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LIFE-CYCLE ASSESSMENT OF NET GREENHOUSE-GAS FLUX FOR BIOENERGY CROPPING SYSTEMS

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Abstract. Bioenergy cropping systems could help offset greenhouse gas emissions, but quantifying that offset is complex. Bioenergy crops offset carbon dioxide emissions by converting atmospheric CO_2 to organic C in crop biomass and soil, but they also emit nitrous oxide and vary in their effects on soil oxidation of methane. Growing the crops requires energy (e.g., to operate farm machinery, produce inputs such as fertilizer) and so does converting the harvested product to usable fuels (feedstock conversion efficiency). The objective of this study was to quantify all these factors to determine the net effect of several bioenergy cropping systems on greenhouse-gas (GHG) emissions. We used the DAYCENT biogeochemistry model to assess soil GHG fluxes and biomass yields for corn, soybean, alfalfa, hybrid poplar, reed canarygrass, and switchgrass as bioenergy crops in Pennsylvania, USA. DAYCENT results were combined with estimates of fossil fuels used to provide farm inputs and operate agricultural machinery and fossil-fuel offsets from biomass yields to calculate net GHG fluxes for each cropping system considered. Displaced fossil fuel was the largest GHG sink, followed by soil carbon sequestration. N_2O emissions were the largest GHG source. All cropping systems considered provided net GHG sinks, even when soil C was assumed to reach a new steady state and C sequestration in soil was not counted. Hybrid poplar and switchgrass provided the largest net GHG sinks, >200 g CO_2e-C·m^{-2}·yr^{-1} for biomass conversion to ethanol, and >400 g CO_2e-C·m^{-2}·yr^{-1} for biomass gasification for electricity generation. Compared with the life cycle of gasoline and diesel, ethanol and biodiesel from corn rotations reduced GHG emissions by ~40%, reed canarygrass by ~85%, and switchgrass and hybrid poplar by ~115%.

Key words: biofuel; carbon sequestration; greenhouse gas (GHG); life-cycle assessment; nitrous oxide.

Introduction

Changes in land use and combustion of fossil fuels have been the largest human impacts on the global carbon cycle (Janzen 2004). Burning fossil fuels has added tremendous quantities of carbon dioxide (CO_2) to the atmosphere; more than 400 times the earth's current net primary productivity were required to produce the quantity of fossil fuels burned in 1997 (Dukes 2003). To stabilize atmospheric CO_2 at 500 ppm and prevent doubling of the preindustrial concentration of 280 ppm, Pacala and Socolow (2004) identified 15 carbon-mitigation strategies based on known technologies already deployed at an industrial scale that could be scaled up; biofuels were identified as one of the options. However, production of biofuels requires fossil-fuel inputs and impacts the fluxes of non-CO_2 greenhouse gases. Without a complete accounting of net greenhouse-gas (GHG) fluxes, developing and evaluating mitigation strategies is not possible (Robertson and Grace 2004). The major sources of GHG fluxes associated with crop production are soil nitrous oxide (N_2O) emissions, soil CO_2 and methane (CH_4) fluxes, and CO_2 emissions associated with agricultural inputs and farm equipment operation (Robertson et al. 2000, Del Grosso et al. 2001*a*, West and Marland 2002). Crop systems emit N_2O directly, produced through nitrification and denitrification in the cropped soil, and also indirectly, when N is lost from the cropped soil as some form other than N_2O (NO_x, NH_3, NO_3) and later converted to N_2O off the farm. Independent of GHG accounting, NO_3 leaching is also important from a water-quality perspective because it contributes to aquatic eutrophication and can pose a health risk to humans.

Bioenergy cropping systems vary with respect to length of the plant life cycle, yields, feedstock conversion efficiencies, nutrient demand, soil carbon inputs, nitrogen losses, and other characteristics, all impacting management operations. These factors affect the magnitude of the components contributing to net GHG flux and N loss vectors. N_2O emissions and NO_3 leaching vary with amount of N fertilizer applied and the

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integration of rainfall, soil temperature and texture, and crop rotation. Soil organic carbon (SOC) sequestration is affected by crop management decisions, which impact the quantity and quality of crop residue added to the soil and rate of decomposition (Paustian et al. 2000, Jarecki and Lal 2003). Crops have different requirements for farm machinery inputs from crop planting, soil tillage, fertilizer and pesticide application, and harvest (West and Marland 2002). Several studies have evaluated the energy balance (Marland and Turhollow, 1991, Shapouri et al. 2002, Farrell et al. 2006) and GHG fluxes (Sheehan et al. 1998, 2004, McLaughlin et al. 2002, Heller et al. 2003, Spath and Mann 2004, Updegraff et al. 2004, Kim and Dale 2005) of specific bioenergy crops, but there is limited information comparing a range of crops (Kim and Dale 2004*b*) and a need to integrate factors contributing to the impact of land-use change on GHG fluxes. The biogeochemistry model DAYCENT can integrate climate, soil properties, and land use (Del Grosso et al. 2001*a*) and can dynamically evaluate the impact of cropping systems on crop production, soil organic carbon, and trace-gas fluxes.

Ethanol and biodiesel from corn and soybean are currently the main biofuel crops in the United States, but the perennial crops alfalfa, hybrid poplar, reed canarygrass, and switchgrass have been proposed as future dedicated energy crops (McLaughlin et al. 2002, Lamb et al. 2003, Lewandowski et al. 2003, Spath and Mann 2004). Rotations of annual and perennial crops are common and the diversity of individual crops will affect GHG fluxes of the cropping system (Robertson et al. 2000). Corn–soybean and corn–soybean–alfalfa rotations are common cropping systems in Pennsylvania, USA. Crop residues have also been proposed as a current source of biomass for energy production (Kim and Dale 2004*a*) such as including corn stover (leaves and stalks of corn) harvest (Sheehan et al. 2004), although this practice is not without controversy (Lal 2005). We considered conversion of biomass to ethanol or biodiesel and gasification of biomass for electricity generation for the perennial grasses and hybrid poplar but only conversion to ethanol or biodiesel for the rotations involving corn, soybean, and alfalfa. Our objective was to use DAYCENT (Del Grosso et al. 2001*a*) to model the net GHG fluxes of bioenergy cropping systems in Pennsylvania for inclusion in a full assessment of GHG emissions associated with energy production from crops.

Methods

DAYCENT model description

DAYCENT is the daily time-step version of the CENTURY (Parton et al. 1994) biogeochemical model. DAYCENT (Parton et al. 1998, Del Grosso et al. 2001*a*) simulates fluxes of carbon (C) and nitrogen (N) between the atmosphere, vegetation, and soil. From weather (daily maximum and minimum air temperature, precipitation), soil-texture class, and land-use inputs, DAYCENT simulates crop production, soil organic-matter changes, and trace-gas fluxes. Key submodels include soil water content and temperature by layer, plant production and allocation of net primary productivity (NPP), decomposition of litter and soil organic matter (SOC), mineralization of nutrients, N gas emissions from nitrification and denitrification, and CH_4 oxidation in nonsaturated soils. Flows of C and N between the different pools are controlled by the size of the pools, C/N and lignin content of material, and abiotic water/temperature controls. The ability of DAYCENT to simulate NPP, SOC, N_2O emissions, NO_3 leaching, and CH_4 oxidation has been tested with data from various native and managed systems (Del Grosso et al. 2001*b*, 2002, 2005). Simulated and observed grain yields for major cropping systems in North America agreed well with data at both the site ($r^2 = 0.90$) and regional levels ($r^2 = 0.66$) (Del Grosso et al. 2005). The CH_4 oxidation submodel correctly simulated the high uptake rates observed in deciduous forests, the intermediate rates observed in coniferous and tropical forests and grasslands, and the low uptake rates observed in cultivated soils (Del Gross et al. 2000). N_2O emission data from eight cropped sites and NO_3 leaching data from 3 cropped sites showed reasonable model performance with r^2 values of 0.74 for N_2O and 0.96 for NO_3 leaching (Del Grosso et al. 2005).

Model simulations

Simulations of net greenhouse-gas (GHG) fluxes using DAYCENT were performed for the following bioenergy crops grown in Pennsylvania: corn (*Zea mays* L.), soybeans (*Glycine max* Merr.), alfalfa (*Medicago sativa* L.), hybrid poplar (*Populus* spp.), reed canarygrass (*Phalaris arundinacea* L.), and switchgrass (*Panicum virgatum* L.). Five bioenergy cropping systems were compared: (1) switchgrass, (2) reed canarygrass, (3) corn–soybean rotation (2 years of corn followed by 1 year of soybeans), (4) corn–soybean–alfalfa rotation (3 years corn, 1 year soybeans, followed by 4 years of alfalfa), and (5) hybrid poplar. Conventional and no tillage were compared within the corn–soybean and corn–soybean–alfalfa rotations. All simulations were for 30 years.

Daily weather data for central Pennsylvania (USA) required to drive DAYCENT were acquired from DAYMET. DAYMET (Thornton et al. 1997, 2000, Thornton and Running 1999; program *available online*)[5] generates meteorological data at 1-km^2 resolution for the United States using weather-station observations and an elevation model. To represent central Pennsylvania, weather from the 1-km^2 cell that was closest to the area-weighted geographical center of cropped land in Centre County, Pennsylvania, was selected. Soil properties representative of central Pennsylvania were

[5] ⟨http://www.daymet.org/⟩

obtained from the erosion–productivity impact calculator (EPIC, Sharpley and Williams 1990). Soil physical properties needed for model inputs were calculated from texture class and Saxton et al.'s (1986) hydraulic properties calculator (*available online*).[6] Soil texture class was loam (30% sand, 48% silt, and 22% clay), the mean annual air temperature was 9.2°C, and total mean annual precipitation was 111 cm.

Land-use parameters were defined for each crop, including crop growth dynamics, N application rate, harvest schedule, and tillage. Crop yields from DAYCENT simulations were calibrated using 10-year averages from agricultural statistics in Centre County, Pennsylvania, for corn, soybeans, and alfalfa (USDA-National Agricultural Statistics Service 2004); and for switchgrass (Adler et al. 2006), reed canarygrass (Cherney et al. 2003), and hybrid poplar (Walsh et al. 2003) were based on regional estimates. To minimize erosion and maintain tolerable soil-loss limits (Nelson 2002, Sheehan et al. 2004), only 50% of the corn stover was harvested for biofuel.

Production parameters for management of alfalfa as a biofuel were based on Lamb et al. (2003). Only alfalfa stems were used for production of biofuel, while leaves were assumed separated for use as a protein source for livestock. The quantity of alfalfa biomass for use as biofuel was calculated by multiplying the yield from DAYCENT by 0.5, since alfalfa stems account for ~50% of total alfalfa biomass when it is managed as a biofuel crop (Lamb et al. 2003). Nitrogen fertilizer application rates were 12.7 g $N \cdot m^{-2} \cdot yr^{-1}$ for corn, 5.6 g $N \cdot m^{-2} \cdot yr^{-1}$ for switchgrass, 15.4 g $N \cdot m^{-2} \cdot yr^{-1}$ for reed canarygrass with half applied in the spring and the other after the first harvest, and 8.4 g N/m^{-2} in years 3, 5, 7, and 9 for hybrid poplar. Nitrogen from soybean and alfalfa supplemented the first year of N applied to corn following the legume crops. In corn following soybean in the 2-year corn–1-year soybean rotation, 3.7 of the 12.7 g $N \cdot m^{-2} \cdot yr^{-1}$ was assumed to come from soybeans. In corn following alfalfa in the 3-year corn–1-year soybean–4-year alfalfa rotation, 8.7 of the 12.7 g $N \cdot m^{-2} \cdot yr^{-1}$ was assumed to come from alfalfa. About one third of the N applied to corn was at planting, the remainder was applied mid-June. Corn, soybeans, and switchgrass were harvested in the fall annually. Alfalfa and reed canarygrass were harvested twice annually in late June and September. Hybrid poplar was harvested once every 10 years. Output from DAYCENT was compiled for above- and belowground NPP with grain yields included separately, SOC changes, and trace-gas fluxes.

Model outputs are sensitive to current SOC levels, which in turn are influenced by previous vegetation cover and land management. To acquire reasonable modern SOC levels, about 1800 years of native vegetation followed by tree clearing, plowing, and about 200 years of cropping were simulated. Native vegetation was assumed to be the potential vegetation from VEMAP (1995) analysis. Plow out was assumed to occur in the year 1789. Historically accurate cropping systems were simulated and improved cultivars and fertilizer applications were introduced at appropriate times. The simulations of the different biofuel systems all used identical initial conditions that included the legacy effects of 215 years of conventional tillage cropping.

Net greenhouse-gas flux determination

Two scenarios comparing net greenhouse-gas (GHG) fluxes for the bioenergy cropping systems were evaluated, near- and long-term net GHG emissions, including the net GHG emissions from crop production through energy generation or fuel use, cradle-to-grave or "well-to-wheel" in life-cycle assessment terminology. The near-term net GHG emissions were calculated as: net greenhouse gas $(GHG_{net}) = (-C_{dff}) + (-\Delta C_{sys}) + (\pm C_{FC}) + (-C_{CH_4}) + C_{N_2O\ Dir} + C_{N_2O\ Ind} + C_{ChIn} + C_{AgMa}$, where the sinks were the amount of fossil fuel (e.g., gasoline, diesel, and coal) displaced by electricity generated from gasification of biomass or ethanol or biodiesel (displaced fossil-fuel C, C_{dff}), the change in soil organic carbon (SOC) and belowground biomass C (change in system C, ΔC_{sys}), the amount of CO_2e (carbon dioxide equivalents) emitted from fossil fuels used in feedstock transport to the biorefinery, conversion to biofuel, and subsequent distribution ($\pm$feedstock-conversion C, C_{FC}; this can be positive or negative depending on the size of the electricity credit for combustion of the coproduct lignin at the biorefinery during production of ethanol from biomass; other coproducts described below can reduce the quantity of energy allocated to feedstock conversion), and CH_4 uptake by the soil (C_{CH_4}); the sources were CO_2e of direct ($C_{N_2O\ Dir}$) and indirect ($C_{N_2O\ Ind}$) N_2O emissions, CO_2 emission from manufacture of chemical inputs (C_{CI}), and fuel used by agricultural machinery for tillage, planting, fertilizer and pesticide application, harvesting, and drying corn grain (C_{AgMa}). The long-term GHG_{net} assumed that ΔC_{sys} was zero because soils were equilibrated and no longer sequestering additional C. The components for GHG_{net} were either from DAYCENT output or calculated as described below. DAYCENT outputs were used to determine C_{dff}, ΔC_{sys}, $C_{N_2O\ Dir}$, $C_{N_2O\ Ind}$, and C_{CH_4} for the GHG_{net} calculations. All DAYCENT outputs are presented as annual means over the entire 30-yr simulation period.

The ethanol yield for cellulosic biomass crops was determined by multiplying the aboveground biomass by about 90% of the theoretical ethanol yield (U.S. Department of Energy 2006*a*) and ethanol yields, using oven-dried biomass (dm) were as follows: corn stover, 381 L/Mg dm; alfalfa stem, 303 L/Mg dm; hybrid poplar, 413 L/Mg dm; reed canarygrass, 311 L/Mg dm; and switchgrass, 391 L/Mg dm. Yields assumed for corn

[6] ⟨http://www.bsyse.wsu.edu/saxton/soilwater⟩

grain ethanol were 467 L/Mg dm (Wang 2001) and from soybean grain for biodiesel were 234 L/Mg dm (Ahmed et al. 1994). The amount of electricity produced from gasification of the various biomass sources was calculated from the product of yield, higher heating value of the biomass (the energy released as heat when a compound undergoes complete combustion with oxygen), and conversion efficiency of the gasification system. The higher heating values were determined from literature (Miles et al. 1996, Brown 2003, Dien et al. 2006, U.S. Department of Energy 2006*b*) as follows: corn stover, 18.0 MJ/kg; alfalfa stem, 18.6 MJ/kg; hybrid poplar, 19.3 MJ/kg; reed canarygrass, 17.7 MJ/kg; and switchgrass, 18.5 MJ/kg. The conversion efficiency of the biomass gasification system was assumed to be the same 37.2% for all biomass sources (Heller et al. 2004).

The quantity of fossil fuel displaced by biofuel was calculated from either the product of biofuel yield of ethanol or biodiesel from the bioenergy crops and the fuel economy ratio of fossil fuel to biofuel (fuel economy values are from Sheehan et al. [2004]) [6.75 km/L ethanol divided by 10.3 km/L gasoline] and based on Sheehan et al. [1998] [0.203 L diesel/bhp-h divided by 0.231 L biodiesel/bhp-h] where "bhp-h" means "brake horsepower-hour") or the product of the quantity of electricity generated from gasification of biomass (megajoules of electricity per square meter) and the heat rate of coal (3.00 MJ/MJ electricity). The heat rate is the amount of energy required in fuel to generate 1 MJ of electricity by the power plant and accounts for all the electricity it consumes to operate. The lower the heat rate, the more efficient an electrical power plant is in turning fuel energy into electrical energy.

The quantity of greenhouse gases from the life cycle of fossil fuel displaced by biofuel (C_{dff}) was calculated from the product of the quantity of fossil fuel displaced by biofuel (as described above) and the total emissions of CO_2, CH_4, and N_2O during the fossil-fuel life cycle (based on Sheehan et al. [2004] for gasoline [~671.3 g CO_2e-C will be emitted per liter of gasoline consumed], Sheehan et al. [1998] for diesel [~857.7 g CO_2e-C will be emitted per liter of diesel consumed], and on Heller et al. [2004] for electricity generated from the U.S. grid average [~74.9 g CO_2e-C will be emitted per megajoule of electricity consumed from the U.S. grid]). The ΔC_{sys} was the average annual change in SOC to a depth of 20 cm and belowground biomass C. The average annual ΔC_{sys} was calculated as the mean of annual differences between initial and final system C levels.

The feedstock-conversion C (C_{FC}) was determined separately for ethanol production from corn stover and other biomass sources and corn grain, biodiesel production from soybean grain, and electricity generation from biomass sources. The C_{FC} for corn stover was calculated to be −135.2 CO_2e-C/L ethanol produced at the biorefinery (Sheehan et al. 2004) and was applied to the other biomass sources. The C_{FC} for corn grain was calculated to be 293.3 CO_2e-C/L ethanol (Shapouri et al. 2002) and for soybean grain was 132.4 CO_2e-C/L biodiesel (Sheehan et al. 1998).

Various coproducts are also generated during production of ethanol and biodiesel from crops. Coproducts such as lignin from biomass converted to ethanol, were already factored into C_{FC} for biomass and was the reason it was negative, a net generator of energy. Other coproducts are generated, such as distiller's dried grains with solubles from corn grain during ethanol production, and soy meal and glycerin from soybean grain during biodiesel production. Since these coproducts have a positive economic value and displace competing products that require energy to make, energy from production needs to be allocated to the coproducts. To determine the amount of energy allocated to coproducts, the displacement method was used, which credits coproducts with the energy required to produce a functionally equivalent quantity of the nearest substitute (Farrell et al. 2006). The coproduct energy and emission credits allocated to corn grain were 109.4 g CO_2e-C/L ethanol (Wang 2001) and to soybean grain were 172.3 g CO_2e-C/L biodiesel (Ahmed et al. 1994). In the future, other coproducts will be extracted from crops at the biorefinery and credited, thereby reducing the energy and emissions associated with biofuel production.

Methane uptake from the soil (C_{CH_4}) was determined from the mean annual CH_4 uptake over the simulation period with DAYCENT. CH_4 uptake was converted to CO_2e by assuming that its global-warming potential is 23 times that of CO_2 on a mass basis (IPCC 2001).

Two ways in which N fertilizers contribute to GHG emissions were modeled by DAYCENT: direct N_2O emissions from the soil ($C_{N_2O\ Dir}$) and indirect N_2O emissions from offsite denitrification of NO_3 and volatilized N that is deposited offsite and converted to N_2O ($C_{N_2O\ Ind}$). The $C_{N_2O\ Dir}$ was the mean annual N_2O emissions over the simulation period. To calculate indirect N_2O, we combined DAYCENT outputs for NO_3 leached and N volatilized with IPCC (1997) methodology. IPCC (1997) methodology assumes that 2.5% of NO_3-N leached is eventually denitrified to N_2O-N in water ways and that 1% of volatilized N (NO_x+NH_3) is deposited on soil and converted to N_2O. N_2O emissions were converted to CO_2e by assuming that its global warming potential is 296 times that of CO_2 on a mass basis (IPCC 2001). For comparison with direct N_2O emissions generated from DAYCENT, direct N_2O emissions were also determined using the IPCC (2000) protocol and calculated by multiplying 1.25% by the sum of N in crop residue, aboveground N fixed by crops, and 90% of fertilizer N applied to soils.

Fuel used by agricultural machinery for tillage, planting, fertilizer and pesticide application, harvesting, and drying corn grain (C_{AgMa}) (Table 1) were determined with the following protocol. Using agricultural machinery management data documented in the Amer-

TABLE 1. Fossil-fuel energy requirements and carbon dioxide emissions from agricultural machinery.

	Conventional tillage			No-till		
Farm operation	Fuel usage (L/ha)	Energy (GJ/ha)	CO_2 emissions (kg C/ha)	Fuel usage (L/ha)	Energy (GJ/ha)	CO_2 emissions (kg C/ha)
Tillage						
Plow	20.05	0.78	17.01	···	···	···
Disk	5.48	0.21	4.65	···	···	···
Seedbed preparation	5.15	0.20	4.37	···	···	···
Cultivation	5.12	0.20	4.34	···	···	···
Planting						
Corn planting	4.64	0.18	3.94	11.25	0.43	9.54
Grain drill planting	3.57	0.14	3.03	8.53	0.33	7.24
Crop management						
Fertilizer application	1.58	0.06	1.34	1.58	0.06	1.34
Pesticide application	2.63	0.10	2.23	2.63	0.10	2.23
Lime application	1.58	0.06	1.34	1.58	0.06	1.34
Grain crop harvest						
Corn grain harvest	33.18	1.28	28.15	33.18	1.28	28.15
Soybean harvest	31.33	1.21	26.59	31.33	1.21	26.59
Forage crop harvest						
Alfalfa mowing						
First harvest	5.09	0.20	4.32	5.09	0.20	4.32
Second harvest	4.73	0.18	4.01	4.73	0.18	4.01
Alfalfa baling						
First harvest	4.50	0.17	3.82	4.50	0.17	3.82
Second harvest	3.05	0.12	2.59	3.05	0.12	2.59
Switchgrass mowing						
Seeding year	6.64	0.26	5.63	6.64	0.26	5.63
Established stand	8.65	0.33	7.34	8.65	0.33	7.34
Switchgrass baling						
Seeding year	8.56	0.33	7.27	8.56	0.33	7.27
Established stand	11.58	0.45	9.83	11.58	0.45	9.83
Reed canarygrass mowing						
First harvest	5.29	0.20	4.49	5.29	0.20	4.49
Second harvest	4.90	0.19	4.16	4.90	0.19	4.16
Reed canarygrass baling						
First harvest	5.49	0.21	4.66	5.49	0.21	4.66
Second harvest	3.51	0.14	2.98	3.51	0.14	2.98
Forage raking	1.11	0.04	0.94	1.11	0.04	0.94
Tree harvest						
Felling	120.89	4.67	102.57	···	···	···
Skidding	115.85	4.48	98.30	···	···	···
Chipping	431.97	16.70	366.52	···	···	···
Herbicide (Roundup post-harvest)†	2.63	0.10	2.23	···	···	···
Post-harvest						
Corn grain drying‡	105.46	2.81	52.45	105.46	2.81	52.45
Corn stover mowing§	5.29	0.20	4.49	5.29	0.20	4.49
Corn stover baling§	3.51	0.14	2.98	3.51	0.14	2.98
Soybean stubble mowing	···	···	···	4.57	0.18	3.87

Notes: Ellipses indicate that farm operation was not used with no-till practice. Fuel usage values were determined from the American Society of Agricultural Engineers standards (ASAE 2000). Fuel usage for harvest operations is dependent on crop yield (all numbers are for dry mass): corn, 5.3 Mg/ha; soybean, 2.2 Mg/ha; alfalfa (1st harvest), 3.8 Mg/ha; alfalfa (2nd harvest), 2.0 Mg/ha; seeding-year switchgrass, 6 Mg/ha; established-stand switchgrass, 10 Mg/ha; reed canarygrass (1st harvest), 5 Mg/ha; reed canarygrass (2nd harvest), 2.7 Mg/ha; mowing corn stover, 5.3 Mg/ha; baling corn stover, 2.65 Mg/ha; soybean stubble, 1 Mg/ha.

† Roundup (glyphosate) was applied after harvest of hybrid poplar.

‡ Corn grain was dried 10 percentage points (e.g., from 25.5% to 15.5% water) with propane fuel.

§ Corn "stover" refers to the leaves and stalks of corn.

ican Society of Agricultural Engineers (ASAE) machinery management standards (ASAE 2000), the integrated farm system model (IFSM; Rotz 2004) was used to calculate fuel use for management practices. Energy use for the hybrid poplar harvest operation was determined as follows: hybrid poplar were felled using a Timberjack 643 H Feller Buncher (Deere and Company, Moline, Illinois, USA) and transported for processing with a Timberjack 648 G III Single Arch Grapple Skidder (Deere and Company) (L. H. Nancarrow [Deere and Company], *personal communication*), and processed using the Peterson Pacific DDC 5000-G Delimber–Debrancher–Chipper (Peterson Pacific Corporation, Eugene, Oregon, USA) (C. Peterson [Peterson Pacific Corporation], *personal communication*; J. Goetsch [Daishowa-Marubeni International Ltd., Vancouver, British Columbia, Canada], *personal communication*); Hartsough et al. 2002). The CO_2 emissions associated with the manufacture of chemical farm inputs (fertilizers, limestone, herbicides, insecticides) were from West and Marland (2002). For limestone, 50% of the C in $CaCO_3$ applied was assumed to be emitted as CO_2 (West and McBride 2005), the rest leached from the soil profile.

Results

Crop and biofuel yield

Hybrid poplar, corn, and switchgrass had the highest harvested biomass yields of the crops considered (Fig. 1a). When considering the annualized yields of the cropping systems, hybrid poplar and switchgrass had the highest yields (Fig. 1c) because corn is typically grown in rotation with soybean, which is much lower yielding.

Biofuel production is directly related to crop yield but not linearly because biomass composition affects conversion efficiency. Ethanol and biodiesel yields for the individual crops ranged from 1.8 to 7.5 $MJ \cdot m^{-2} \cdot yr^{-1}$; corn (grain plus 50% stover) had the highest biofuel yield, hybrid poplar and switchgrass were similar but about 10–15% lower than corn, reed canarygrass was ~40% lower, and alfalfa stems and soybean grain had about 75–85% lower biofuel yields (Fig. 1b). The pattern between crop and biofuel yield among cropping systems was similar, with hybrid poplar comparable to switchgrass, and corn–soybean rotation, reed canarygrass, corn–soybean–alfalfa rotation having progressively lower yields (Fig. 1d). The electricity yields from gasification of biomass for cropping systems were highest for hybrid poplar and switchgrass, and reed canarygrass was ~20% lower (Table 2).

The quantity of gasoline and diesel displaced by the production of ethanol and biodiesel from cropping systems followed the same pattern as ethanol/biodiesel yields, but values were lower (Table 3, Fig. 1d) because although the energy content of biodiesel and diesel are similar, ethanol has about two thirds the energy content of gasoline. The quantity of coal displaced by the production of electricity from gasification of biomass from cropping systems ranged from 14.7 to 18.4 $MJ \cdot m^{-2} \cdot yr^{-1}$ for the perennial crops (Table 2).

Greenhouse-gas sinks

Displaced fossil fuel (C_{dff}) was the largest greenhouse gas (GHG) sink (Fig. 2a); hybrid poplar and switchgrass displaced the most fossil fuel. System C (ΔC_{sys}, SOC plus belowground biomass C) was the second largest GHG sink (Fig. 2b). Hybrid poplar stored the most C followed by switchgrass, reed canarygrass, corn–soybean rotation, and corn–soybean–alfalfa rotation. No-till corn–soybean and corn–soybean–alfalfa rotations had higher ΔC_{sys} than conventional tillage. The amount of CO_2 equivqlents (CO_2e) emitted from fossil fuels used in feedstock transport to the biorefinery, conversion to biofuel, and subsequent distribution (feedstock-conversion C, C_{FC}) was negative for the perennial grasses and hybrid poplar and positive for the grain crops when both biomass and grain were converted to ethanol or biodiesel (Fig. 2c). Methane uptake (C_{CH_4}) was the smallest GHG sink (data not shown). Hybrid poplar had the highest C_{CH_4} at −3.98 CO_2e-C $g \cdot m^{-2} \cdot yr^{-1}$, the other cropping systems increased in CH_4 uptake from −1.41 to −1.57 in the order of switchgrass, conventional tillage corn–soybean and corn–soybean–alfalfa rotation, reed canarygrass, and no-till corn–soybean–alfalfa and corn–soybean rotation. High CH_4 uptake by hybrid poplar compared to the other systems is consistent with data from various global sites showing that mean CH_4 uptake rates by deciduous forests exceed those in grasslands, cropped soils, and non-deciduous forests by a factor of 2 or more (Del Grosso et al. 2000). Feedstock conversion to biofuel was a net source of energy for hybrid poplar and the perennial grasses (Fig. 2c).

Greenhouse-gas sources

The CO_2e–C of N_2O emissions estimated by the biogeochemical model DAYCENT were the largest GHG source (Fig. 2d). The corn–soybean rotation had the highest emissions followed by reed canarygrass, corn–soybean–alfalfa rotation, switchgrass, and hybrid poplar. As expected, estimated N_2O emissions were driven largely by N inputs from fertilizers and fixation. Corn rotations under conventional tillage had slightly higher direct C_{N_2O} ($C_{N_2O\ Dir}$) than under no-till. The relationship of direct soil N_2O emissions between cropping systems calculated with the IPCC (2000) protocol differed from those predicted by DAYCENT (Fig. 3). The N_2O emissions calculated from IPCC were highest for the corn–soybean–alfalfa rotation, followed by the corn–soybean rotation and reed canarygrass; N_2O emissions from hybrid poplar and switchgrass were much less. The difference between IPCC (2000)-calculated N_2O emissions and DAYCENT were <20% for hybrid poplar, corn–soybean rotation, and reed canarygrass. However, the IPCC (2000)-calculated N_2O emissions for the rotations that featured N fixers were significantly

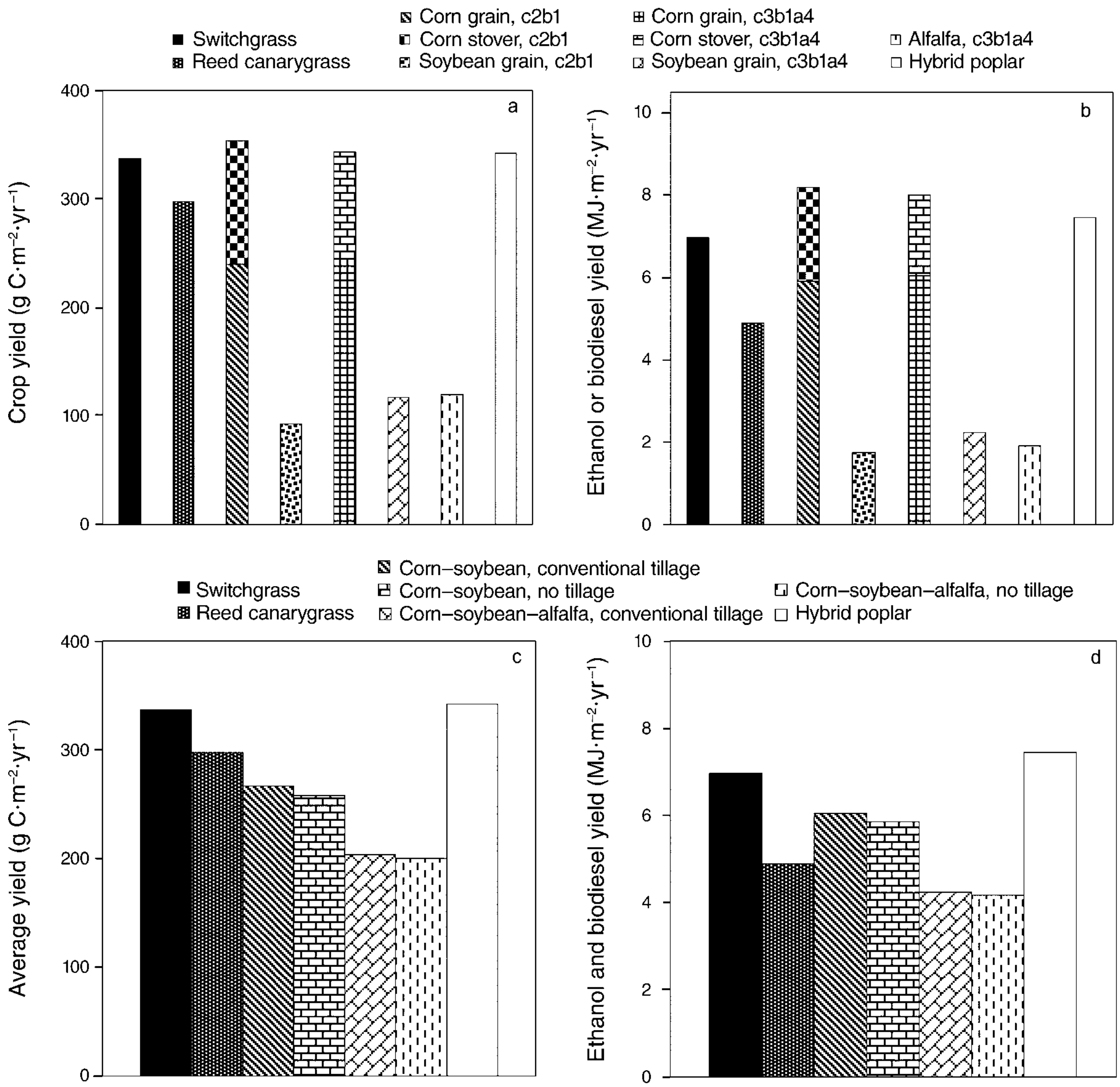

FIG. 1. Crop and fuel yield from bioenergy cropping systems. Yields are expressed either as crop component (a, b) or system (c, d) yields. Corn yields assumed that only 50% of the corn stover (leaves and stalks) was harvested; alfalfa yields only contained stems, 50% of the total yield. (a) Component yields are presented; the 2-yr corn and 1-yr soybean (c2b1) rotation and 3-yr corn, 1-yr soybean, and 4-yr alfalfa (c3b1a4) rotation yields are from the conventional-tillage system. (b) All crop components were converted to ethanol except soybean grain, which was converted to biodiesel. (c) System yields were combined from crop rotations and annualized over the rotation cycle. (d) Crop component fuel yields of ethanol and biodiesel were combined to give system yields.

higher than DAYCENT (almost 40% and >50% for the corn–soybean–alfalfa rotation under conventional and no-till, respectively). IPCC (2000) estimates of N_2O emissions from switchgrass are ~35% lower than DAYCENT. Indirect N_2O emissions differed widely among crops (combined with direct N_2O emissions in Fig. 2d). NO_3 leaching, the major source of indirect emissions in this case, ranged from ~0.5 g N·m^{-2}·yr^{-1} for switchgrass, to ~1 g N·m^{-2}·yr^{-1} for hybrid poplar, to >2 g N·m^{-2}·yr^{-1} for reed canarygrass and the corn rotations.

Emissions from chemical inputs were low for hybrid poplar and switchgrass and somewhat higher for the other cropping systems (Table 4, Fig. 2e). Emissions from chemical inputs were high for reed canarygrass and the corn–soybean rotation largely because N fertilizer inputs are high for these crops.

The energy required for farm operations varied widely, with CO_2 emissions ranging from 128 kg CO_2-C·ha^{-1}·yr^{-1} for corn to <20 kg CO_2-C·ha^{-1}·yr^{-1} for established alfalfa and switchgrass (Table 5). Differences are a result of the frequency of farm implement use, the load the equipment was under during operation, and the required crop-specific equipment. These data are similar to those collected by others (West and Marland 2002, Lal

TABLE 2. Energy yields and greenhouse gas (GHG) emissions from gasification of biomass for production of electricity.

Energy and emissions parameters	Biomass Type: Switchgrass	Reed canarygrass	Hybrid poplar
Energy yield ($MJ \cdot m^{-2} \cdot yr^{-1}$)	5.80	4.90	6.15
Coal displaced ($MJ \cdot m^{-2} \cdot yr^{-1}$)	17.4	14.7	18.4
Displaced fossil fuel (g CO_2e-C$\cdot m^{-2} \cdot yr^{-1}$)	435	367	460
Net GHG emissions (%)†	−93	−85	−93
Net GHG emissions (g CO_2e-C/MJ)†	−69	−64	−70
Net GHG emissions ratio (gasification : ethanol)‡	2.42	3.65	2.37

Notes: Carbon dioxide equivalent (CO_2e) of carbon is the common currency used for comparison purposes. N_2O emissions and CH_4 uptake were converted to CO_2e by assuming that its global-warming potential is 296 and 23 times that of CO_2 on a mass basis, respectively (IPCC 2001).

† Reduction in net GHG emissions associated with using biomass gasification compared with coal expressed either as a percentage (quotient of values in Fig. 4d divided by values above under displaced fossil fuel) or unit biomass energy yield (quotient of values in Fig. 4d divided by values above under energy yield).

‡ Ratio of long-term net GHG emissions (quotient of values in Fig. 4d divided by values in 4b) displaced by gasifying biomass and substituting for coal compared to conversion to ethanol or biodiesel and substituting for gasoline or diesel.

2004), but the integrated farm system model (IFSM; Rotz 2004) allowed comparison of current energy use from agricultural machinery between all farm operations under standardized conditions. The exception was for hybrid poplar; since IFSM does not include forestry operations, data from separate sources, as described above (see *Methods: Net GHG flux...*), were used. Perennial cropping systems can have lower agricultural machinery inputs than annual systems thereby reducing C_{aAgMa} as seen in this study (Fig. 2f). The exception to this trend is hybrid poplar because energy costs of harvesting are high (Table 6). Propane was used to dry corn and usually accounted for about one third of the C emissions for the corn rotations. Tillage accounted for almost 30% of the C emissions in the corn rotations but less than 10% in the switchgrass and reed canarygrass and less than 2% in hybrid poplar, where tillage was only used the first year. Harvesting was responsible for the majority of emissions for the hybrid poplar and perennial grass systems and at least 30% for the corn rotations.

Feedstock conversion to biofuel was a net consumer of energy for all the corn, soybean, and alfalfa rotations (Fig. 2c) and was also a net consumer when the grasses and hybrid poplar were gasified for electricity generation.

Net greenhouse-gas flux

Hybrid poplar and switchgrass provided the largest net GHG sinks with both systems having net CO_2 e-C fluxes of less than −200 $g \cdot m^{-2} \cdot yr^{-1}$ for the near term scenario when biomass and grain are converted to ethanol and biodiesel (Fig. 4a). The sink for reed canarygrass was about −120 $g \cdot m^{-2} \cdot yr^{--1}$ and the sink for the conventional-till corn–soybean–alfalfa rotation was the smallest at about −50 $g \cdot m^{-2} \cdot yr^{-1}$ for the near-term scenario. Trends among the different cropping systems for the long-term scenario were similar, but the sinks were smaller because C storage in soil and belowground biomass was considered negligible in the long term (Fig. 4b). The sinks were even greater when biomass was converted to electricity by gasification at the power plant, and there was a similar relationship among cropping systems (Fig. 4c, d). On a unit-area basis of crop production, gasification of the grasses and hybrid poplar yielded more than twice the GHG reduction than did converting these crops to ethanol (Table 2). Net GHG emissions were from about −8 to −9 g CO_2e-C/MJ ethanol for corn rotations, but about −18 g CO_2e-C/MJ for reed canarygrass and less than −24 g CO_2e-C/MJ for switchgrass and hybrid poplar (Table 3). This resulted in a reduction of GHG emissions for corn rotations in the near term of about 50–65%,

TABLE 3. Quantity of gasoline and diesel displaced by production of ethanol and biodiesel and reduction of greenhouse gas (GHG) emissions from life cycle of ethanol and biodiesel compared with gasoline and diesel.

Bioenergy cropping system	Gasoline or diesel displaced ($MJ \cdot m^{-2} \cdot yr^{-1}$)	Net GHG emissions† (%)	Net GHG emissions† (g CO_2e-C/MJ ethanol)
Switchgrass	6.96	−114	−23.9
Reed canarygrass	4.88	−84	−17.5
Corn–soybean			
Conventional tillage	6.05	−38	−8.1
No till	5.84	−41	−8.6
Corn–soybean–alfalfa			
Conventional tillage	4.24	−41	−8.6
No till	4.16	−43	−9.0
Hybrid poplar	7.45	−117	−24.3

† Reduction in net GHG emissions associated with using ethanol or biodiesel compared with gasoline or diesel expressed either as a percentage (quotient of values in Fig. 4b divided by values in Fig. 2a) or unit ethanol consumed (quotient of values in Fig. 4b divided by values in Fig. 1d).

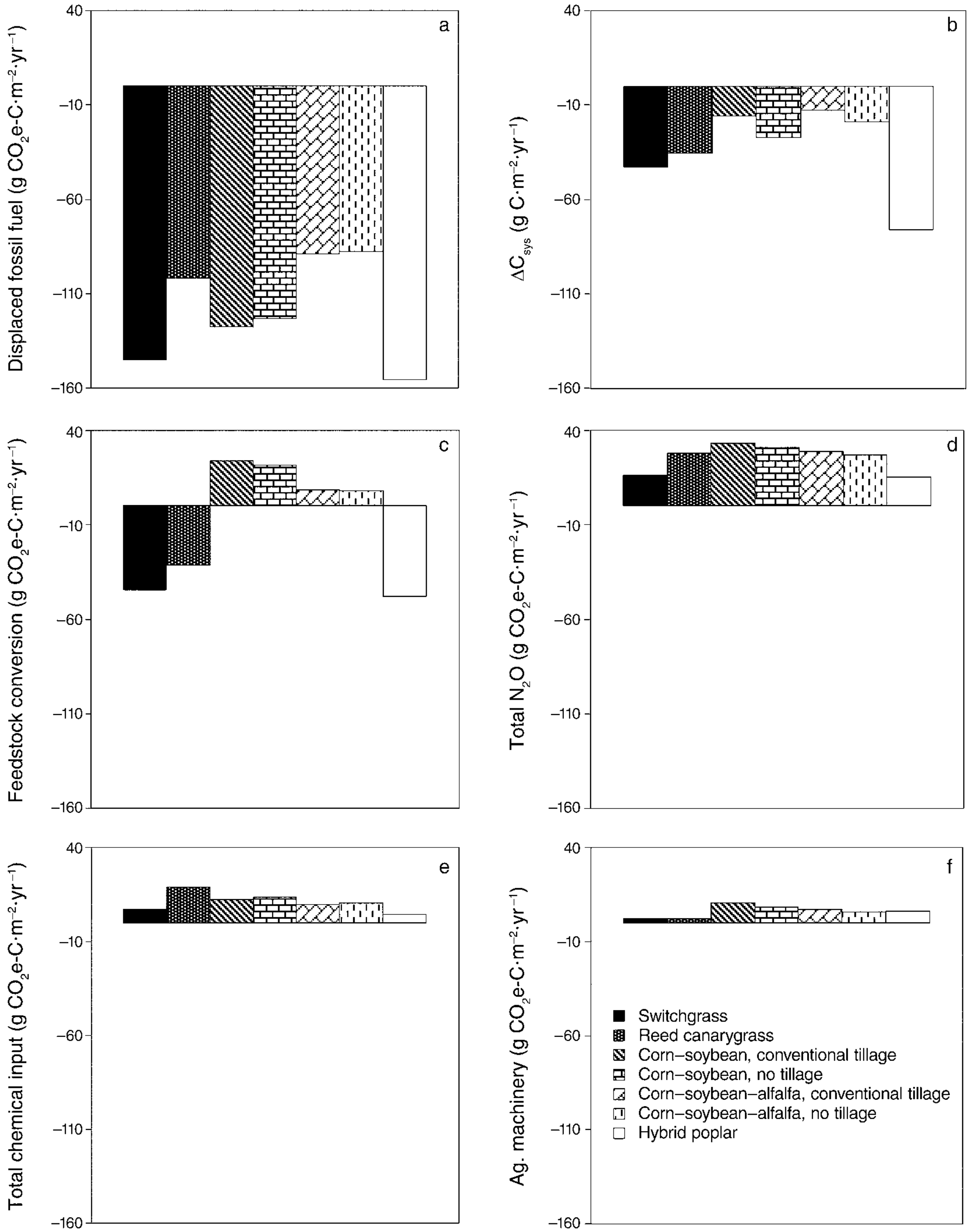

FIG. 2. Components of the net greenhouse-gas (GHG_{net}) profile from different bioenergy cropping systems. Displaced fossil fuel and feedstock conversion are based on displacement of gasoline and diesel and conversion of crop components to either ethanol or biodiesel. CO_2e stands for "CO_2 equivalent"; see Table 2 note for definition.

reed canarygrass ~120%, and about 145% and 165% for switchgrass and hybrid poplar, respectively, compared with the life cycle of gasoline and diesel (Fig. 5). In the long term, where soil C sequestration was assumed to no longer occur, this resulted in a reduction of GHG emissions for corn rotations of ~40%, reed canarygrass ~85%, and ~115% for switchgrass and hybrid poplar compared with the life cycle of gasoline and diesel (Table 3). The GHG_{net} reduction from gasifying biomass instead of coal was about −64 to −70 g CO_2e-C/MJ, an 85–93% reduction in greenhouse gases compared with the coal life cycle (Table 2).

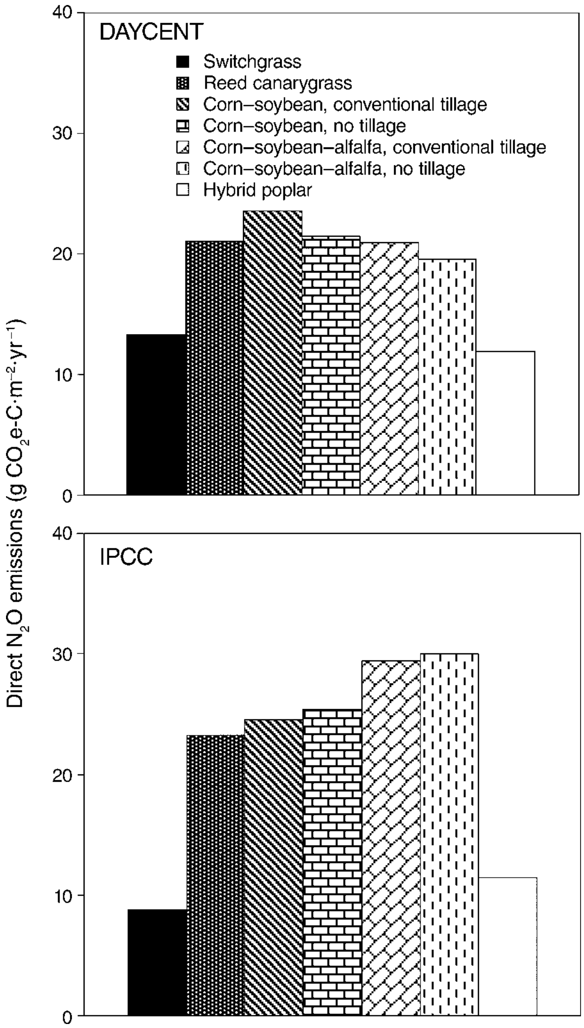

FIG. 3. DAYCENT (Del Grosso et al. 2001*a*) and Intergovernmental Panel on Climate Change (IPCC 2000) calculated direct N_2O emissions from bioenergy cropping systems.

DISCUSSION

Crop and biofuel yield

Yields for cropping systems depended on the component crops. Since soybean and alfalfa had lower yields than the other crops, their inclusion in the crop rotation reduced overall yield of the corn cropping system. If 100% of the corn stover (stalks and leaves) was harvested, that too would have increased the biomass yield of the corn rotations. However, only 50% of the stover was harvested, to provide residue to reduce soil erosion (Nelson 2002).

Both crop yield and composition affect biofuel production from energy crops. There are more differences in the components of composition between grain and biomass that affect energy yield than between different sources of biomass (U.S. Department of Energy 2006*a*) resulting in greater differences in biofuel yield than crop yield when comparing grain and biomass crops. The effect of composition on biofuel yield is why corn biofuel yield was 10–15% higher than hybrid poplar and switchgrass even though crop yields of corn, hybrid poplar, and switchgrass were all within ~5% of each other. Based on composition, grain has higher conversion efficiency to ethanol per unit mass than non-grain biomass, ~20% higher than switchgrass. Therefore some differences between crop yield and ethanol and biodiesel yield are expected, as was seen in this study. Since the composition between non-grain biomass sources is similar, ethanol yield differences per unit mass are small (U.S. Department of Energy 2006*a*) and biomass yield is the most important factor determining biofuel production from a cropping system. As expected, the crops with the highest biofuel yield were those with the highest biomass yield. Corn is typically grown in rotation with other crops and in this study the crops in the rotation with corn—soybean and alfalfa—had much lower biofuel yields than corn; therefore the system yields were lower than the other cropping systems. We assumed that electricity generation was only from gasification of biomass in cropping systems and did not include grain. Therefore we only considered switchgrass, reed canary-

TABLE 4. Carbon dioxide emissions from production of N, P, K, limestone, and pesticides used in bioenergy cropping systems.

Bioenergy cropping systems	CO_2 emissions (g CO_2-C·m^{-2}·yr^{-1}) N	P	K	Limestone†	Herbicides	Insecticides
Switchgrass	4.48	0.37	0.49	1.70	0.04	0.00
Reed canarygrass	12.33	1.04	2.50	3.02	0.03	0.00
Corn–soybean						
Conventional tillage	6.12	1.01	1.09	3.02	1.05	0.04
No till	6.12	1.01	1.09	3.02	2.44	0.04
Corn–soybean–alfalfa						
Conventional tillage	3.12	0.89	1.45	3.26	0.78	0.16
No till	3.12	0.89	1.45	3.26	1.63	0.16
Hybrid poplar	2.88	0.19	0.26	0.85	0.14	0.11

† Limestone, $CaCO_3$ equivalents.

TABLE 5. Fossil-fuel energy requirements and carbon dioxide emissions for operation of agricultural machinery from the six bioenergy crops.

	Conventional tillage, CT			No-till, NT†		
Crop	Fuel usage (L/ha)	Energy (GJ/ha)	CO_2 emissions (kg C/ha)	Fuel usage (L/ha)	Energy (GJ/ha)	CO_2 emissions (kg C/ha)
Corn‡	194.03	6.23	127.60	167.10	5.19	104.76
Soybean§	75.27	2.91	63.87	51.28	1.98	43.51
Alfalfa						
Seedling year, SY‖	59.89	2.32	50.80	31.33	1.21	26.60
Established stand, EST¶	28.00	1.08	23.80	28.00	1.08	23.80
Final year, FY‖¶	30.63	1.18	26.00	30.63	1.18	26.00
Switchgrass						
Seedling year, SY#	59.14	2.29	50.18	30.58	1.18	25.95
Established stand, EST††	21.81	0.84	18.51	21.81	0.84	18.51
Reed canarygrass						
Seedling year, SY‡‡	55.82	2.16	47.37	27.26	1.05	23.13
Established stand, EST§§	24.56	0.95	20.84	24.56	0.95	20.84
Hybrid poplar‖‖	72.88	2.82	61.84	…	…	…

Notes: Ellipses indicate that the crop was not produced using no-till practice. Total fuel usage, energy, and carbon emissions for cropping systems would be calculated as follows: switchgrass [1(SY) + 14(EST)]; reed canarygrass [1(SY) + 14(EST)]; corn–soybean [2(corn) + 1(soybean)]; corn–soybean–alfalfa [3(corn) + 1(soybean) + 1(alfalfa FY) + 2(alfalfa EST) + 1(alfalfa FY)]; hybrid poplar [10(hybrid poplar)].

† NT corn, soybean, alfalfa SY, switchgrass SY, and reed canarygrass SY operations are the same as respective CT crop operations except: substitute CT planting with NT planting; eliminate plow, disk (two times), and seedbed preparation; add an additional pesticide application; for NT soybean operations add soybean stubble mowing.

‡ CT corn operations: plow, disk (two times), seedbed preparation, corn planting, fertilizer application (two times), pesticide application, corn grain harvest, grain drying, stover [leaves and stalks] mower, stover baling.

§ CT soybean operations: plow, disk (two times), seedbed preparation, fertilizer application, grain drill planting, pesticide application, soybean harvest.

‖ CT alfalfa SY operations: plow, disk (two times), seedbed preparation, fertilizer application, grain drill planting, pesticide application (three times), alfalfa mowing (1st harvest), forage raking, alfalfa baling (1st harvest).

¶ CT and NT alfalfa EST and FY operations: fertilizer application (two times), pesticide application (two times), alfalfa mowing (1st and 2nd harvest), forage raking (two times), alfalfa baling (1st and 2nd harvest); plus for alfalfa (FY) add pesticide application.

CT switchgrass SY operations: plow, disk (two times), seedbed preparation, fertilizer application, grain drill planting, pesticide application, switchgrass mowing (SY), switchgrass baling (SY).

†† CT and NT switchgrass EST operations: fertilizer application, switchgrass mowing (EST), switchgrass baling (EST).

‡‡ CT reed canarygrass SY operations: plow, disk (two times), seedbed preparation, fertilizer application, grain drill planting, pesticide application, mowing (1st harvest), forage raking, baling (1st harvest).

§§ CT and NT reed canarygrass (RCG) EST operations: fertilizer application (two times), forage raking (two times), RCG mowing (1st and 2nd harvest), RCG baling (1st and 2nd harvest).

‖‖ Hybrid poplar energy usage and carbon emission values were annualized over a 10-yr crop cycle. Hybrid poplar operations: disk (two times 1st year), tree transplanting (1st year), pesticide application (two times 1st year; one time 2nd year; one time 10th year), cultivation (three times 1st year; two times 2nd year; one time 3rd year), lime application (3rd year), fertilizer application (3rd, 5th, 7th, and 9th years), felling (10th year), skidding (10th year), chipping (10th year).

TABLE 6. Relative contribution of management practices to CO_2 emissions from operation of agricultural machinery from the seven bioenergy cropping systems.

Bioenergy cropping systems	Tillage (%)	Harvesting (%)	Other† (%)	Propane (%)	Annual (kg CO_2-C/ha)
Switchgrass	9.9	81.9	8.2	0.0	20.6
Reed canarygrass	9.0	77.9	13.0	0.0	22.6
Corn–soybean					
Conventional tillage	28.8	30.7	7.6	32.9	106.4
No till	0.0	40.2	18.4	41.5	84.3
Corn–soybean–alfalfa					
Conventional tillage	26.9	33.7	11.9	27.6	71.4
Corn–soybean–alfalfa					
No till	0.0	42.8	22.8	34.4	57.2
Hybrid poplar	1.5	91.8	6.7	0.0	61.8

† Fertilizing, planting, and herbicide application.

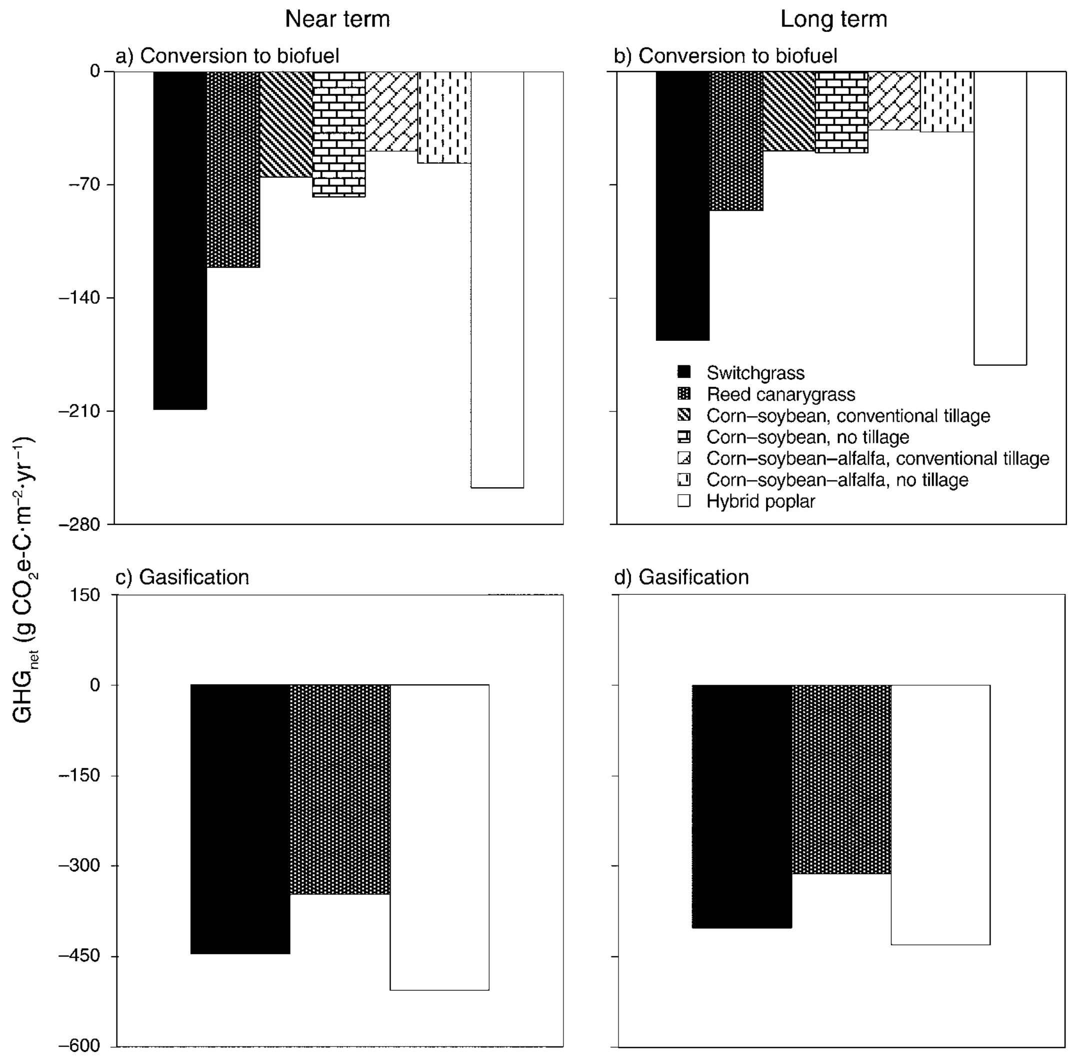

FIG. 4. Net greenhouse-gas (GHG_{net}) emissions from different bioenergy cropping systems with conversion to ethanol or biodiesel (a, b) or gasification of biomass (c, d). Near-term GHG_{net} is the sum of displaced fossil fuel, net change (Δ) in system C, feedstock conversion, direct and indirect N_2O emissions, fossil fuel used to produce chemical inputs, and fossil fuel used in agricultural-machinery operations. Long-term GHG_{net} is the sum in near-term GHG_{net} except Δ(system C), because soils will come to equilibrium with C inputs, and further soil C sequestration will not occur.

grass, and hybrid poplar for electricity generation from gasification. The energy content of biomass for conversion to electricity by gasification follows the C content (Brown 2003) and decreased in the order of hybrid poplar, switchgrass, and reed canarygrass as described by the heating values in the above section (see *Methods: Net GHG flux...*). There was about a 10% difference in energy content between the lowest (reed canarygrass at 17.7 MJ/kg) and highest materials (hybrid poplar at 19.3 MJ/kg). Therefore the differences in electricity production between cropping systems in this study are due to biomass yield, not energy content.

Greenhouse-gas sinks

Displaced fossil fuel (C_{dff}) was the largest greenhouse-gas (GHG) sink. There is a higher emission of CO_2e-C associated with generation of electricity from coal gasification compared with gasoline and diesel (CONCAWE 2004). Therefore, the C_{dff} from biomass gasification was greater than from liquid biofuels.

Storage of carbon in soil resulted from changes in C inputs, tillage intensity, and residue decomposition. Soil C inputs from root turnover, crop residue, and live root biomass varied with crop. Although the perennial grass crops reed canarygrass and switchgrass had larger C inputs from roots, most of the aboveground biomass was removed with harvest and not returned to the soil. However, only 50% of the corn stover was removed, resulting in large soil C inputs in corn rotations from aboveground biomass. Soil organic carbon (SOC) levels increase with crop residue input such as when higher yielding crop species are planted (Campbell et al. 2005), increased fertilizer applied (Studdert and Echeverria 2000, Campbell et al. 2005), and with cropping frequency when fallow is part of the crop rotation (Campbell et al. 2005). A decrease in residue decomposition due to reduced soil tillage (Paustian et al. 2000, West and Post 2002) and reduced quality of crop residues (Heal et al. 1997) also increases SOC. Results from this study are consistent with these previous findings; the higher yielding crop species with lower quality residues had higher SOC. The no-till corn rotations also had higher SOC compared to conventional-tillage rotations.

Increased crop diversity in rotations will increase SOC if subsequent crops included in the rotation add greater amounts of residue to the soil and/or decrease SOC decomposition, such as crops with more recalcitrant residue or perennials that have reduced tillage. Monoculture corn has been observed to have higher SOC than corn–soybean rotation (Havlin et al. 1990, Studdert and Echeverria 2000, West and Post 2002) since soybean provides less residue input to the soil than corn. Replacing wheat with lower-yielding flax reduced SOC (Campbell et al. 2005). Perennial crops can increase SOC through elimination of tillage and increased root biomass relative to annual crops. However, in contrast to Russell et al. (2005), alfalfa reduced SOC when added to the corn–soybean rotation.

The change in SOC and belowground biomass C, Δ system C (ΔC_{sys}) will approach zero as soil C levels reach equilibrium for a given quantity of C inputs and C losses from decomposition (Paustian et al. 2000). However, even though changes in soil C will approach zero, some cropping systems will have higher long-term SOC storage due to higher inputs and/or reduced decomposition. The long-term C sequestration potential of soils is also affected by soil properties such as texture, and some will saturate at higher SOC levels than others (Six et al. 2002). Therefore the potential long-term storage of SOC will depend on the cropping system and how it is managed, and the specific soil. Variation in SOC under the same crop is expected due to the identity of other crops in the rotation, crop yield, tillage intensity, and soil texture.

The feedstock-conversion C (C_{FC}) varied from being positive (a net consumer of energy) to negative (a net producer of energy). Initially, this may seem to be a surprising result. However, negative values result from an electricity credit at the conversion facility for combustion of the lignin fraction of biomass (Sheehan et al. 2004). The lignin fraction of biomass is not converted to ethanol, but to electricity when combusted. Cropping systems with a smaller electricity credit are net consumers of energy for this component and have positive values. Hybrid poplar, switchgrass, and reed canarygrass were net producers of energy during conversion (Fig. 2c) and the corn–soybean–alfalfa rotation used less energy than the corn–soybean rotation due to higher production of biomass relative to grain.

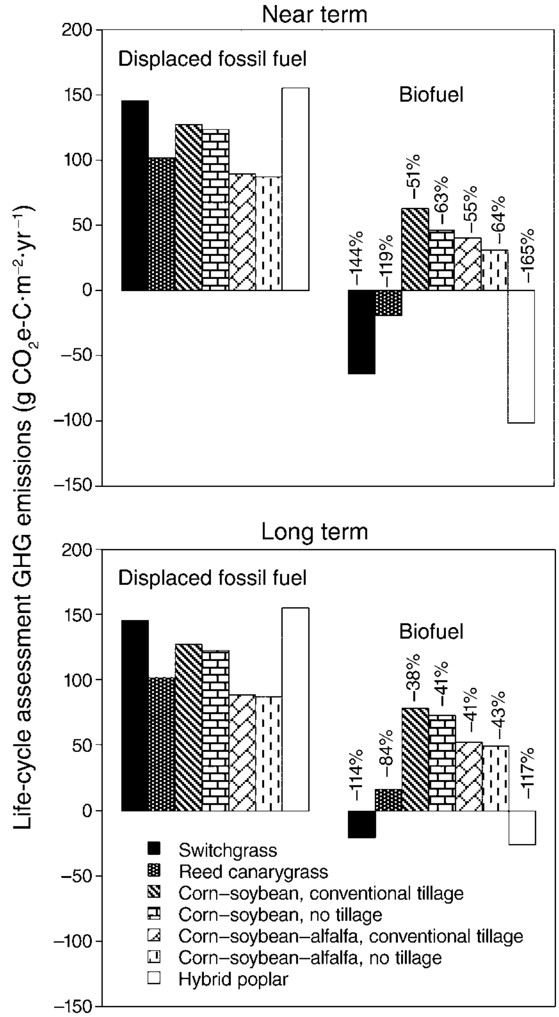

FIG. 5. Comparison of the life-cycle greenhouse-gas (GHG) emissions associated with the quantity of gasoline and diesel displaced by ethanol and biodiesel produced from the cropping systems (displaced fossil-fuel C [C_{dff}]) with the quantity of GHG emissions associated with the life cycle of biofuel (ethanol and biodiesel) production (feedstock-conversion C [C_{FC}] + C_{CH_4} + direct C_{N_2O} + indirect C_{N_2O} + chemical-inputs C [C_{CI}] + agricultural-machinery C [C_{AgMa}]); near-term includes change in system C [ΔC_{sys}]). The percentage reduction in GHG emissions was calculated as the difference in the biofuel emissions and fossil-fuel emissions displaced from biofuel produced by a given crop expressed as a percentage of the displaced fossil-fuel emissions.

Cropping systems with grain crops had higher C_{FC} than biomass crops because they lacked the coproduct lignin, which was a source of energy when combusted.

Greenhouse-gas sources

There were four sources of greenhouse gases quantified in this study, direct soil N_2O emissions ($C_{N_2O\ Dir}$), indirect N_2O emissions from offsite denitrification of NO_3 and volatilized N that was deposited offsite and converted to N_2O in soil ($C_{N_2O\ Ind}$), CO_2 emissions from manufacture of fertilizers, lime, and pesticides (chemical-inputs C, C_{CI}), and CO_2 from fuel used by agricultural machinery for tillage, planting, fertilizer and pesticide application, harvesting, and drying corn grain (C_{AgMa}). It has often been observed that N_2O emissions increase with conversion of conventional tillage land to no-till (Six et al. 2004, Smith and Conen 2004). However, Six et al. (2004) found that while N_2O emissions were higher the first 10 years after conversion to no-till from conventional tillage, 20 years after no-till adoption, N_2O emissions were higher in conventional-tillage systems as was observed in this study. Our simulations were for 30 years and estimating higher N_2O emissions with conventional tillage would be consistent with what has been observed in other studies (Six et al. 2004).

The comparison of Integrate Panel on Climate Change (IPCC 2000)-calculated N_2O emissions with those determined by DAYCENT varied with cropping system (Fig. 3). As the proportion of legumes in the crop rotations increased, the overestimate of N_2O emissions by IPCC relative to DAYCENT increased as observed with the corn–soybean–alfalfa rotation. These results are consistent with previous work showing that DAYCENT and IPCC (2000) methodology estimated similar emissions for non-N-fixing crops, but IPCC (2000) methodology was about twice as high for N fixers (Del Grosso et al. 2005). Data from soybean and alfalfa cropping in Canada (Rochette et al. 2004) and Michigan (Robertson et al. 2000) suggest that IPCC (2000) methodology overestimates N_2O emissions from N fixers. In contrast to the N-fixing crops, IPCC (2000) estimates of N_2O emissions from switchgrass were lower than DAYCENT. Since IPCC (2000) methodology bases N_2O emissions strictly on N inputs from fixation, fertilization, and aboveground residue, IPCC does well estimating N_2O fluxes from crops where the majority of N comes from these sources. However switchgrass does not fix N, has low N fertilizer inputs, and aboveground inputs of N from residue are close to 0 because virtually all of the biomass is harvested. More N comes from decomposition of SOC and roots, a source not considered by IPCC. In DAYCENT, N_2O emissions are based not only on N inputs from fixation, fertilization, and aboveground residue, but also on N inputs from decomposition of belowground residue and mineralization of soil organic matter. Consequently, DAYCENT estimates higher emissions than IPCC (2000) methodology for this crop. Indirect N_2O emissions from NO_3 leaching and volatilization, like direct soil N_2O emissions, varied across cropping systems largely as a function of N inputs from fertilizer and fixation. This is because other factors that influence N losses (soil texture, weather) were considered constant for this study. The rate and time of N fertilizer application are critical components of N fertilizer management (Dinnes et al. 2002) and followed standard recommendations in this study. Farmers will often apply all the nitrogen at corn planting; however, in this study, only one third of the N was applied at planting, to ensure greater N-use efficiency. DAYCENT predicted a small reduction in NO_3 leaching under no-till compared to conventional tillage in crop rotations. Soil NO_3 concentrations tend to be higher under conventional tillage but the volume of water flowing through the soil tends to be higher under no-till, leading to variable results on the effect of tillage on NO_3 leaching (Dinnes et al. 2002).

The CO_2 costs of chemical inputs were mainly due to fertilizer production, followed by limestone, herbicides, and insecticides. N production was responsible for most of the CO_2 costs from fertilizer input for all the cropping systems. However, because N was only applied in years corn was grown in the corn rotations and in the other years soybean and alfalfa legume crops contributed fixed N, the average N application rate for the corn cropping systems was much lower than the annual N application for corn. Reducing synthetic N use is important to decreasing GHG emissions from cropping systems whether through use of legumes in the cropping systems, or more efficient N-use strategies or crops.

C_{AgMa} and C_{CI} are affected by both the choice of crop and management practices. Reducing farm operations through reducing tillage, planting, and N fertilizer applications significantly reduced net GHG emissions as shown in this study (Table 5) and others (West and Marland 2002, Kim and Dale 2004*b*). However, the fuel savings from less plowing with no till is partially offset by higher emissions from herbicide inputs (Table 4). Some of these decisions are inherent with the specific crop chosen, e.g., no tillage with perennial crops or no N application with legume crops. However, other management practices, such as no-till vs. conventional tillage for annuals, are decisions made by the farm manager.

Global-warming potential

The near-term scenario combined all the GHG sinks and sources evaluated in this study, and considered how using biofuels would reduce GHG_{net} compared to continuing to use fossil fuels in the near-term. The displaced fossil-fuel C (C_{dff}) was the dominant factor in determining GHG_{net}. In general, switchgrass and hybrid poplar had higher yields, greater soil C sequestration, reduced GHG emission from feedstock conversion, reduced soil N_2O emissions, and reduced GHG emissions from chemical input manufacture and agricultural machinery operation.

The long-term GHG_{net} assumed that ΔC_{sys} was zero because soils were equilibrated and no longer sequestering additional C (Six et al. 2002). This scenario considers how using biofuels would reduce GHG_{net} compared to continuing to use fossil fuels in the long term. All cropping systems were still GHG sinks compared to their fossil fuel counterparts. Biofuels have been considered to have a near-zero net emission of greenhouse gases (McLaughlin et al. 2002). However, coproducts such as lignin and protein, along with soil C sequestration, can reduce GHG_{net}, making these system sinks, and when compared with the life-cycle GHG emissions of the displaced fossil fuel, our analysis shows biofuels having net GHG benefits.

Producing energy from crops is a land extensive approach to energy production. In addition to having metrics that allow easy comparison across technologies (Farrell et al. 2006; e.g., GHG emissions per megajoule of fuel), to evaluate land-use implications of bioenergy cropping systems, a metric expressed in terms of policy impact per unit land area is needed. In this study cellulosic crops had higher biofuel yield and lower GHG emissions per unit land area than corn rotations. Cellulosic crops also had a greater reduction in GHG emissions per unit biofuel produced than corn rotations, resulting in greater reductions in GHG emissions associated with energy use compared with fossil fuels.

Capture of CO_2 from fuel production and energy generation would further increase the impact of biofuels on reducing GHG_{net}. Only a portion of biomass C is retained in ethanol and biodiesel. In an ethanol conversion facility for corn stover, about one third of the biomass C is converted to ethanol, the remainder of biomass C was emitted as combustion exhaust and fermentation-generated CO_2 (Sheehan et al. 2004). Similar proportions of biomass C were converted to ethanol in this study. Two thirds of the C could be captured at a biorefinery and nearly 100% could be captured at a biomass-gasification power plant (Spath and Mann 2004). Spath and Mann (2004) have quantified the impact of CO_2 capture for both coal and biomass-gasification systems. They found that even with CO_2 capture, fossil-based systems still have greater GHG emissions per kilowatt-hour of electricity than for biomass power-generation systems without C capture.

Carbon credit markets associated with GHG mitigation strategies have been developed (McCarl and Schneider 2001, Paustian and Babcock 2004). Short-term strategies for mitigating greenhouse gases using biofuels include soil C sequestration. However, displacement of greenhouse gases associated with the use of fossil fuels is the only long-term mitigation mechanism when using biofuels and would be easier to track for carbon markets.

Implications of bioenergy on the net greenhouse-gas flux of energy use

The use of biofuel could reduce the net GHG flux of energy use, whether from production of liquid fuels, e.g., ethanol and biodiesel, or generation of electricity from gasification of biomass. The choice of crop and management practices will affect the net GHG fluxes of energy use from biofuel. Cellulosic energy crops such as switchgrass and hybrid poplar have the greatest potential to reduce net emissions of energy use in the near- and long-term.

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