Energy Use and Carbon Dioxide Emissions from Cropland Production in the United States, 1990–2004

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Changes in cropland production and management influence energy consumption and emissions of CO_2 from fossil-fuel combustion. A method was developed to calculate on-site and off-site energy and CO_2 emissions for cropping practices in the United States at the county scale. Energy consumption and emissions occur on-site from the operation of farm machinery and occur off-site from the manufacture and transport of cropland production inputs, such as fertilizers, pesticides, and agricultural lime. Estimates of fossil-fuel consumption and associated CO_2 emissions for cropping practices enable (i) the monitoring of energy and emissions with changes in land management and (ii) the calculation and balancing of regional and national carbon budgets. Results indicate on-site energy use and total energy use (i.e., the sum of on-site and off-site) on U.S. croplands in 2004 ranged from 1.6 to 7.9 GJ ha^{-1} yr^{-1} and from 5.5 to 20.5 GJ ha^{-1} yr^{-1}, respectively. On-site and total CO_2 emissions in 2004 ranged from 23 to 176 kg C ha^{-1} yr^{-1} and from 91 to 365 kg C ha^{-1} yr^{-1}, respectively. During the period of this analysis (1990–2004), national total energy consumption for crop production ranged from 1204 to 1297 PJ yr^{-1} (Petajoule = 1×10^{15} Joule) with associated total fossil CO_2 emissions ranging from 21.5 to 23.2 Tg C yr^{-1} (Teragram = 1×10^{12} gram). The annual proportion of on-site CO_2 to total CO_2 emissions changed depending on the diversity of crops planted. Adoption of reduced tillage practices in the United States from 1990 to 2004 resulted in a net fossil emissions reduction of 2.4 Tg C.

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Agricultural lands have potential to sequester soil carbon following changes in land management (West and Post, 2002; Ogle et al., 2005) and to mitigate fossil-fuel emissions through production of dedicated bioenergy crops (Adler et al., 2007). Investigating changes in energy consumption and CO_2 emissions associated with conventional and alternative crop production will aid in measuring the effects of various carbon emission and sequestration strategies as well as contributing to future policy directions for energy use and agricultural production. The objective of this research was to quantify on-site and off-site energy consumption and CO_2 emissions from fossil-fuel combustion associated with U.S. cropland production from 1990 to 2004. Specifically, variations in energy consumption and CO_2 emissions were examined across current field management scenarios (e.g., planting, harvesting, weed and pest control, and soil amendments) consisting of conventional tillage, reduced tillage, and no-till field operations for corn (*Zea mays* L.), soybean [*Glycine max* (L.) Merr.], wheat (*Triticum aestivum* L.), sorghum [*Sorghum bicolor* (L.) Moench], barley (*Hordeum vulgare* (*L.*), oat (*Avena sativa* L.), rice (*Oryza sativa* L.), cotton (*Gossypium* spp.), and hay (e.g., Poaceae, Gramineae).

On-site energy use and emissions result from fossil-fuel combustion (i.e., primarily diesel fuel) occurring on the farm that is directly related to crop production. Off-site energy and emissions result from fossil-fuel combustion associated with the production and transport of crop production inputs, such as fertilizers, pesticides, and seeds. Off-site emissions also include emissions from power plants producing electricity that is used on-site. On-site and off-site emissions are estimated separately because on-site emissions are commonly associated with the agricultural sector, while off-site emissions (e.g., from fertilizer production) are associated with the industrial and manufacturing sectors (see USEPA, 2007; Intergovernmental Panel on Climate Change, 2006). On-site and

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Abbreviations: ABS, Agriculture Budget System; CRP, Conservation Reserve Program; CTIC, Conservation Technology Information Center; NASS, National Agricultural Statistics Service.

off-site energy and emissions are combined in accounting procedures when a need exists to understand the total impact of a change in land management (e.g., carbon credit transactions). For example, methods used in the United Nations Framework Convention on Climate Change (UNFCCC) require accounting of leakage, defined as the "net change of anthropogenic emissions by sources and/or removals by sinks of greenhouse gases [that occur] outside of the project boundary…[and that are] directly attributable to the…project (UNFCCC, 2006)."

Energy use and associated CO_2 emissions can increase or decrease with changes in cropland management. The crop species planted and associated production inputs can change due to market demands or incentives provided for land management (e.g., carbon sequestration or conservation programs). An example of a recent change in land management is the additional 6 million ha of corn planted in 2007 in response to the dramatic increase in corn price from 2006 to 2007 (USDA, 2008). Quantifying changes in energy and fossil-fuel use provides an understanding of how changes in cropland management impact on-site and off-site CO_2 emissions (see West and Marland, 2002a), and also contributes information needed for developing regional and national carbon budgets (see USDA, 2004; CCSP, 2007; Denning, 2004).

Fossil-fuel consumption and associated CO_2 emissions for agricultural inputs have been estimated for some cropping practices in the United States (West and Marland, 2002b; Lal, 2004; Adler et al., 2007). Similar analyses have been conducted for Canada (Dyer and Desjardins, 2005), Croatia (Filipovic et al., 2006), northeastern Italy (Borin et al., 1997), and northern Japan (Koga et al., 2003). Total energy use for U.S. cropland production has been estimated at 1184 PJ yr^{-1} (Petajoule = 1×10^{15} Joule) (USDA, 2004). Total CO_2 emissions from U.S. cropland production has been estimated at 111 Tg CO_2 yr^{-1} (Teragram = 1×10^{12} gram) (USDA, 2004) and at 103 Tg CO_2 yr^{-1} (CCSP, 2007). Current national estimates of CO_2 emissions from cropland production have been based on national averages of cropland production inputs or on gross fossil-fuel consumption in the agricultural sector, neither of which adequately reflect the local variability in cropping practices.

Estimates are needed of national agricultural energy use and CO_2 emissions based on more spatially-specific cropping practices. In this paper, we use a combination of independent survey data, national inventory data, established energy consumption parameters for field-scale operation budgets, and CO_2 emissions coefficients to estimate annual CO_2 emissions for cropland practices in each U.S. county. Estimates are developed for on-site energy consumption and CO_2 emissions from fossil-fuel use. Separate estimates are also provided for total energy use and CO_2 emissions from fossil-fuel use, which includes CO_2 emitted off-site from the production and transport of cropland management inputs (e.g., fertilizers, lime, and pesticides) and from the use of on-site electricity.

Methods

County level estimates of energy consumption and CO_2 emissions for cropland production inputs were calculated by integrating data on (i) annual land area of crop and tillage practices, (ii) management inputs for combinations of crop and tillage practices, and (iii) energy consumption and associated CO_2 emissions for on-site and off-site production inputs. The compilation and analysis of the aforementioned data are discussed below.

Land Area

Annual area estimates of agricultural commodity production per county from 1990 to 2004 were obtained from the U.S. Dep. of Agriculture, National Agricultural Statistics Service (NASS). The annual maximum of planted or harvested area for each commodity by county was selected. This method allows for inclusion of planted crop area needed to estimate production inputs, and for inclusion of perennial crops (e.g., hay) that are not planted annually. Cropland commodity area estimates from NASS were supplemented with fallow land area estimates from the Conservation Technology Information Center (CTIC) (CTIC, 2005), land area under Conservation Reserve Program (CRP) contracts (USDA, 2006), and land area in earlier set-aside programs (Brenda Chewning, USDA Farm Service Agency, personal communication, July 1998).

Survey data containing tillage practices conducted on croplands for 1989 to 1998, 2000, 2002, and 2004 were obtained from CTIC. Estimates for 1999, 2001, and 2003 were obtained by linearly interpolating tillage estimates for preceding and succeeding years. The NASS commodity areas, including CTIC fallow and CRP land areas, and the fraction of crops in each county using specific tillage practices from the CTIC data were joined using a lookup table that mapped each NASS commodity code to a CTIC crop category. Once merged, CTIC tillage fractions were multiplied by their corresponding NASS area to generate tillage area estimates for each NASS commodity. Tillage fractions from the CTIC forage category were applied to hay and forage lands from NASS for only those years when seeding was estimated to occur. In some counties, NASS commodities were reported without corresponding CTIC tillage estimates. In these cases, state-level averages of tillage percentages were applied to the county-level NASS areas. This method of data integration follows that used by West et al. (2008).

Cropland Management Inputs

Management inputs associated with unique combinations of crops and tillage for all counties were obtained from the Univ. of Tennessee's Agriculture Budget System (ABS), a database component of an agricultural economics model (De La Torre Ugarte and Ray, 2000; Ray et al., 1998). The ABS was developed from enterprise budgets obtained from state agricultural extension offices between 1995 and 1998 (APAC, 1996). Enterprise budgets, consisting of production costs, were converted to operational budgets, consisting of actual practices and production inputs. These budgets were updated in 2003 and again in 2006. The most recent update incorporated different tillage intensities per crop and revised pesticide application rates according to recent restrictions for herbicide and insecticide use (Meister Publishing Company, 2002a, 2002b). The ABS currently consists of more than 3500 conventional and alternative management practices for corn, soybean, wheat, sorghum, barley, oat, rice, cotton, and hay. As of 2006, these nine crops comprised an estimated 96% of total crop production in the United States (USDA, 2008). Management inputs for each crop in the ABS include planting and harvesting operations, tillage practices, and application rates of fertilizers, pesticides, and agricultural lime. In the case of hay, seeding operations were based on multi-year seeding rotations and harvest operations occurred three to six times annually, depending on the geographic region.

Energy Use and Carbon Dioxide Emissions

Estimates of energy and fuel use for all farm operations included in each operational budget were calculated based on established standards for time and speed of machine operation and for machine efficiency obtained from the American Society of Agricultural Engineering (ASAE, 2004, p. 353–366), the American Agricultural Economics Association (AAEA, 2000), and the USDA-Economic Research Service (USDA-ERS, unpublished data, 2007). Emissions of CO_2 associated with fuel use were estimated according to fuel type and carbon dioxide coefficients, based on previous work by West and Marland (2002b) and on revised CO_2 emissions per unit of fossil fuel (EIA, 2007). Fossil-fuel use, energy use, and CO_2 emissions were estimated for 283 farm machines with varying horsepower, 81 combinations of organic and inorganic fertilizers, and 403 chemical pesticides. These estimates for individual management inputs, along with application of agricultural lime and seed production, were linked in a database to more than 3500 combinations of cropping practices in the United States, included in the ABS. Using this method, national estimates of energy use and CO_2 emissions were developed based on summation of individual management practices as opposed to the extrapolation of national average estimates. Estimates of CO_2 emissions in this analysis are based on the higher heating value of fossil fuels.

Energy consumption and CO_2 emissions were estimated for on-site and off-site activities directly related to crop production. On-site emissions consist of CO_2 emitted from the combustion of fossil fuel on the farm, primarily diesel fuel consumed during field operations. Off-site emissions include CO_2 emissions associated with the production and transport of fertilizers, pesticides, agricultural lime, and seed. Off-site emissions also include emissions from the production of electricity occurring off farm. Total energy and emissions, which are the sum of on-site and off-site energy and emissions, provide an overall estimate of how energy use and emissions can potentially vary with changes in agricultural management. This analysis focuses on fossil-fuel based CO_2 emissions. Net soil carbon fluxes from the application of agricultural lime (West and McBride, 2005) or from the accumulation or decomposition of soil carbon (West and Post, 2002) are not included here.

Emissions from set-aside lands are included in our final national estimates of energy use and CO_2 emissions, but are not estimated at the county level due to limited spatial resolution of acquired survey data. Since the Agricultural Act of 1956, the USDA has required farmers to set aside land area and cease commodity production on these lands to qualify for government payments (Halcrow et al., 1994). Historically, farm programs used set-aside requirements as a tool to stabilize commodity supplies and prices. Set-aside land area varied over the time period of this analysis from a high of 12.4 million ha in 1991 to a low of 5.8 million ha in 1994; the historical peak of 31.5 million ha was reached in 1983 (APAC, 2001). Set-aside requirements were eliminated with the passage of the 1996 Farm Bill.

Emissions from management of lands enrolled in the CRP are not included in final estimates. Contracts for lands in the CRP normally run for 10 to 15 yr during which farmers perform few management operations. Haying or grazing on CRP land is allowable for 1 out of every 3 yr following full establishment of ground cover and compliance with wildlife regulations (USDA, 2003). Haying is also permitted if the USDA-Farm Service Agency calls for emergency release of CRP lands during drought conditions to supply feed for livestock. From 2003 to 2006, an average 0.5 million ha yr^{-1} of cropland enrolled in CRP were harvested for hay under managed and emergency release contracts (USDA-Farm Service Agency, unpublished data, 2007). If one cutting per year was performed on these areas at an estimated emissions rate of 0.0435 Mg C ha^{-1} yr^{-1}, then an average 21,750 Mg C yr^{-1} would have been emitted; this is approximately 0.1% of annual CO_2 emissions associated with U.S. cropland production.

Mean ($\bar{x}$) and standard deviation (SD) for national estimates of energy use and carbon emissions were calculated. Mean (Eq. [1]) and SD (Eq. [2]) are weighted statistics:

$$\bar{x} = \sum a_i x_i / \sum a_i \qquad [1]$$

$$\mathrm{SD} = [\sum a_i (x_i - \bar{x})^2 / \sum a_i]^{1/2} \qquad [2]$$

where x_i is a county-level estimate for one observation (e.g., total energy) and a_i is the corresponding county area. Each observation is a unique combination of crop species, tillage, and land management scenarios. Variation among mean observations is due to different amounts of energy inputs for the same crop and tillage type in different regions of the United States.

Results and Discussion

Estimates were completed for energy use and CO_2 emissions on-site, off-site, and the sum of the two. A weighted average of nine primary crops across three tillage intensities, based on land area, is provided for comparison (Table 1). As expected, no-till generally requires less energy and produces less CO_2 emissions than reduced till, and reduced till uses less energy and produces less CO_2 emissions than conventional tillage. In some cases, for barley, cotton, and soybean in particular, reduced tillage is shown to use slightly more energy than conventional tillage. This is due in part to the weighting of crop and tillage practices by land area which is conducted here to summarize our results for individual cropping practices. For example, some regions in the United States use more fuel to till heavy clay soils, apply more fertilizers and chemicals, or use higher seeding rates for the same combination of crop and tillage category. If regions with higher input intensity make up a greater proportion of land in reduced tillage than conventional tillage, the national weighted averages will show higher energy use of reduced tillage over conventional tillage. In the case of oat, reduced tillage is used more in regions where the soil requires disking, but these

Table 1. Average energy use and CO_2 emissions from cropland management in 2004 associated with combinations of crop and tillage intensities.

Crop	Tillage†	No. of observation‡	Land area in 2004	On-site energy (SD)§		On-site C emissions (SD)		Total energy (SD)		Total carbon emissions (SD)	
			ha × 10^3	GJ/ha		kg C/ha		GJ/ha		kg C/ha	
barley	CT	386	548	2.46	(0.81)	50.93	(16.30)	7.70	(2.45)	121.43	(48.44)
barley	RT	647	948	2.47	(0.69)	51.20	(13.85)	8.11	(2.41)	123.33	(47.54)
barley	NT	271	257	2.15	(0.62)	39.66	(13.10)	7.55	(2.06)	120.59	(35.05)
corn	CT	1815	12,190	3.64	(1.33)	73.90	(25.72)	15.36	(4.32)	263.32	(70.30)
corn	RT	3040	13,856	3.63	(2.07)	72.26	(40.69)	13.44	(3.36)	228.98	(55.71)
corn	NT	1612	6427	2.86	(0.91)	55.59	(16.45)	13.65	(3.78)	231.10	(62.78)
cotton	CT	431	3,565	6.87	(2.37)	138.50	(46.58)	16.37	(5.28)	291.92	(89.41)
cotton	RT	398	872	7.72	(2.52)	157.65	(49.65)	18.33	(5.46)	329.46	(93.90)
cotton	NT	300	930	4.22	(2.08)	81.93	(44.41)	15.20	(4.55)	260.53	(83.54)
hay	CT	1878	9085	7.90	(1.37)	176.30	(30.47)	11.78	(1.51)	231.53	(27.38)
hay	RT	2467	4570	7.53	(1.57)	167.94	(34.97)	11.36	(1.57)	224.57	(31.00)
hay	NT	1565	7,747	6.82	(1.41)	152.10	(31.51)	10.53	(1.55)	210.59	(32.02)
oat	CT	819	569	2.40	(0.69)	48.67	(12.93)	8.74	(2.72)	146.60	(46.38)
oat	RT	1393	652	2.43	(0.78)	49.39	(14.55)	8.54	(2.68)	143.10	(46.35)
oat	NT	502	172	1.55	(0.47)	23.31	(12.09)	5.98	(1.93)	91.08	(28.83)
rice	CT	93	1056	7.37	(1.56)	153.93	(32.64)	20.54	(4.00)	365.29	(69.58)
rice	RT	99	207	7.16	(0.65)	149.53	(13.57)	18.41	(1.87)	329.88	(32.44)
rice	NT	47	74	3.88	(1.77)	69.13	(37.13)	19.14	(2.53)	312.38	(51.38)
sorghum	CT	446	1259	3.74	(1.24)	74.87	(24.69)	10.17	(3.11)	176.85	(51.57)
sorghum	RT	692	981	2.65	(1.06)	52.82	(20.77)	8.56	(2.06)	149.62	(35.70)
sorghum	NT	271	662	2.01	(0.33)	38.89	(7.80)	7.97	(1.47)	134.98	(22.85)
soybean	CT	1479	6114	3.10	(0.83)	63.82	(16.79)	6.07	(1.35)	114.99	(25.36)
soybean	RT	2540	12,566	3.14	(1.27)	64.53	(26.03)	6.18	(1.40)	117.77	(26.04)
soybean	NT	1496	11,654	2.09	(0.50)	42.96	(10.01)	5.49	(1.25)	101.91	(25.34)
wheat	CT	1497	9716	2.67	(0.61)	54.21	(11.75)	7.36	(2.50)	127.12	(39.49)
wheat	RT	2,390	9958	2.56	(0.63)	52.53	(12.19)	6.93	(2.48)	118.48	(39.14)
wheat	NT	1177	3671	1.94	(0.47)	38.53	(8.92)	6.24	(1.87)	105.86	(28.65)

† CT, RT, and NT are respectively conventional plow tillage, reduced tillage, and no tillage.

‡ The number of observations include the number of unique combinations of crop, tillage intensity, and production inputs in the United States.

§ Standard deviation (SD) of mean energy use and of carbon emissions are based on the number of observations weighted by respective land areas. Observations are unique combinations of crop species, tillage, and land management scenarios. Variation among mean observations, shown here as a standard deviation, is due to different amounts of energy inputs for the same crop and tillage type in different regions of the United States.

regions also tend to have lower fertilizer application rates than conventional tillage areas. This causes the weighted average on-site energy for oat to be roughly the same as conventional tillage, while the weighted total CO_2 emissions are less.

On-site energy use ranges from 1.6 GJ ha^{-1} yr^{-1} for no-till oat to 7.9 GJ ha^{-1} yr^{-1} for conventional-till hay. On-site CO_2 emissions range from 23.3 kg C ha^{-1} yr^{-1} for no-till oat to 176.3 kg C ha^{-1} yr^{-1} for conventional-till hay. Total energy use ranges from 5.5 GJ ha^{-1} for no-till soybean to 20.5 GJ ha^{-1} yr^{-1} for conventional-till rice. Total CO_2 emissions range from 91.1 kg C ha^{-1} yr^{-1} for no-till oat to 365.3 kg C ha^{-1} yr^{-1} for conventional-till rice. Conventional-till hay has the largest on-site energy use and CO_2 emissions, but conventional-till rice has the largest total energy use and CO_2 emissions. This is due to the larger relative on-site energy use in hay production vs. off-site energy use and CO_2 emissions (e.g., pesticides and fertilizers) associated with rice production (Table 1). Tillage intensity for hay refers only to tillage associated with seeding which occurs once every several years and, hence, has little impact on energy consumption and emissions.

On-site CO_2 emissions from cropland production generally coincide with known areas of concentrated croplands (Fig. 1). The spatial distribution of emissions is more closely related to energy use than density of cropland area. In this respect, an emissions map based on land management and energy use is more informative for estimates of regional CO_2 flux than a common land cover map. For example, an inverse relationship exists between cropland density and on-site CO_2 emissions in Pocahontas and Calhoun Counties in west central Iowa. Calhoun County has 128,447 ha of cropland and 6859 Mg C emissions, while Pocahontas County has 133,991 ha of cropland with 4806 Mg C emissions. This inverse relationship is caused by Pocahontas County having about 1200 more hectares in no-till than Calhoun County, and from Calhoun having twice as much land in hay production as Pocahontas.

The analysis completed for 2004 (Table 1) was also completed for years 1990 to 2004 and was analyzed for trends in energy use (Fig. 2) and CO_2 emissions (Fig. 3). On-site CO_2 emissions generally follow off-site CO_2 emissions (Fig. 3), except in years 1992, 1999, and 2001. Exceptions to this trend are primarily caused by changes in planted area of individual crop species that subsequently change energy use and CO_2 emissions. In 1992, a decrease in set-aside lands (Fig. 4) and an increase in lands planted to crops resulted in a continuation of field cultivation (i.e., similar on-site emissions), but an increase in fertilizer use (i.e., increase in total emissions). In 1999, a decrease in corn (Fig. 5) resulted in a decrease in fertilizer use and associated emissions, but on-site emissions increased as corn was replaced by hay and cotton. In 2001, another decrease in planted corn area and an increase in hay and sorghum (Fig. 5)

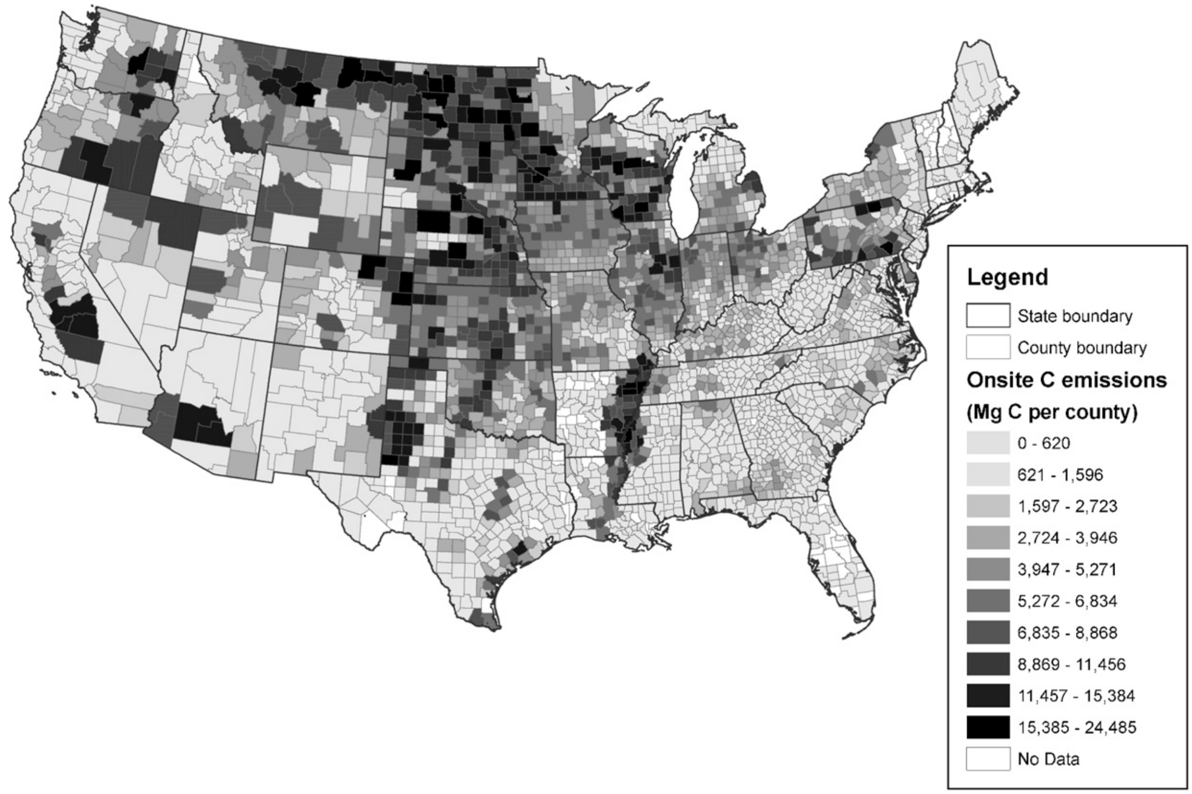

Fig. 1. On-site CO_2 emissions per county for U.S. cropland production in 2004. Annual energy and emissions data per county are archived at http://cdiac.ornl.gov/carbonmanagement/cropfossilemissions (verified 25 Nov. 2008).

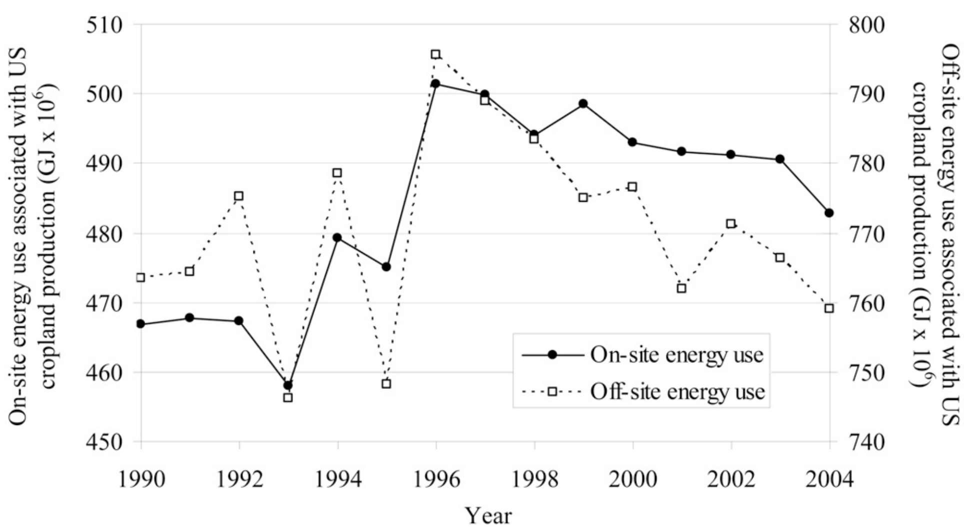

Fig. 2. Estimated on-site and off-site energy use for cropland production in the United States, 1990 to 2004. These estimates do not include CO_2 emissions associated with the management of Conservation Reserve Program (CRP) or set-aside lands.

resulted in decreased total emissions due to decreased fertilizer use, while maintaining approximate on-site emissions.

Several abrupt annual changes in emissions occurred that can be explained by agricultural policy decisions, weather events, and commodity prices. The spring and summer of 1993 experienced above-average precipitation and fields were flooded in Minnesota, Iowa, Missouri, Kansas, and Nebraska. As a result, farmers had difficulty accessing fields to plant crops. Planted corn area was impacted more than other crops (Fig. 5) because of the relatively small window of opportunity for planting. Total cropland planted to the nine major crops fell by 2.5 million ha in 1993 (Fig. 4). Total set-aside lands increased by 1.9 million ha, as farmers were allowed to enroll flooded land in the set-aside program as a way to mitigate financial loss (Brad Karmen, USDA-Office of the Chief Economist, personal communication, 2008).

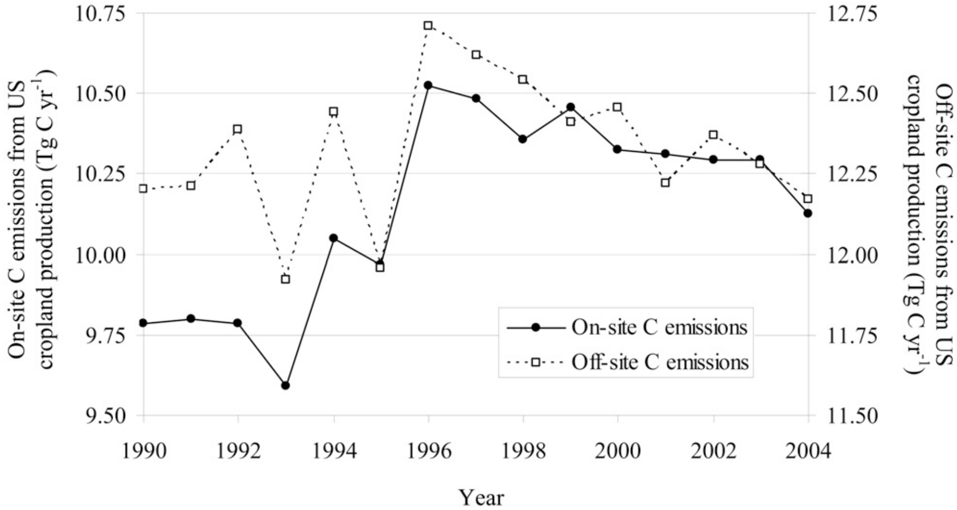

Fig. 3. Estimated on-site and off-site fossil-fuel CO_2 emissions from cropland production in the United States, 1990 to 2004. These estimates do not include CO_2 emissions associated with the management of Conservation Reserve Program (CRP) or set-aside lands.

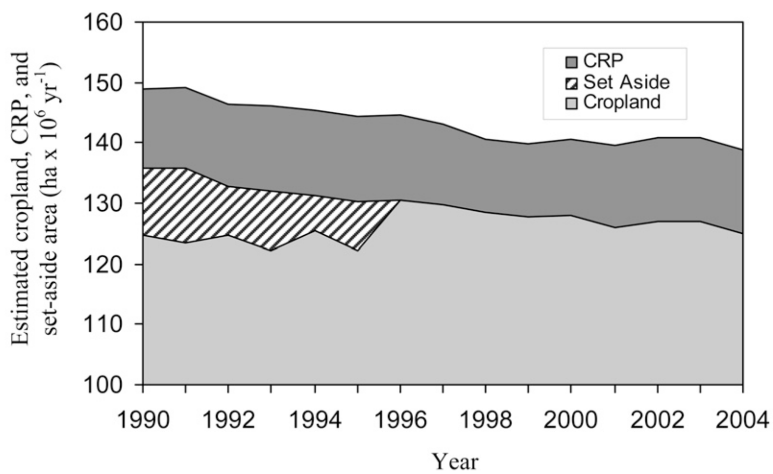

Fig. 4. Planted cropland, Consrvation Reserve Program (CRP), and set-aside land area in the United States, 1990 to 2004.

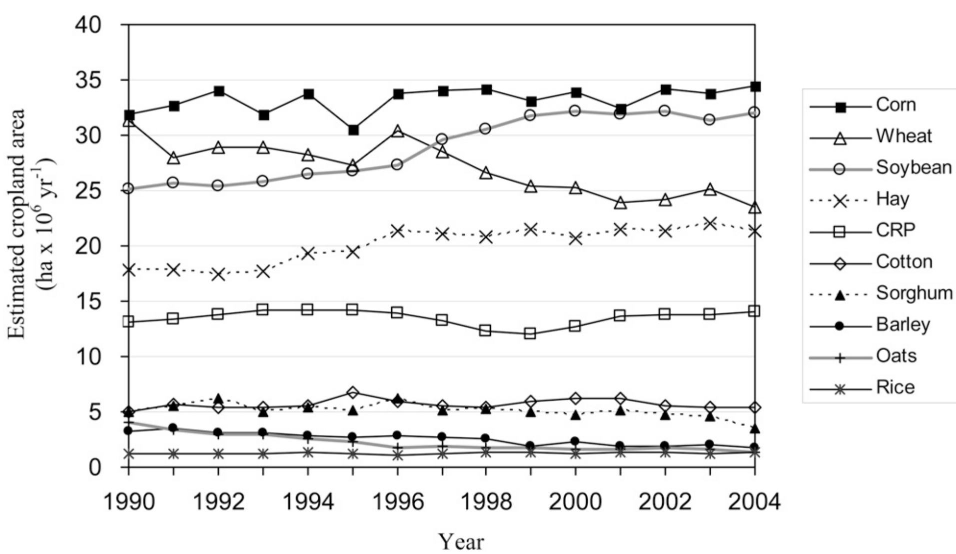

Fig. 5. Planted cropland area for individual crops in the United States, 1990 to 2004.

In 1995, total planted cropland decreased by 3.3 million ha. While 1995 also experienced a wet spring that prohibited planting on some lands, wet conditions were not the major cause of acreage reduction. Low crop prices and high commodity supplies at the end of the 1994 growing season led the USDA to require increases in set-aside land area for farmers to qualify for government subsidies. Set-aside increased by 2.2 million ha from 5.8 to 8.1 million ha (Fig. 4). The remaining decline in cropland area was due to wet spring weather that prohibited corn planting and to voluntary farmer reductions as a reaction to lower commodity prices.

A major change in farm policy occurred with the passage of the 1996 Farm Bill which eliminated use of set-aside requirements for eligibility in farm programs (see Ray et al., 2003). This allowed all 8.1 million ha in set-aside programs (e.g., Acreage Reduction Program) to be released for planting (Fig. 4). Lands enrolled in CRP also fell by 0.2 million ha. During use of set-aside requirements, farmers were required to plant set-aside croplands in a nonmarket commodity, typically a legume, and to control noxious weeds. This meant that several common field operations, including disking, drilling, mowing, and spraying, were conducted each year. These operations amount to 1.84 GJ ha^{-1} yr^{-1} and 38.5 kg C ha^{-1} yr^{-1} of on-site energy and CO_2 emissions, respectively; and to 3.89 GJ ha^{-1} yr^{-1} and 78.11 kg C ha^{-1} yr^{-1} of total energy and CO_2 emissions, respectively.

The resulting increase in CO_2 emissions from moving set-aside lands to cropland production in 1996 was more than 1 Tg C, a 4% increase in 1 yr. By 2004, emissions had once again fallen to 1995 levels. Low prices caused by the release of set aside acreage led farmers to voluntarily idle cropland. Total planted acreage declined by 5.6 million ha from 1996 to 2004 in response to falling commodity prices. In 2001, there was a 1 yr decrease in emissions as total cropland declined by 2.0 million ha. The combination of a wet spring and 3 yr of low commodity prices led to a reduction in planted cropland in 2001.

Total energy use in U.S. cropland production ranged from 1204 PJ in 1993 to 1297 PJ in 1996. Total CO_2 emissions from U.S. cropland production ranged from 21.5 Tg C in 1993 to 23.2 Tg C in 1996. Our estimates are similar to gross national estimates of 1184 PJ by USDA (2004) and to the 28 and 30 Tg C documented by USDA (2004) and CCSP (2007), respectively. An additional carbon accounting simulation was conducted using a 1990 tillage intensity baseline (Fig. 6). In doing so, the percentage adoption of no-tillage and reduced tillage, collectively referred to as conservation tillage, was held constant at 1990 levels from 1990 to 2004. The annual reduction in CO_2 emissions due to adoption of conservation tillage after 1990 ranged from 0.03 to 0.28 Tg C yr^{-1}. Total reduction of CO_2 from adoption of conservation tillage practices from 1990 to 2004 was 2.36 Tg C.

While fossil-fuel energy use and CO_2 emissions are the focus of this analysis, we note here that fossil-fuel emissions are only one component of full carbon accounting in the agricultural sector (Marland et al., 2003). Other components include changes in soil carbon flux, CO_2 released from the dissolution of lime, N_2O emissions from nitrogenous fertilizer use, and CH_4 flux from flooded fields. Combining all components results in a carbon budget for the agricultural sector (Smith et al., 2008) that can be compared over time.

Conclusions

Changes in agricultural policy and extreme weather events influence agricultural land use and subsequent energy consumption and CO_2 emissions associated with crop production in the United States. The 1993 flood and the 1996 Farm Bill influenced the amount of land cultivated, land set aside, and crop species that were planted. Energy use and emissions do not always change proportionally with the area of cropland in production, they instead vary by crop and by management practice. This is exemplified by corn having higher total emissions than wheat or soybean, and by

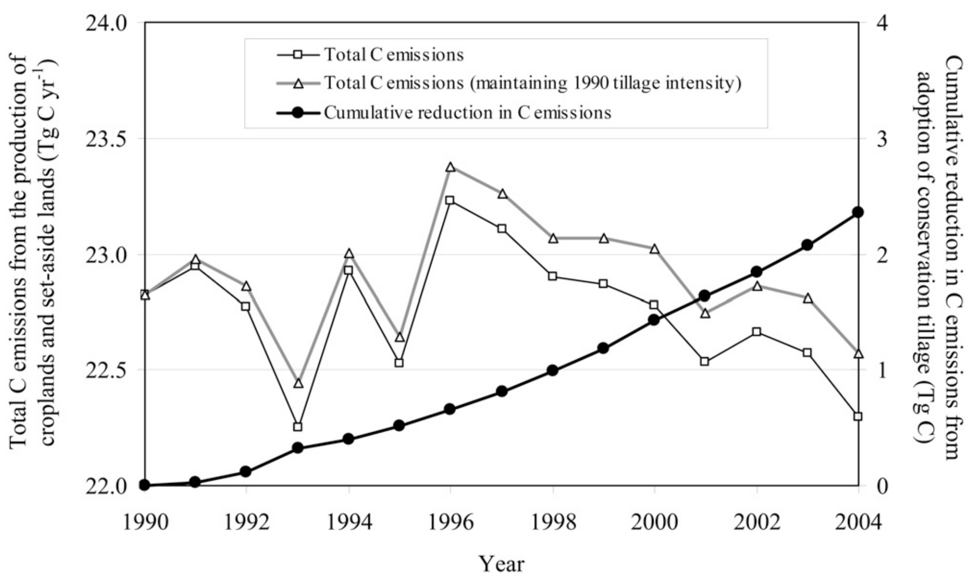

Fig. 6. Total fossil-fuel CO_2 emissions from U.S. cropland production compared to total emissions estimated while holding conservation tillage adoption steady after 1990, and cumulative difference between the two scenarios. Conservation tillage includes reduced tillage and no-till operations.

cotton and rice being about 50% higher than corn. With respect to tillage intensity, on-site emissions can be reduced by half for some crops when changing from conventional tillage to no-till. Trends in on-site emissions do not always coincide proportionally with total emissions. Accounting of total emissions, also referred to as full carbon accounting, is helpful in understanding the total impact of changes in land management.

This analysis provides a bottom-up estimate of energy and CO_2 emissions associated with cropland production within each county in the United States. In doing so, it provides a framework for monitoring changes in fossil-fuel emissions associated with changes in national cropland production. As the United States changes agricultural policies and economic markets respond to a new demand for biomass-based fuels, crop management and associated energy and emissions will continue to fluctuate. Through continued analyses, we will have a better understanding of how carbon dynamics in U.S. agriculture are being impacted by changes in land cover and land management.

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References

AAEA. 2000. Commodity costs and returns estimation handbook. Available at http://www.ers.usda.gov/Data/CostsAndReturns (verified 18 Nov. 2008). American Agric. Economics Assoc., Ames, IA.

Adler, P.R., S.J. Del Grosso, and W.J. Parton. 2007. Life-cycle assessment of net greenhouse-gas flux for bioenergy cropping systems. Ecol. Appl. 17:675–691.

APAC. 1996. Economic and environmental impacts of movement toward a more sustainable agriculture in the United States, Appendix 3: Data sources used in developing the ABS budgets. Project No. 43-3AEK-3-80080. Univ. of Tennessee, Knoxville.

APAC. 2001. The APAC databook: An analytical database of U.S. agriculture 1950–1999, 2001 ed. Staff Paper Ser. no. 01-1. Univ. of Tennessee, Knoxville.

ASAE. 2004. ASAE standards: Standards, engineering practices, and data adopted by the American Society of Agricultural Engineers. American Society of Agricultural Engineers, St. Joseph, MI.

Borin, M., C. Menini, and L. Satori. 1997. Effects of tillage systems on energy and carbon balance in north-eastern Italy. Soil Tillage Res. 40:209–226.

CCSP. 2007. The first state of the carbon cycle report (SOCCR): The North American carbon budget and implications for the global carbon cycle. A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. *In* A.W. King et al. (ed.) National Oceanic and Atmospheric Administration, National Climatic Data Ctr., Asheville, NC.

CTIC. 2005. National crop residue management survey. Conservation, 1989–2004. Conservation Technology Information Ctr., West Lafayette, IN.

De La Torre Ugarte, D.G., and D.E. Ray. 2000. Biomass and bioenergy applications of the POLYSYS modeling framework. Biomass Bioenergy 18:291–308.

Denning, A.S. (ed.). 2004. Science implementation strategy for the North American Carbon Program. U.S. Carbon Cycle Sci. Program, Washington, DC.

Dyer, J.A., and R.L. Desjardins. 2005. Analysis of trends in CO_2 emissions from fossil fuel use for farm fieldwork related to harvesting annual crops and hay, changing tillage practices and reduced summerfallow in Canada. J. Sustain. Agric. 25:141–155.

EIA. 2007. Emissions of greenhouse gases in the United States, 2006. DOE/EIA-0573(2006). Energy Information Administration, Office of Integrated Analysis and Forecasting, U.S. Dep. of Energy, Washington, DC.

Filipovic, D., S. Kosutic, Z. Gospodaric, R. Zimmer, and D. Banaj. 2006. The possibilities of fuel savings and the reduction of CO_2 emissions in the soil tillage in Croatia. Agric. Ecosyst. Environ. 115:290–294.

Halcrow, H.G., R.G.F. Spitze, and J.E. Allen-Smith. 1994. Food and agricultural policy: Economics and politics. McGraw-Hill, New York.

Intergovernmental Panel on Climate Change. 2006. 2006 IPCC guidelines for national greenhouse gas inventories. Prepared by the Natl. Greenhouse Gas Inventories Programme. H.S. Eggleston et al. (ed.) Inst. for Global Environ. Strategies, Kanagawa, Japan.

Koga, N., H. Tsuruta, H. Tsuji, and H. Nakano. 2003. Fuel consumption-derived CO_2 emissions under conventional and reduced tillage cropping systems in northern Japan. Agric. Ecosyst. Environ. 99:213–219.

Lal, R. 2004. Carbon emissions from farm operations. Environ. Int. 30:981–990.

Marland, G., T.O. West, B. Schlamadinger, and L. Canella. 2003. Managing soil organic carbon in agriculture: The net effect on greenhouse gas emissions. Tellus B 55:613–622.

Meister Publishing Company. 2002a. Weed control manual. Meister Publ. Co., Willoughby, OH.

Meister Publishing Company. 2002b. Insect Control Guide. Meister Publ. Co., Willoughby, OH.

Ogle, S.M., F.J. Breidt, and K. Paustian. 2005. Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions. Biogeochemistry 72:87–121.

Ray, D.E., D.G. De La Torre Ugarte, M.R. Dicks, and K.H. Tiller. 1998. The POLYSYS modeling framework: A documentation. Available at http://www.agpolicy.org/polysys.html (verified 18 Nov. 2008). Agric. Policy Analysis Ctr., Univ. of Tennessee, Knoxville.

Ray, D.E., D.G. De La Torre Ugarte, and K.H. Tiller. 2003. Rethinking U.S. agricultural policy: Changing course to secure farmer livelihoods worldwide. Available at http://agpolicy.org/blueprint.html (verified 18 Nov. 2008). Agric. Policy Analysis Ctr., Univ. of Tennessee, Knoxville.

Smith, P., G.-J. Nabuurs, I.A. Janssens, S. Reis, G. Marland, J.-F. Soussana, T.R. Christensen, L. Heath, M. Apps, V. Alexeyev, J. Fang, J.-P. Gattuso, J.P. Guerschman, Y. Huang, E. Jobbagy, D. Murdiyarso, J. Ni, A. Nobre, C. Peng, A. Walcroft, S.Q. Wang, Y. Pan, and G.S. Zhou. 2008. Sectoral approaches to improve regional carbon budgets. Clim. Change 88:209–249.

UNFCCC. 2006. Guidance on criteria for baseline setting and monitoring. Available at http://ji.unfccc.int/Ref/Documents/Baseline_setting_and_monitoring.pdf (verified 25 Nov. 2008). Joint Implementation Supervisory Committee, United Nations Framework Convention on Climate Change, Bonn, Germany.

USDA. 2003. Agricultural resource conservation program. FSA Handb. 2-CRP (Revision 4). Farm Service Agency, USDA, Washington, DC.

USDA. 2004. U.S. Agriculture and forestry greenhouse gas inventory: 1990–2001. Technical Bull. 1907. Global Change Program Office, Office of the Chief Economist, U.S. Dep. of Agriculture, Washington, DC.

USDA. 2006. Conservation Reserve Program Statistics, 1986–2005. Conservation Reserve Program, Farm Service Agency, U.S. Dep. of Agriculture, Washington, DC.

USDA. 2008. Crop production–2007 Summary. Natl. Agric. Statistics Serv., U.S. Dep. of Agriculture, Washington, DC.

USEPA. 2007. Inventory of U.S. greenhouse gas emissions and sinks: 1990–2005. U.S. Environment Protection Agency, Washington, DC.

West, T.O., C.C. Brandt, B.S. Wilson, C.M. Hellwinckel, D.D. Tyler, G. Marland, D.G. De La Torre Ugarte, J.A. Larson, and R. Nelson. 2008. Estimating regional changes in soil carbon with high spatial resolution. Soil Sci. Soc. Am. J. 72:285–294.

West, T.O., and G. Marland. 2002a. Net carbon flux from agricultural ecosystems: Methodology for full carbon cycle analyses. Environ. Pollut. 116:437–442.

West, T.O., and G. Marland. 2002b. A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: Comparing tillage practices in the United States. Agric. Ecosyst. Environ. 91:217–232.

West, T.O., and A.C. McBride. 2005. The contribution of agricultural lime to carbon dioxide emissions in the United States: Dissolution, transport, and net emissions. Agric. Ecosyst. Environ. 108:145–154.

West, T.O., and W.M. Post. 2002. Soil organic carbon sequestration rates by tillage and crop rotation: A global analysis. Soil Sci. Soc. Am. J. 66:1930–1946.