements), most regional or national scale estimates of soil C change depend on model-based approaches (van Wesemael et al. 2010), using so-called bottom-up methods based on soil, climate, land use and management activity data (Paustian et al. 2002; Andrén et al. 2004, 2008; Ogle et al. 2007; West et al. 2008). For both top-down and bottom-up approaches, interannual variability in NPP and residue C inputs, respectively, represents a signal-to-noise problem in that estimates based on observations in a particular year or over a few years may not represent longer-term underlying trends.

Most model-based analyses of regional to national scale soil C dynamics estimate C inputs by simulating crop and residue production as a function of climate, soil and management (Ogle et al. 2010) and/or utilize estimates of production based on remote sensing (Potter et al. 2007). US crop yield data, collected annually by the National Agricultural Statistics Service (NASS) have also been used in broad-scale crop NPP estimates (Prince et al. 2001; Lobell et al. 2002; Johnson et al. 2006). One drawback of the standard NASS data is missing data and gaps in coverage. To address this, Lokupitiya et al. (2007)

derived a comprehensive database of county level crop areas and yields in the US for the period 1982–1997 by combining data from NASS and the US AgCensus and using statistical models to fill data gaps.

The objective of our study was to use this database to explore trends and interannual variability of US cropland C balances, focusing on the spatial and temporal patterns of net C uptake, crop residue inputs and soil C dynamics. To estimate soil C changes, we coupled our empirically-based estimates of C inputs to a simple model, the Introductory Carbon Balance Model (ICBMr; Andrén and Kätterer 1997, 2001; Andrén et al. 2004, 2008), which has been previously applied to broad-scale assessments in Sweden, Canada, and Africa.

Materials and methods

Estimation of crop NPP and residue C inputs

We used the gap-filled county-level crop yield and area database developed by Lokupitiya et al. (2006, 2007; Fig. 1). Estimates of residue C inputs were made for the nine most dominant crops in the US, that together make up over 90% of the total US harvested cropland area: alfalfa (*Medicago sativa* L.) hay, barley (*Hordeum vulgaris* L.), corn (*Zea mays* L.) for grain, corn for silage and green chop, oats (*Avena sativa* L.), other hay (hay other than alfalfa; i.e., tame hay, small grain hay, wild hay), sorghum (*Sorghum bicolor*), soybean (*Glycine max* L.), and wheat (*Triticum aestivum* L.). Using the approach presented in earlier studies, (Bolinder et al. 1999; Clapp et al. 2000; Prince et al. 2001; Allmaras et al. 2004), we estimated the above- and belowground crop biomass and residue C inputs using algorithms (Table 1) based on crop-specific harvest indices and root:shoot ratios from published biomass partitioning studies (Lawes 1977; Wych and Stuthman 1983; Buyanovsky and Wagner 1986; Russell 1991; Bolinder et al. 1997, 1999; Juma et al. 1997; Peters et al. 1997; Pierce and Fortin 1997; Vanotti et al. 1997; Campbell and de Jong 2001; IPCC 2006). Yield data were first corrected for water content and total (aboveground and belowground) residue dry matter (kg ha^{-1}) was estimated from yields (reported as tons acre^{-1} for hay and silage crops and bushels acre^{-1} for grain crops) using the algorithms given in Table 1. The algorithms given in Table 1 are a combination of separate algorithms for estimating aboveground and belowground residues, including relevant unit conversions. Carbon content in the residues was then calculated by multiplying the residue biomass values by 43%, an average based on a range of values (i.e., between 40 and 45%) from past studies (Buchanan and King 1993; Bolinder et al. 1997; Vanotti et al. 1997; Baran et al. 2001; Burgess et al. 2002; Torbert et al. 2004). Crop area from the database was used to estimate NPP (estimated as yield plus total residues) and residue C inputs over the cropland area in each county. Estimated residue carbon inputs were validated against the independent measurements at several long-term agricultural experiment sites (Bruce and Langdale 1997; Halvorson et al. 1997; Hendrix 1997; Lyon et al. 1997; Peters et al. 1997; Peterson and Westfall 1997) that had data for annual residue amounts. For most of the analyses, county-level data were aggregated into seven Crop Production Regions (CPRs) for the conterminous US (i.e., lower 48 States): Far West, Central and Northern Plains, Southern Plains, North Central, Delta States, Northeast, Southeast (Young et al. 2001; Lin et al. 2000; Fig. 1).

Analyses of residue carbon inputs in relation to weather variables

County-level monthly precipitation and temperature data for the period 1982–1997 were computed using the PRISM database (Daly et al. 1994), which consists of gridded (4 km^2) values for the conterminous US. Monthly potential evapotranspiration (PET) was estimated using the method by Thornthwaite (1948). For summary interpretations, county-level estimates of C inputs and weather variables were aggregated by CPR (Fig. 1) and to the national-level, using area-weighted averaging. Correlations between each weather variable and residue production (in Mg C ha^{-1} year^{-1}) for each CPR were determined using the Pearson correlation. To determine which combination of weather variables could best predict the observed temporal pattern of residue C input rates (i.e., as an indicator of primary productivity), annual, monthly, or mean growing season weather data were used as independent variables in a suite of linear mixed-effect models (in SAS version 9.1), applied to each CPR. The best model was chosen based on the Akaike

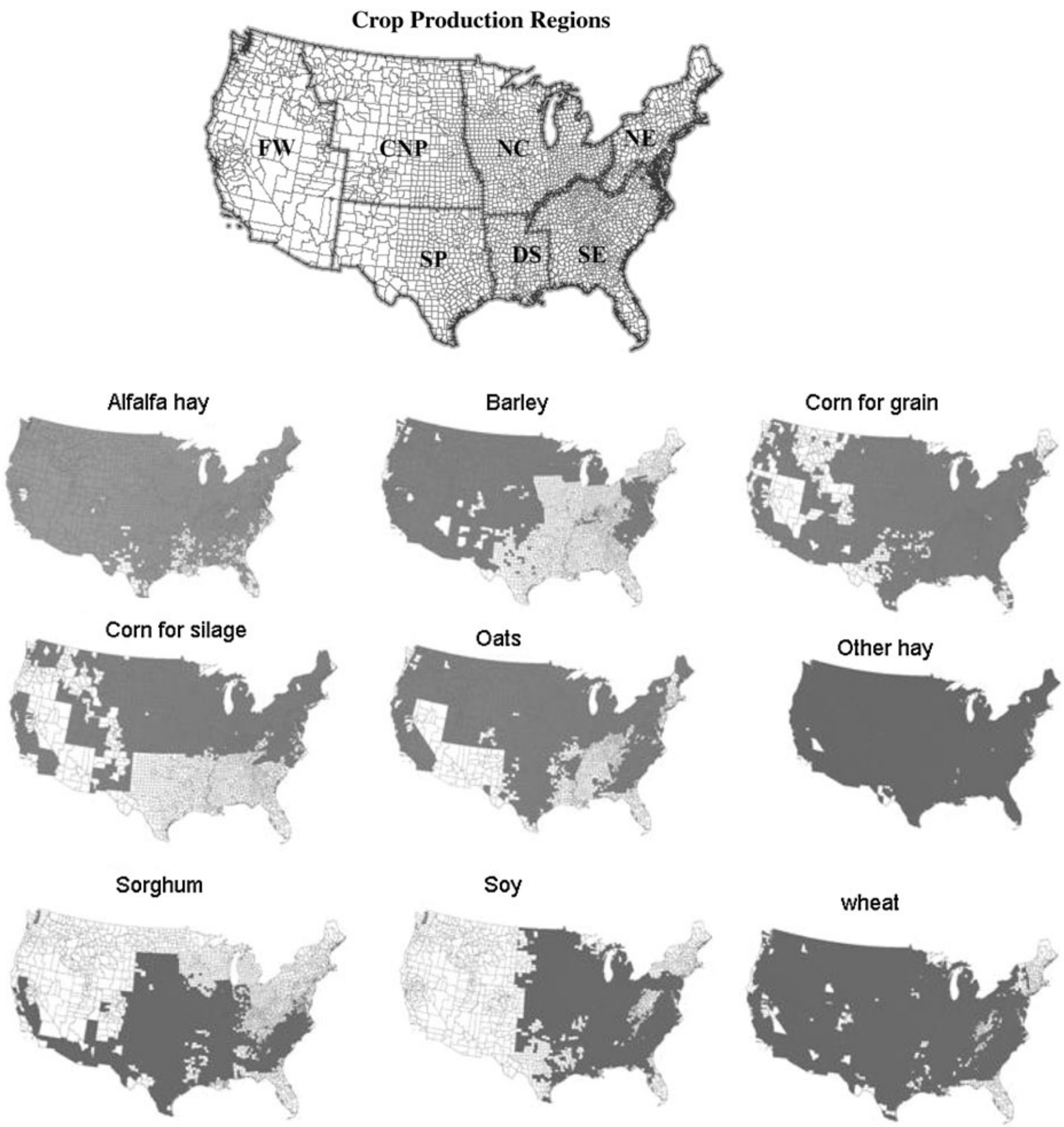

Fig. 1 Crop Production Regions (CPR) of the conterminous US (*top*) (*CNP* Central and Northern Plains, *DS* Delta States, *FW* Far West, *NC* North Central, *NE* Northeast, *SE* Southeast, *SP* Southern Plains) and maps showing the counties reporting major crops for 1982–1997 according to the database developed by Lokupitiya et al. (2007)

Information Criterion (AIC; Eq. 1), which is a measure of goodness of fit that is widely used for selecting among several alternative models. The AIC includes a 'penalty' for the number of free parameters in a model and thus both the model error (e.g., residuals of predicted versus observed values) and model complexity (i.e., number of parameters) are both factored in, with the objective of identifying the simplest model that best explains the observations (Akaike 1974; Vaida and Blanchard 2005). Thus the model with the lowest AIC was chosen as the best model.

Table 1 Algorithms[a] used in the calculation of total residue dry matter (kg ha^{-1}) from yield (bushels acre^{-1}) in major crops

Crop	Slope	Intercept
Barley	64.34	753.62
Corn for grain	78.45	735.26
Corn for silage	207.32	0
Hay alfalfa	1623.85	0
Oats	52.87	491.02
Other hay	1137.43	0
Sorghum	76.93	1192.08
Soybean	95.39	1456.25
Wheat	118.49	594.08

[a] Slope and intercepts corresponding to the final equation derived using several steps and algorithms (developed by Steve Williams (IPCC 2006) using published past studies) for estimating aboveground and belowground residue dry matter from yields after correcting for moisture, are given. The dry matter values derived needs to be multiplied by the fraction of carbon, to get the carbon content. Note that the slope and intercept values given here also include the unit conversions

$$\mathrm{AIC} = 2p - 2\ln(L) \tag{1}$$

p, number of parameters in the model; L, maximum likelihood function for the estimated model (which is a measure of how close the model parameters (sample) are to the “true” (population) values).

Interannual variability in C input rates in different CPRs were computed using the first-difference approach (i.e., the difference between the value for a time period in year t minus the corresponding period in year $t-1$; Peterson et al. 1998) and the deviation from the mean for the entire study period. The temporal trends in yields and residue C inputs were analyzed using a 5-year moving average across the study period (1982–1997).

Our main focus was on the magnitude and variability of C fluxes involving managed cropland. To exclude the effects of the fluctuations in total cropland area and changes in land use, such as conversion of cropland to perennial grass set-aside land in the Conservation Reserve Program (CRP), the analyses were normalized to per hectare rates and only the land that was under crop production during the entire study period was included in the analysis; this land area (i.e., 89.4 Mha) was considered as the permanent cropland, which included 91% of the area as rainfed and 9% as irrigated cropland.

Estimation of soil C stocks and stock changes

ICBM regional (ICBMr) model description

The ICBMr model (Andrén et al. 2004, 2008) has two main soil C pools: a ‘young’ C pool (Y) and an ‘old’ C pool (O). The model incorporates annual carbon inputs i (Mg ha^{-1} year^{-1}) and four other parameters/variables: first-order decomposition constants for Y (k_Y year^{-1}) and O (k_O year^{-1}), a variable to represent influence from soil climate r_e (dimensionless), and humification coefficient h (fraction of decomposed Y that is transferred to O, after subtracting the CO_2–C outflow from Y; dimensionless). Since our objective was to analyze interannual variability and trends over the study period, we initialized soil C stocks by computing the average steady-state C stocks (Andrén and Kätterer 1997; Andrén et al. 2004, 2008), using the mean residue C input rates and the average r_e value, averaged over the 16 year period, by county.

Equations 2 and 3 below were the first order decomposition equations used in the calculation of the young and old soil C stocks (Andrén et al. 2004).

$$Y_t = (Y_{t-1} + i_{t-1})e^{-k_Y r_e} \tag{2}$$

$$O_t = \left(O_{t-1} - h\frac{k_Y(Y_{t-1} + i_{t-1})}{k_O - k_Y}\right)e^{-k_O r_e} + h\frac{k_Y(Y_{t-1} + i_{t-1})}{k_O - k_Y}e^{-k_Y r_e} \tag{3}$$

Y, Young C pool (Mg ha^{-1}); O, old C pool (Mg ha^{-1}); t, time (year); i, annual C input (Mg ha^{-1}); h, humification coefficient (dimensionless); k_Y, decomposition constant for ‘young’ organic matter (i.e., fraction of Y that decomposes in a year; year^{-1}); k_O, decomposition constant for ‘old’ organic matter (i.e., fraction of O that decomposes in a year; year^{-1}); r_e, external influence coefficient (dimensionless).

Model inputs and parameter estimation

County-level annual crop residue C inputs (Mg ha^{-1} year^{-1}) for the US (estimated as described above) were the C inputs to the model. We used, as recommended, the ICBMr default values for the decomposition and humification coefficients ($k_Y = 0.8$, $k_O = 0.006$, and $h = 0.13$; Andrén et al. 2004), which are constants that had been derived based on the data from field experiments with common agricultural crops and other experiments using litter bags and ^{14}C-labeling techniques (Andrén and Kätterer 1997). For example, the h parameter is higher, about 0.3, for more recalcitrant materials such as farmyard manure. The model is designed to summarize all external influence on decomposition rates due to differences in crop transpiration, soil types, climate or weather into the coefficient r_e. The r_e coefficient was estimated using the weather to soil climate module ($W2r_e$) as detailed in Andrén et al. (2004). Parameter r_e incorporates three sub-parameters representing soil water balance (r_w), soil temperature (r_t), and a cultivation factor (r_c) as shown in Eq. 4.

$$r_e = r_W \times r_T \times r_c. \tag{4}$$

Since the focus of our study was on the magnitude and variability of C inputs as they impact the soil C balance, we used a constant (default) value of $r_c = 1$.

The r_e values using the other two components of (r_W and r_T) were estimated for specific crop types ($n = 9$) and soil types ($n = 11$) of the US at county level, annually for the period 1982–1997. Soil types were based on the soil texture, i.e., the proportions of silt, clay, and sand. Soil data used (i.e., volumetric water content at field capacity and wilting point by soil type), and the percentage of each soil type at county level for the US were obtained from the STATSGO database (http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/).

Soil water balance calculations for r_W (Eq. 5) were based on FAO guidelines (Allen et al. 1998), including daily precipitation (PPT), actual evapotranspiration (actual evaporation from soil and actual transpiration from crops), crop interception, runoff and percolation, as previously described by Andrén et al. (2004). PET was estimated using the Hargreaves ET_o equation (Hargreaves and Samani 1985; Allen et al. 1998; Samani 2000). The daily precipitation, minimum and maximum temperatures, solar radiation (W m^{-2}) at county level were extracted using the Daymet database (http://www.daymet.org/) for the PET calculation. For counties with both irrigated and rainfed agriculture, irrigation amounts for each crop were extracted from the Census of Agriculture, and added to precipitation. Crop coefficients for estimating interception (K_c, K_{cb}, and K_e; Allen et al. 1998) considered the growth period of each crop, using crop calendars published by USDA (1997); for alfalfa, the start dates of the growth period within a year were based on the last frost date in the spring.

$$r_w = \theta_r^{\gamma} \tag{5}$$

r_w, water response factor (soil water balance; dimensionless); θ_r, relative water content (dimensionless; see Eq. 6); γ, 1.3 (chosen to approximate the water response function according to Lomander et al. 1998; Andrén et al. 2004).

Volumetric water content at field capacity and wilting point for different soil types in the US was thus used in calculating the relative water content and r_W (Eq. 6; Andrén et al. 2004). Air temperature from the Daymet database was adjusted to soil temperature using a simple empirical equation (Eq. 7), and soil temperature was used in a quadratic relationship to derive r_T (Eq. 8; Andrén et al. 2004).

$$\theta_r = \frac{\theta - \alpha\theta_{wilt}}{\theta_{fc} - \alpha\theta_{wilt}} \tag{6}$$

θ, volumetric water content (dimensionless), which is a fraction derived by dividing the top soil water store (mm; calculated using the FAO guidelines (Allen et al. 1998)) by the top soil thickness (mm); θ_{wilt}, volumetric water content at wilting point; θ_{fc}, volumetric water content at field capacity; α, fraction of the water content at wilting point that contributes to yield the minimum water store in the top soil.

$$T_{soil} = \max(-2; 0.92\ T_{air}) \tag{7}$$

T_{soil}, soil temperature °C; T_{air}, air temperature °C.

$$r_T = \frac{(T_{soil} - T_{\min})^2}{(30 - T_{\min})^2} \tag{8}$$

r_T, temperature factor; T_{soil}, soil temperature °C; $T_{\min}$, lower temperature limit for decomposer activity (i.e., −3.8°C; Kätterer et al. 1998).

Model runs

In this study, we ran ICBMr separately for irrigated and rainfed cropland in each county using combined C inputs from all the crops. Daily r_e values at county level were calculated for each crop by soil type, for a topsoil depth of 20 cm, separately for irrigated crop areas and rainfed areas over a 17-year period from 1981 to 1997. A depth of 20 cm was chosen as a representative top-soil depth that captures most of the short-term and interannual variability in soil C stocks and to facilitate comparisons with regional and national estimates using soil carbon models such as Century. Average r_e values for irrigated and rainfed cropland in each county was then calculated using the area weighted r_e values from different crop/soil categories. Carbon stocks from the irrigated, rainfed, and total cropland in each county and the whole US were estimated for the period 1982–1997, using Eqs. 2 and 3. The analyses could be performed up to 1997, since the gap-filled, complete county-level crop yield and area data were not available for more recent years. Estimated C stocks during the study period were then analyzed considering the variation associated with weather changes, C inputs, and cropping practice (i.e., irrigated versus rainfed).

Results

The largest proportion of the total cropland area over the study period was occupied by corn for grain (24%), wheat (22%), and soybean (22%). These crops were followed by hay (other hay and alfalfa hay; jointly about 21% of the cropland area), sorghum, barley, oats, and corn for silage, each of which occupied less than 5% of the total cropland area.

Spatial variation of residue C inputs

Spatial variation in residue C inputs depends on the relative dominance of different crop species, their production potential and biomass allocation, weather and other environmental factors. Most counties in the western US had very low residue C inputs per total county area, although the C inputs per ha of cropland (within each county) were often high (Fig. 2), due to the prevalence of irrigation. Per county C input rates were highest in the counties of the Corn Belt region (Fig. 2), which falls within the North Central CPR (Fig. 1).

Total residue C inputs were highest in the North Central region and Central and Northern Plains regions (Table 2), representing the major proportion of US cropland (ca. 40% of the US cropland in North Central and 30% in Central and Northern Plains). Delta States and Northeast regions, which had the lowest percentage ($\sim$10–15%) of total cropland area in any given year, together encompassed about 10% of the total annual C inputs in the US cropland.

Highest yields and C input rates per hectare were observed in Far West and North Central regions for majority of the crops. Delta States, Southern Plains and Central and Northern Plains regions usually produced lower yields and residue C inputs for most crops. Of all the crops, corn for grain production had the highest C inputs per cropland hectare, followed by sorghum, wheat, and soybean. Barley and oats had relatively low residue C input rates, and alfalfa hay had the highest C input rates of the hay crops.

Crop residue C input rates clearly showed correlations with regional climate, especially with mean growing season temperature. On average, mean growing season temperature differed by a maximum of 6°C between CPRs, with Southern Plains (24.6 $\pm$ 0.45°C), Delta States (24.8 $\pm$ 0.56°C), and Southeast (23.2 $\pm$ 0.6°C) regions having the highest temperatures, and the Far West and North Central regions (averaging between 17 and 20°C), having the lowest temperatures during the growing season. Annual C input rates from all CPRs (combined) were negatively correlated with mean growing season temperatures ($r = -0.65$; $P < 0.05$).

Precipitation/potential evapotranspiration (P/PET) ratio, which reflects the moisture availability for plant growth, differed greatly across the different CPRs. The percentage of counties with P/PET ratio less than 1 (i.e., low moisture availability) was high for the Central and Northern Plains (34–91% of counties within the region), Far West (34–70%), and Southern Plains (47–91%). The majority of the counties in Far West and Southern Plains had a large proportion of irrigated crop area (>50% of the total cropland area). CPRs in the eastern half of the US had the highest average P/PET ratios. However, at the scale of CPRs, there were no statistically significant correlations between C input rates and P/PET alone.

Regional distribution of cropland NPP and C inputs to soil

Total annual C uptake in NPP by the US permanent cropland over the analysis period averaged 401.5 $\pm$ 34.2 Tg year^{-1}. The residue C inputs were about 55% of NPP. Highest per ha NPP and C input rates were observed in the Far West (irrigated areas) and North Central regions, followed by Central and Northern Plains. The average regional annual cropland NPP over the study period ranged from

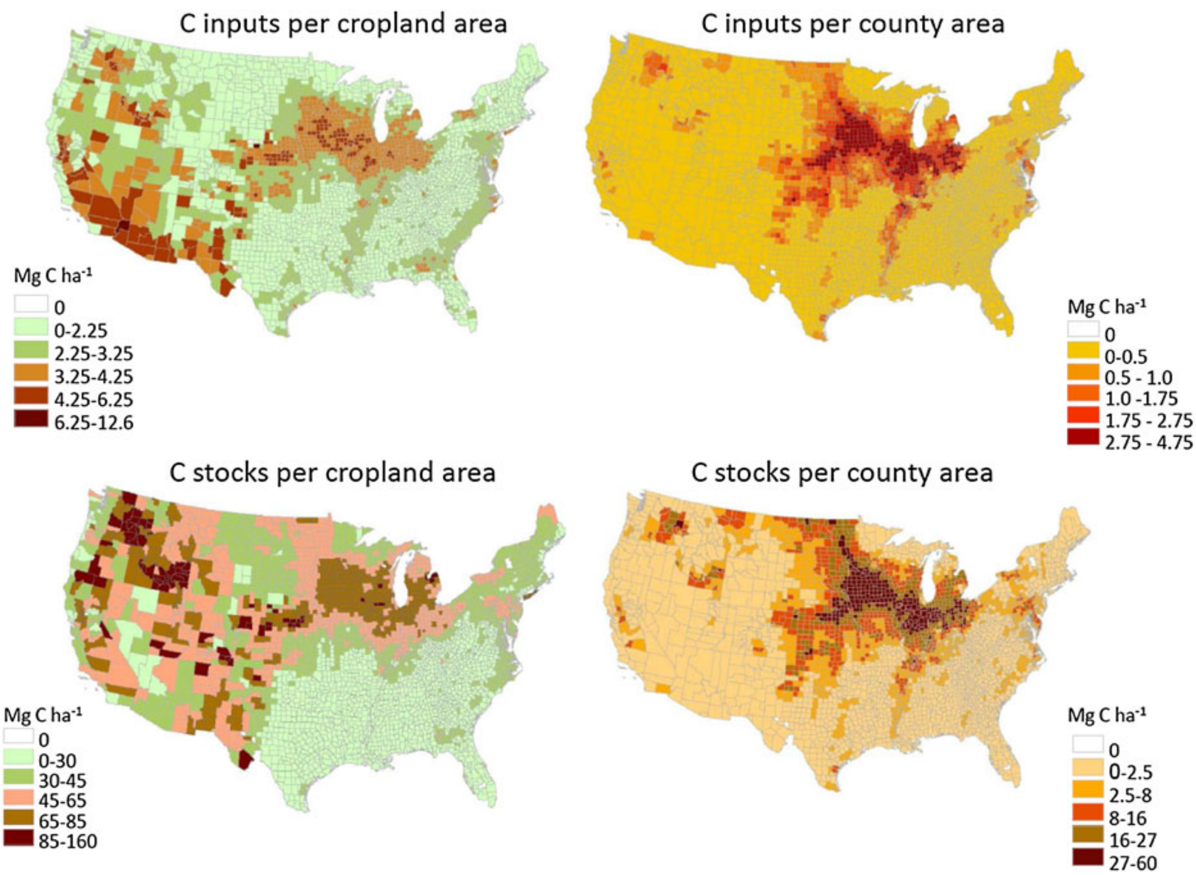

Fig. 2 County-level total C inputs and C stocks on permanent cropland during 1997. Maps on the *left-hand side* show values (C input rates and stocks) per unit area of cropland only, while maps on the *right-hand side* show values expressed per unit total land area. Note that the high levels of C inputs and soil C stocks per unit of cropland only, in semi-arid and arid areas in the western US, reflect irrigated areas that comprise a small portion of the total land area

3.1 ± 0.25 Mg ha^{-1} year^{-1} in Delta States to 5.36 ± 0.22 Mg ha^{-1} year^{-1} in the Far West. Although the average NPP in crop areas was high in Far West, cropland comprised a small percentage (ca. 5%) of the land area in the region. At national scale, the US cropland NPP over the study period ranged from 3.61 Mg ha^{-1} year^{-1} (in 1988) to 5.07 Mg ha^{-1} year^{-1} (in 1994), while the residue C inputs over the period ranged between 2.23 Mg ha^{-1} year^{-1} (in 1988) and 3.14 Mg ha^{-1} year^{-1} (in 1994).

Total NPP in the permanent cropland ranged between 324 Tg C year^{-1} (in 1988) and 457 Tg C year^{-1} (in 1994). Interannual variability of NPP on permanent cropland ranged between 2 and 87 Tg C year^{-1}. The annual residue C inputs added on permanent cropland over the study period ranged between 178 Tg C year^{-1} (in 1988) and 251 Tg C year^{-1} (in 1994; Table 2), and the interannual variability based on the first-difference approach ranged between 1 and 48 Tg C year^{-1}.

Temporal variation in residue C inputs

Any impact of the management practices used during the study period was reflected in the variation of crop productivity and thus residue C inputs. The lowest between-year variation for C input rates (i.e., 19% difference between the minimum and maximum) over the study period was observed for the Delta States region, and the highest variation (i.e., 40% difference between the minimum and maximum) was observed for the North Central region.

Average yields of barley, corn, oats, sorghum, soybean, and wheat showed an overall increasing trend over the study period, although there was considerable variation from year to year (data not

Table 2 Average C inputs and stocks (Tg) in Crop Production Regions (CPRs) within the US cropland

Year	CNP		DS		FW		NC[a]		NE[a]		SE[a]		SP		US total	
	Input	Stock	Input	Stock	Input	Stock	Input	Stock	Input	Stock	Input	Stock	Input	Stock	Input	Stock
1982	55	910	6	47	13	247	113	1541	8	109	12	112	12	126	219	3091
1983	52	908	5	47	14	247	87	1537	7	109	9	111	12	126	186	3084
1984	54	905	6	47	14	247	107	1529	8	108	12	111	12	126	213	3074
1985	58	906	6	47	13	247	119	1533	9	108	12	112	12	127	229	3079
1986	59	907	6	47	13	247	119	1537	8	109	11	112	12	126	226	3085
1987	59	905	6	47	14	246	116	1533	8	109	11	111	12	126	225	3077
1988	48	906	6	47	14	247	80	1533	7	108	11	112	12	126	178	3079
1989	50	903	6	47	14	247	112	1530	8	108	12	112	11	127	212	3074
1990	59	904	6	47	14	247	117	1537	8	108	11	112	12	127	227	3081
1991	57	905	6	47	14	247	107	1533	7	108	11	111	12	127	214	3078
1992	63	904	7	47	14	247	127	1531	8	108	13	111	13	127	244	3074
1993	56	911	6	47	15	247	100	1547	7	109	11	112	12	127	207	3100
1994	64	910	7	47	14	248	132	1534	9	109	13	112	12	127	251	3087
1995	56	911	6	47	15	247	112	1544	8	109	12	112	11	127	219	3097
1996	64	910	7	48	15	247	118	1541	9	109	13	112	11	127	236	3094
1997	64	913	7	48	15	248	122	1549	8	109	12	112	13	127	240	3105

The description of the CPRs is as follows: *CNP* Central and Northern Plains, *DS* Delta States, *FW* Far West, *NC* North Central, *NE* Northeast, *SE* Southeast, *SP* Southern Plains. C inputs given under each year corresponds to the input by the end of the previous year, which was used in the C stocks as given. Totals are computed for a fixed cropland area of 89.4 Mha

[a] Irrigated crop area was much less than 1% of the total cropland

shown). Average yields of hay crops and corn for silage remained relatively stable.

Based on 5-year moving averages, average C input rates (from all the crops combined) increased from 1982 to 1997 (Fig. 3), by 0.22 Mg ha^{-1} in the Central and Northern Plains, 0.23 Mg ha^{-1} in the Delta States, 0.42 Mg ha^{-1} in the Far West, 0.25 Mg ha^{-1} in North Central, 0.08 Mg ha^{-1} in Northeast, 0.23 Mg ha^{-1} in Southeast. In the Southern Plains, the overall trend was neither increasing nor decreasing over the study period (Fig. 3).

Carbon input rates varied with changing weather over the study period. The lowest C inputs to US cropland soils were observed in 1988 (Table 2; Fig. 4), a prominent drought year with the lowest average annual precipitation (82 ± 35.4 cm), and the second highest mean growing season temperature (21.6 ± 3.26°C) during the period. Within the different regions, there was no statistically significant relationship between temporal variation of C input rates and precipitation alone. Area-weighted annual residue C input rates (Mg ha^{-1} year^{-1}) for the whole US were negatively correlated with the mean growing season temperature over the study period (i.e., $r = -0.65$; $P < 0.05$). At individual CPR level, such a significant negative correlation could be found for Delta States ($r = -0.51$; $P < 0.05$), North Central ($r = -0.62$; $P < 0.05$), Northeast ($r = -0.62$; $P < 0.05$), and Southeast ($r = -0.74$; $P < 0.05$) regions.

The observed temporal variation in C input rates was well described by a quadratic relationship, which had the lowest AIC in the mixed model runs. For instance, for CNP, the AIC values predicted for all the other models with different parameter combinations yielded much higher AIC values compared to the quadratic model. Table 3 shows the lowest AICs (i.e., the last row of the table) for different regions obtained by the quadratic relationship, which incorporated mean growing season temperature, squared mean growing season temperature, total growing season precipitation, squared total growing season precipitation, and interaction between the mean growing season temperature and mean growing season precipitation. With this model, the coefficient for the quadratic term for mean growing season temperature (i.e., Gtmean^2; Table 3) was negative for all the CPRs, and the

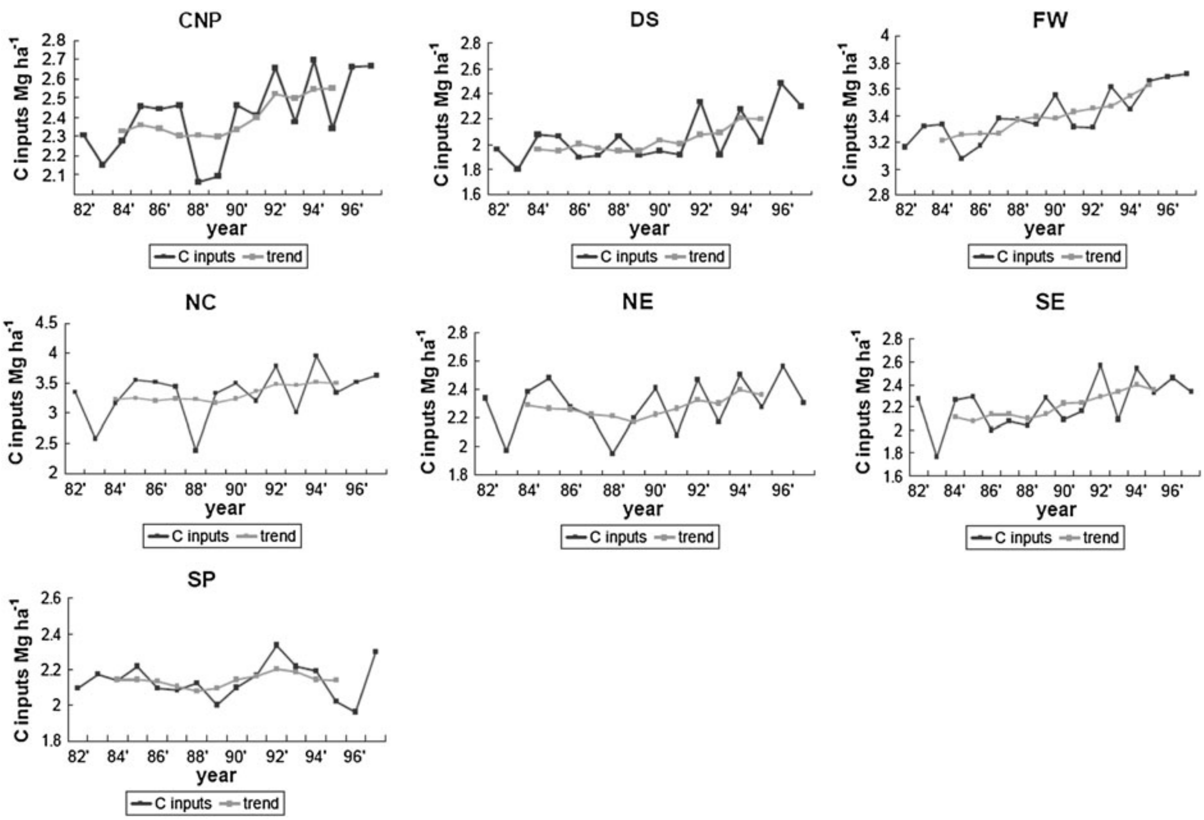

Fig. 3 Temporal trends of carbon input rates during the study period, estimated for different CPRs using the 5-year moving averages. *CNP* Central and Northern Plains, *DS* Delta States, *FW* Far West, *NC* North Central, *NE* Northeast, *SE* Southeast, *SP* Southern Plains

weather variables closely predicted the very low C input rates observed in 1988, and 1993 in the Central and Northern Plains and North Central regions (Fig. 5).

Validation of residue C inputs

The estimated residue C inputs were mostly within 0.15 relative error (i.e., (observed − predicted)/observed), when the estimated values were compared against the observed data at several long-term experimental sites (Table 4). Because of the limited set of independent residue measurements available, no clear trends were found in model deviations as a function of crop type or region.

Estimation of soil carbon stock changes

According to the ICBM simulations carried out in Sweden, Canada, and Africa, mean annual r_e values (by definition 1 in Uppsala, Sweden) are typically greater than 1 in more temperate and tropical climates except for very dry soils. In relatively moist and temperate climates r_e values approaching 3 are not uncommon (Andrén et al. 2007, 2008). The r_e values reflected the combined temperature and precipitation influences on decomposition, with the highest values in the Southeast region and irrigated crop areas in the western US (Fig. 6). The drought years (i.e., 1983, 1988) had the lowest r_e values during the period, reflecting the reduced decomposition during those periods, and the highest r_e values were observed during 1992, 1995, and 1997 (data not shown).

Carbon stocks on permanent cropland showed a clear spatial pattern across the country, with the upper midwest region (Corn Belt) having the highest C stocks (Fig. 2). The model also predicts high soil C stocks for some irrigated cropland soils in more arid regions of the western US, due to the high C inputs under irrigation, although these areas represent a

Fig. 4 Temporal variation of annual C input rates with **a** mean annual precipitation and **b** mean growing season temperature in the US agricultural soils

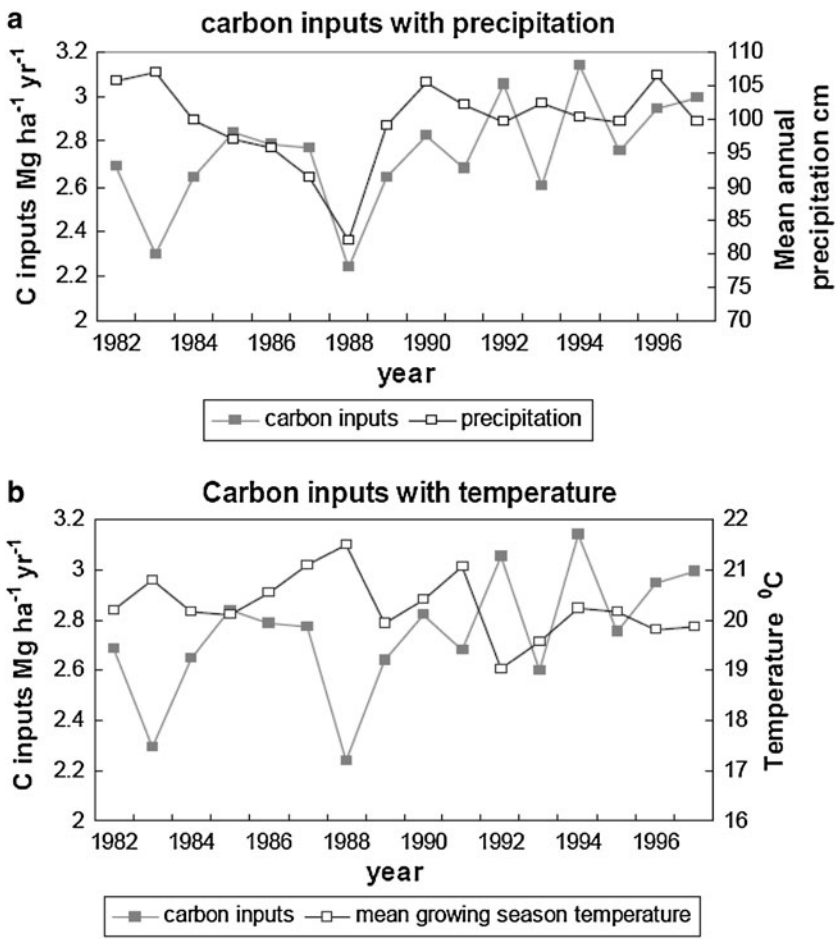

Table 3 AIC values from several different model options attempted for weather and C input relationships

Model	CNP	DS	FW	NC	NE	SE	SP
Gppt Gtmean	8482	−750	2186	16500	658	2863	13654
Gppt Gtmean Gppt * Gtmean	8466	−757	2172	16181	601	2748	13645
Gtmean Annppt	8445	−695	2231	16499	636	2810	13862
Gtmean Gratio Gtmean * Gratio	8462	−769	2176	16021	574	2742	13679
Gtmean Annppt Gtmean * Annppt	8446	−694	2194	16460	627	2700	13808
Gtmean Annratio	8462	−704	2231	16484	687	2833	13927
Gtmean Gratio	8466	−757	2182	16498	684	2865	13732
Gtmean	8486	−681	2229	16498	775	2881	13967
Gppt Gtmean Gppt * Gtmean $Gppt^2$ $Gtmean^2$	7885	−791	2150	13208	400	2626	13545

The quadratic relationship in the last row was chosen as the best overall model to predict the observed trends in C input rates. *ppt* precipitation, *tmean* mean monthly temperature, *ratio* precipitation/potential evapotranspiration, prefix 'G' indicates the growing season and 'Ann' stands for "Annual"

small fraction of the total land area, Over the study period, predicted soil C stocks in the US permanent cropland ranged from a minimum of 3,073 Tg in 1984 to a maximum of 3,105 Tg in 1997 (Table 2; Fig. 7). The ICBMr model partitions most of the soil C to the old pool, which was roughly 30 times the

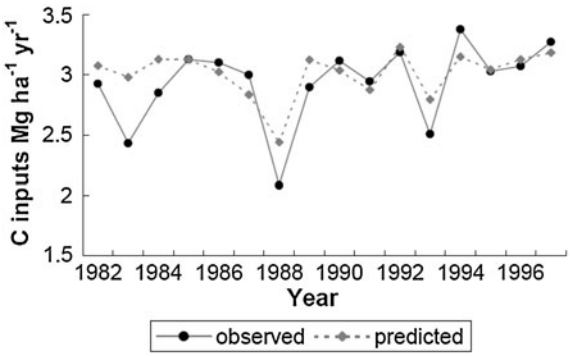

Fig. 5 Interannual variability of observed C input rates and those predicted using the weather variables in a mixed model[a], for North Central region. [a] C = 0.0035 * Gppt + 0.6920 * Gtmean + 0.0002 * (Gppt * Gtmean) − 7.5E-06 * (Gppt2) − 0.024 * (Gtmean2) − 3.065. *C* = C input rate. Please see the caption of Table 3 for description of the predictor variables. Although the variable terms used in this model were consistent for all the CPRs, the values for model coefficients varied by region, and occasionally the coefficients for certain variable terms were too small (e.g., for NC region the coefficient for Gppt2 was quite low). However, such term/s were still included within the model for region wise consistency (even if its influence on predicting C was minimal), as the coefficients were statistically significant

size of the young pool. The old pool exhibited little interannual variability but a slow increase of 19 Tg C from the beginning to the end of the period (Fig. 7a). Soil C stocks in the young pool ranged from 86 to 109 Tg over the study period; When we consider the overall trend (and assuming steady-state initial conditions), the total C stocks were more or less stable or slightly (<1 Tg year^{-1}) decreasing prior to 1990, and the stocks were increasing at an average rate of 4 Tg year^{-1} in the 1990s (Fig. 7b).

As would be expected, interannual variability of soil C stocks was relatively low compared to that of the residue C inputs, which was true for each CPR and the US as a whole (Table 2; Fig. 8). There was generally an alternating pattern in C inputs and C stocks in the young pool (Fig. 8). Estimated soil C stocks (0–20 cm) on permanent cropland ranged between 3.07 and 3.1 Pg due to interannual variation in the mix of crop species and residue C inputs (Table 2). The mean residue C input and soil C stock over the study period were 220 ± 19 Tg C year^{-1} and 3.08 ± 0.01 Pg, respectively. The year-to-year change in soil C stocks fell within 20 Tg compared to the mean C stock; however, that of C inputs showed significant dampening with a year-to-year variation that ranged between 1 and 43 Tg compared to the mean C input over the study period (Fig. 8).

Discussion

Regional patterns in crop production in agricultural ecosystems are driven by differences in the productivity potential of different crop species, which are largely governed by climate, but modified by management (e.g., irrigation). Temporal trends in production are influenced by developing technology (i.e., crop genetics, fertilization) and changes in management and agricultural policies, and by long-term trends in climate and CO_2 concentrations. Embedded

Table 4 Comparison of the estimated residue C inputs (kg ha^{-1}) against the observed data at several long term experimental sites

Site	County and state	Crop	Year/period[a]	Observed	Predicted	Relative error
Sidney	Cheyenne, NE	Wheat	1997	2226	2260	−0.02
Akron	Washington, CO	Wheat	1982–1991	2774	2350	0.15
Watkinsville	Oconee, GA	Sorghum	1983–1987	2830	2460	0.13
		Soybean	1988–1990	3380	2540	0.25
Stratton[b]	Kit Carson, CO	Wheat	1989–1993	2092	1636	0.22
Sterling[b]	Logan, CO	Wheat	1989–1993	1526	1343	0.12
Horseshoe Bend[b]	Clark, GA	Soybean	1985	1108	990	0.10
		Sorghum	1982–1984	1534	1380	0.10
Rodale[b]	Berks, PA	Corn	1984–1991	3582	2993.2	0.16
		Soybean	1982–1992	1794	1569	0.12

[a] Average observed and predicted values are given when several years were involved

[b] Only the aboveground residue measurements are available

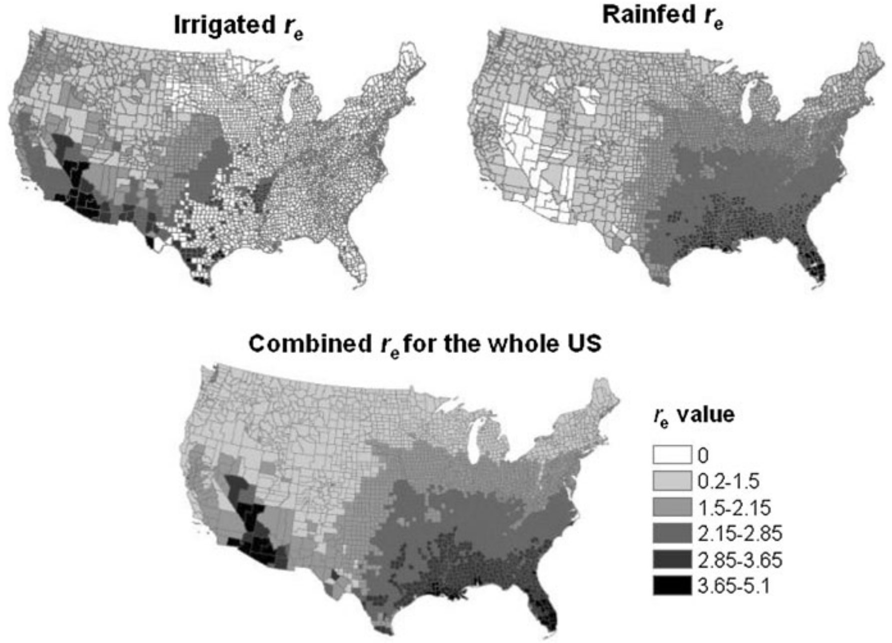

Fig. 6 External influence coefficient (r_e) estimated from irrigated (*top left*), rainfed (*top right*), and area weighted average (using combined rainfed and irrigated areas; *bottom*) for the US counties

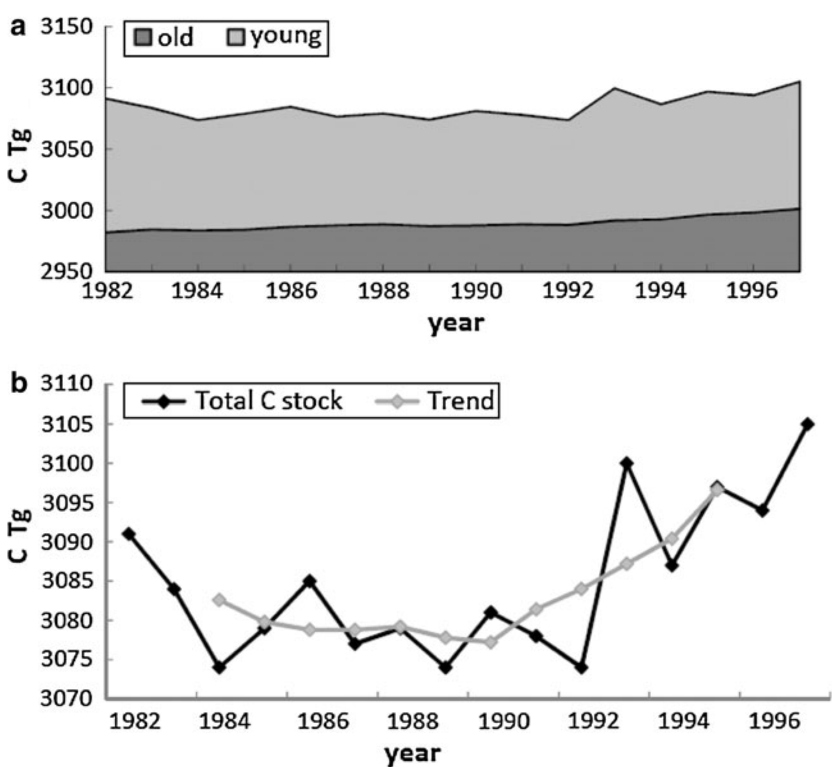

Fig. 7 Temporal Variation in **a** young, old, total C stocks and **b** total C stock against the overall trend (derived using 5-year moving average) in the US permanent cropland. The variation in the C stocks in the permanent cropland mostly reflected the variation in the young pool. Note that the *Y*-axis is cut at 2,950 Tg in **a** and 3,070 Tg in **b**, exaggerating the dynamics

within these longer trends, is the interannual variability of production, largely driven by weather variability and climate cycles (e.g., El Niño, La Niña), the effects of which also vary spatially across the continental US. Spatial variability is also related to differences in soil quality, moisture and nutrient availability that may be directly or indirectly related to climatic differences.

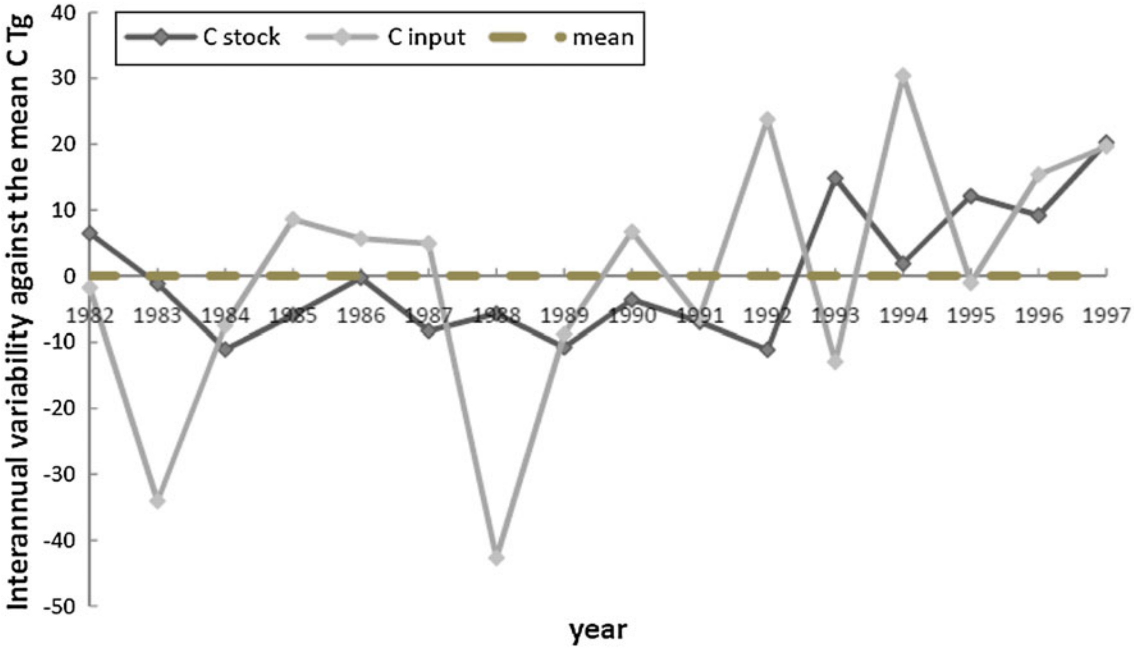

Fig. 8 Interannual (year-to-year) variation in C inputs and total soil C stock in the permanent cropland in the US computed against the mean values (set to zero) over the study period

Carbon fluxes associated with cropland is a significant component of the US carbon cycle (e.g., Jackson and Schlesinger 2004), especially in the central parts of the country having a high percentage of land in crops. According to our study, yields and residue C input rates in different regions showed an overall increase over the study period, with an increase of around 0.22–0.25 Mg C ha^{-1} in the C input rates for most CPRs. The long-term trend of increasing yields for most major crops since the 1930s is largely attributed to an array of technology and management developments, including increased and improved fertilizer use, crop genetics, and pest management (Reilly and Fuglie 1998). Although genetic improvements, particularly development of shorter stature varieties for small grains (e.g., wheat, barley) in the 1960–1970s, led to an increase in harvest index, characteristic harvest indices have remained relatively constant in recent decades (IPCC 2006). Hence, the trend in yield increases during our study period has driven a commensurate increase in the estimated net CO_2 assimilation and C inputs to soil.

In general, crop residue C input rates tended to be inversely proportional to the mean growing season temperature over the 16-year period. The inverse relationship with increasing growing season temperature was quite prominent for the C input rates observed in the North Central region. For instance, for a 1°C increase in the growing season temperature (and a decrease in precipitation of 80 mm compared to the previous year), a decrease of 0.76 Mg ha^{-1} in C input rate was observed in 1983. The same change in magnitude (i.e., a decrease by 0.76 Mg ha^{-1}) was observed in 1993, when the growing season temperature in the North Central increased by 1°C (compared to 1992), with the highest growing season precipitation observed for the region during the 16-year period. This might imply a potential reduction in productivity in the region with increases in growing season temperature, despite any associated variation in precipitation. Lobell and Asner (2003) observed decreasing trends for soybean and corn yields with increase in the growing season temperature and they also could not observe a relationship between the yields and precipitation alone (Lobell and Asner 2003). However, inclusion of growing season precipitation in a quadratic model with mean growing season temperature in our study, helped predict the observed pattern of C input rates in the main CPRs, Central and Northern Plains, and North Central region, over the study period (Fig. 7).

As described above, the temporal variation we observed in C input rates was mostly related to changes in weather driven by climatic events such as El Niño, which was a causal factor in the drought in 1988 (Trenberth et al. 1988; Palmer and Branković 1989). Drought in the mid-west region occurred from April to June 1988, and by July of the same year, 43% of the area of the country was in severe drought (Trenberth et al. 1988). According to our analyses, the major impacts were observed during the El Niño events 1982–1983, 1987–1988, and 1992–1993, the effects of which were reflected mostly in the reduced yields and C inputs during the latter part of the episode. For instance, during the 1992–1993 episode, growing season temperature in North Central region in 1993 was higher than the previous year and floods in the Mississippi river valley occurred due to very high precipitation. Fungal epidemics in corn, soybean and alfalfa caused by high moisture, and outbreak of soybean sudden death syndrome in the US Midwest in 1993 (Rosenzweig et al. 2000), may have led to the low productivity and low residue C inputs observed. During the same year, severe summer drought occurred in the Southeast region causing yield losses (Lott 1994), and therefore reduced residue C inputs as we observed in our study. Thus the same El Niño event yielded differential responses in different CPRs.

Although such interannual variability could be observed, the overall trend in NPP and residue C inputs was increasing during the period. This implies that management and technological improvements could still help increase C uptake in the US croplands through increased NPP and higher productivity, which in turn could lead to increased soil C storage, despite certain short-term impacts from the extreme weather events.

In this study we estimated trends in soil C stocks at county-level for permanent cropland as a function of residue inputs and climate impacts on soil organic matter decomposition. Average C stocks (0–20 cm) estimated for permanent cropland (89.4 Mha) in the US were about 3,085 Tg during the study period. While we did not compare predicted stock levels directly with observed stocks, the general pattern of the highest cropland soil C stocks being in the upper midwest region (Fig. 2) is consistent with national scale C stocks maps produced from soil survey (Kern 1994; Waltman and Bliss 1996). Both C input rates (Fig. 2) and the environmental factors affecting decomposition rates (Fig. 6) determined the overall pattern. In the simulations, the interannual variation in soil C stocks was largely confined to the young soil C pool which is directly impacted by the residue C inputs added in the previous year. Hence, there was a lag between the variation in C inputs and C stocks; high residue C inputs in a given year were reflected in the high C stock in the following year.

According to estimates from the US national GHG inventory for agriculture, soil C stocks on permanent cropland during the 1990s increased by 4–7 Tg C year^{-1}, if the effects of the CRP, emissions from cultivated organic soils and effects of land use change are excluded (USDA 2008). In our study, we estimated an average increase of 4 Tg C year^{-1} for the 1990s. However, our estimates do not include impacts of reductions in tillage intensity and manure additions that are accounted for in the cropland inventory estimates, which also includes a somewhat larger land base (ca. 125 Mha) than our study (ca. 90 Mha). Our estimates of a net increase over the time period are also dependent on the initial steady-state conditions used for the two C pools. However, the relative magnitude of interannual variability and the relative trends in soil C with respect to the trends in C inputs are not affected by assumptions in the model initialization.

Our estimates and those from the US national inventory are relatively independent, in that the US inventory does not use the NASS crop yield data in estimating C inputs to soil and it uses a different simulation model (Century) to derive its soil C balance estimates (USEPA 2009). Our per ha estimates (44 kg C ha^{-1} year^{-1}) are also close to the range of rates expected due to enhancing cropland productivity (i.e., 50–76 kg C ha^{-1} year^{-1}) compiled by the IPCC (2000). It should be noted that these rates represent a 'baseline' condition for permanent cropland associated with increasing productivity only and hence they are much lower than potential rates of SOC increase (e.g., Lal et al. 1998; Sperow et al. 2003; Paustian et al. 2006) that might occur with an aggressive GHG reduction policy to encourage practices to maximize soil C sequestration.

As shown in this study, the interannual variability in cropland NPP as well as crop residue inputs (which constitute a relatively ephemeral C stock but with some carry-over between years) can be several times the magnitude of the average long-term change in the cropland ecosystem C balance. This magnitude of interannual variability presents a challenge for efforts to estimate continental-scale C balances using 'top-down' approaches such as atmospheric inversion models (e.g., Denning et al. 1995; Gurney et al. 2002), since even if estimates for individual years are highly accurate, several years of data would be necessary to ascertain whether cropland ecosystems are net sources or sinks of CO_2. Likewise, this interannual variability in cropland C balances will need to be considered in monitoring programs to be used in conjunction with promoting C sequestration in agricultural soils as part of GHG mitigation policies. The knowledge of not only crop yields but also crop residue production and variability is also of increasing importance given the potential use of crop residues as biofuel feed stocks (Sheehan et al. 2004; Graham et al. 2007).

Conclusion

Carbon fluxes associated with croplands are a significant component of the US C balance, especially in the central parts of the country having a high percentage of land under crops. In contrast to other anthropogenic processes in the C cycle such as CO_2 emissions from energy-use, C fluxes associated with CO_2 assimilation, harvest export and crop residue inputs exhibit a high degree of interannual variability. Cropland NPP and residue carbon input rates over the study period showed significant interannual variability, depending on the changes in crop production and weather variability.

The interannual variability in soil C stocks on permanent cropland was as much as 20 Tg C over the study period, although it was much lower compared to the interannual variation of crop residue C inputs. Although the interannual variability in C stocks occurred within a narrow range relative to total stocks, the stocks clearly reflected the influences of the production (i.e., variation in the C inputs added), and associated changes in weather, and predicted between-year changes were much larger than the long-term average change. Predicted average soil C stock changes due to trends in crop productivity and climate for the 1990s ($\sim$4 C Tg year^{-1}) were in line with estimates produced in the US national GHG inventory, using different methods and databases. Thus the findings of our study could be considered as a "de-trended", baseline C stock change estimate, emphasizing the short-term C dynamics in US croplands that are useful for climate change policy and inventory purposes.

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