

# Do Mitigation Strategies Reduce Global Warming Potential in the Northern U.S. Corn Belt?

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Agricultural management practices that enhance C sequestration, reduce greenhouse gas emission (nitrous oxide [ $\text{N}_2\text{O}$ ], methane [ $\text{CH}_4$ ], and carbon dioxide [ $\text{CO}_2$ ]), and promote productivity are needed to mitigate global warming without sacrificing food production. The objectives of the study were to compare productivity, greenhouse gas emission, and change in soil C over time and to assess whether global warming potential and global warming potential per unit biomass produced were reduced through combined mitigation strategies when implemented in the northern U.S. Corn Belt. The systems compared were (i) business as usual (BAU); (ii) maximum C sequestration (MAXC); and (iii) optimum greenhouse gas benefit (OGGB). Biomass production, greenhouse gas flux change in total and organic soil C, and global warming potential were compared among the three systems. Soil organic C accumulated only in the surface 0 to 5 cm. Three-year average emission of  $\text{N}_2\text{O}$  and  $\text{CH}_4$  was similar among all management systems. When integrated from planting to planting,  $\text{N}_2\text{O}$  emission was similar for MAXC and OGGB systems, although only MAXC was fertilized. Overall, the three systems had similar global warming potential based on 4-yr changes in soil organic C, but average rotation biomass was less in the OGGB systems. Global warming potential per dry crop yield was the least for the MAXC system and the most for OGGB system. This suggests management practices designed to reduce global warming potential can be achieved without a loss of productivity. For example, MAXC systems over time may provide sufficient soil C sequestration to offset associated greenhouse gas emission.

AGRICULTURE CONTRIBUTES TO anthropogenic release of greenhouse gases, including  $\text{CO}_2$ ,  $\text{N}_2\text{O}$ , and  $\text{CH}_4$ , but it can also serve as sink for greenhouse gases. In addition, increased atmospheric  $\text{CO}_2$  has coincided with measureable losses in soil organic C (Huggins et al., 1998; Slobodian et al., 2002). Currently, many strategies exist that may increase soil C and mitigate global warming potential, including reducing tillage, increasing the number of crops grown in rotation, adding perennials or cover crops within a rotation, and applying manures (West and Post, 2002; Johnson et al., 2007b). However, concerns have been raised that eliminating tillage may require additional N fertilizer, which could lead to more  $\text{N}_2\text{O}$  emission, reducing the mitigating benefit of storing soil C (Johnson et al., 2005). Global warming potential is reduced when the amount of sequestered soil organic C exceeds greenhouse gas emission from soil processes and fuel use (Johnson et al., 2005; Mosier et al., 2006). The balance among the interconnected sources and sinks determines the global warming potential of a given system.

The goal of this study was to assess whether modifications to a common cropping system found in the northern edge of the U.S. Corn Belt could reduce global warming potential without sacrificing plant productivity. The majority of crop land in the northern Corn Belt (e.g., Minnesota) is devoted to corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] and managed with inorganic fertilizer and intensive tillage (Archer et al., 2007). While some form of conservation tillage is used on >30% of the farmed land, <5% of this area is managed without tillage (Johnson et al., 2005). Therefore, we defined a corn-soybean rotation using conventional tillage and applying inorganic N-P-K fertilizer as the BAU system.

Increasing soil organic C is a greenhouse gas mitigation strategy. Tillage-induced  $\text{CO}_2$  flux is proportional to the volume of soil disturbed (Reicosky and Lindstrom, 1993). Strip tillage is a management practice intended to increase surface residue and reduce tillage-induced  $\text{CO}_2$  flux (Reicosky and Lindstrom, 1993) but avoid adverse microclimate impacts of no-tillage systems,

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**Abbreviations:** BAU, business as usual;  $\text{CH}_4$ , methane;  $\text{CO}_2$ , carbon dioxide; MAXC, maximum carbon sequestration;  $\text{N}_2\text{O}$ , nitrous oxide; OGGB, optimum greenhouse gas benefits.

which can delay crop growth and reduce yields in cool, wet soils (Venterea et al., 2006). Strip-tillage with a mole knife would take less fuel than tilling with a chisel or moldboard plow (Archer and Reicosky, 2009; Schnitkey, 2010). Converting from a 2-yr to a 4-yr rotation and adding perennials within a rotation are management changes that may increase soil C sequestration (West and Post, 2002). A corn–soybean–wheat (*Triticum aestivum* L.)/alfalfa (*Medicago aestivum* L.)–alfalfa rotation with strip tillage and inorganic N–P–K fertilizer application system was designated as the MAXC system. This system was included as an alternative system that may mitigate global warming potential through soil C sequestration without a loss of plant productivity.

Reducing CH<sub>4</sub> and/or N<sub>2</sub>O emission or increasing CH<sub>4</sub> oxidation can also mitigate global warming potential. Methane flux from row crop systems tends to be small and near background levels (Johnson et al., 2010). Furthermore, interactions between management and soil moisture management can result in either increased CH<sub>4</sub> oxidation or increased emission (Johnson et al., 2005). Application of N-fertilizer is recognized as an important contributor to N<sub>2</sub>O emission; reducing the amount of N<sub>2</sub>O emission related to fertilization thus has potential to mitigate global warming potential (Johnson et al., 2005). Therefore, eliminating fertilizer was predicted to reduce N<sub>2</sub>O flux, thereby reducing overall greenhouse gas emission compared with the BAU and MAXC systems. A corn–soybean–wheat/alfalfa–alfalfa rotation with strip tillage but without inorganic N–P–K fertilizer application was designated as the OGGB system. The OGGB system may mitigate global warming potential through soil C sequestration and reduced N<sub>2</sub>O emission but at a loss of crop yield.

Previously, we (Johnson et al., 2010) presented a comparison of greenhouse gas emission from contrasting management, which does not directly permit an estimation of global warming potential. Addressing global warming potential and global warming relative to productivity requires assessing both plant productivity and soil carbon. Therefore, this study's objectives were to compare overall productivity, greenhouse gas emission, and change in soil C over time and to assess if global warming potential and global warming potential per unit biomass produced were reduced through combined mitigation strategies when implemented in the northern Corn Belt.

## Materials and Methods

### Experimental Site

The study was conducted at the Swan Lake Research Farm (45°41' N; 95°48' W; elevation 370 m) and established in

2002 (Archer et al., 2007; Johnson et al., 2010). Thirty-year (1971–2000) average annual precipitation recorded at the University of Minnesota West Central Research and Outreach Center in Morris, MN, is 645 mm, and 30-yr (1971–2000) mean monthly temperatures range from −13.1°C in January to 21.7°C in July (NOAA–NCDC, 2002). The area averages 1204 growing degree days (base 10°C, 1992–2005). The Swan Lake weather station is within 1 km of the experimental field and records year-round soil temperature at 5 cm under bare soil. The entire experimental site had 192 (6 by 12 m) plots, but only 40 plots representing three management systems are presented in this paper.

This site is located on glacial till from the Des Moines Lobe deposited during the Wisconsin glaciations and has inherently high soil variability. Five similar soils (Table 1)—Barnes loam (fine-loamy, mixed, superactive, frigid Calcic Hapludolls), Flom silty clay loam (fine-loamy, mixed, superactive, frigid Typic Endoaquolls), Hamerly clay loam (fine-loamy, mixed, superactive, frigid Aeris Calcicquolls), Parnell silty clay loam (fine, smectitic, frigid Vertic Argiaquolls), and Vallers silty clay loam (fine-loamy, mixed, superactive, frigid Typic Calcicquolls), from the Barnes/Aastad soil catena—are found within the entire experimental site (USDA–SCS, 1971; Soil Survey Staff, 2008). Very little land area was classified as Parnell within the experimental site, and most in designated alleyways, so it was not included in the sampled area for this study. Nearly 40% of the systems included in this study were on Barnes soil, with the remainder distributed as follows: BAU system—Hamerly (25%), Vallers (25%), and Flom (12.5%); MAXC system—Hamerly (50%) Flom (6%), and Vallers (6%); and the OGGB system—Hamerly (37.5%), Vallers (16%), and Flom (6%). Although soil types were not ideally balanced among the systems, soil distributions were not overtly biased toward one soil in a system at the exclusion of others.

For this study, four replications of three crop management systems were included (Table 2). All crop phases of each rotation were grown every year, such that there were eight plots in BAU and 16 plots in each MAXC and OGGB systems for a total of 40 plots. Extensive management details were published previously (Archer et al., 2007; Johnson et al., 2010). Briefly, in the BAU system, primary tillage occurred in the fall with chisel plow (~15 cm) following soybean and moldboard plow (~20 cm) after corn. In addition, the soil was tilled with a field cultivator (10 cm) in the spring before planting. In the MAXC and OGGB, the soil was fall tilled with a mole knife (20 cm) after corn, soybean, and alfalfa. The following varieties were planted: Dekalb 'DK4446' (corn), Pioneer '91B33' (soybean),

**Table 1. General characterization of the soil series located within the experimental study area.**

Soil series	Sand	Clay	Total C		Inorganic C		pH <sub>CaCl2</sub>	
	0–30 cm	0–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm
	g kg <sup>-1</sup>							
Barnes	359	271	32.9	29.9	2.60	4.36	7.09	7.22
Flom	335	262	34.6	33.3	3.64	10.8	7.32	7.38
Hamerly	381	232	34.4	31.8	2.98	4.82	7.30	7.38
Parnell	334	227	36.6	35.7	0.20	0.25	7.01	7.04
Vallers	409	252	32.4	25.7	1.63	3.76	7.42	7.49

and 'Wrangler' (alfalfa) each year, 'Alsen' (wheat) in 2004 and 2006, and 'Oklee' (wheat) in 2005.

In the MAXC system, urea ( $\text{CH}_4\text{N}_2\text{O}$ ) ( $83 \text{ kg N ha}^{-1}$ ) was applied before planting wheat (Table 2). Starter N–P was added each year to corn and in 2004 and 2005 to soybean in both BAU and MAXC systems. Additional N-fertilizer was not added during the corn phase in the MAXC system. In the BAU system during the corn phase, about  $132 \text{ kg N ha}^{-1}$  as ammonium nitrate ( $\text{NH}_4\text{NO}_3$ ) (2004 and 2005) or as anhydrous ammonia ( $\text{NH}_3$ ) (2006) was applied as a side-dress in June based on preplant soil tests. Anhydrous  $\text{NH}_3$  was applied in 2006 because  $\text{NH}_4\text{NO}_3$  was not available. Pesticides and herbicides were used as needed (Archer et al., 2007).

## Plant Biomass

Grain yield was measured with a two-row plot combine from the center of each plot. Nongrain residue (stover, stubble, and straw) from corn, soybean, and wheat was determined in a  $1\text{-m}^2$  area after the crop reached physiological maturity. Soybean biomass is underestimated as leaves senesce as soybeans mature. Total aboveground biomass was calculated as grain plus residue. Alfalfa aboveground biomass was a total of three annual cuttings ( $1\text{-m}^2$  area). Alfalfa was cut at about 2 cm above the ground surface. The equivalent of 5% of harvested alfalfa residue was assumed to have remained in the field. Total unharvested biomass includes root biomass.

Roots were collected at 75% silk in corn, first full pod for soybean, 75% booting for wheat and at the third cutting (August) for alfalfa. These sampling stages represent the transition in annual species from vegetative to reproductive growth, which generally represents peak root:shoot ratio (Klepper, 1992). Soybean roots were not sampled in 2006 due to extremely dry soil conditions. Therefore, in 2006, we estimated soybean root biomass using an empirical average root to shoot ratio of 0.0936 based on all 2004 and 2005 root and non-grain shoot observations (data not shown). To account for the nonrandom and nonuniform nature of root growth (Allmaras and Nelson, 1971), roots were collected from four positions to 60 cm at each of three sites within a plot. Corn and soybean roots were sampled between crop rows along a transect starting near a plant and at 13, 25, and 38 cm from the row. In wheat and alfalfa, which were narrowly spaced ( $\sim 18 \text{ cm}$ ), two soil cores were taken near plants and two were centered between

rows. Soil cores were pooled for each plot sampled. Roots were separated from the soil using 2- and 0.5-mm sieves, a manual equivalent of an elutriation system described by Smucker et al. (1982). The roots were dried at  $45^\circ\text{C}$  and biomass determined. Root and shoot biomass was analyzed for C and N. Small roots and rhizodeposition are not accounted for with this method; however, it provides a relative comparison among systems.

## Greenhouse Gas Emission

Greenhouse gas flux was monitored from April 2004 to April 2007. Generally, flux was measured at 2-wk intervals with additional sampling during episodic events such as spring thaw, fertilizer applications, and tillage operations until flux rate returned to baseline (Johnson et al., 2010). Two semi-permanent polyvinyl chloride collars (26 cm diam. by 7 cm tall) were installed per plot with about 2 cm remaining above the soil surface. Collars were removed just before tillage and returned immediately thereafter. Corn and soybean were grown in 76-cm rows; thus, one collar was centered in the interrow and the other next to the row. This placement was designed to help account for the nonrandom distribution of crop roots (Allmaras and Nelson, 1971). Wheat and alfalfa were planted in 18-cm rows; therefore, collars were placed randomly in relation to the plants. The chamber size did not facilitate excluding alfalfa or wheat shoots (Johnson et al., 2010). Closed-vented chambers were constructed from polyvinyl chloride end caps (26 cm diam. by 12 cm tall) with a vent (3.8 mm by 175 mm) and a sample port, similar to those described by Hutchinson and Mosier (1981), Hutchinson and Livingston (1993), and Parkin and Venterea (2010).

Immediately after manually placing the chamber on a collar, the first air sample was collected. At approximately 10- to 15-min intervals (actual interval time recorded), three subsequent air samples were collected during a 25- to 40-min deployment, at which time the chambers were removed. To minimize ambient air from diffusing into the sample vial, samples were drawn and handled similar to that described by Venterea et al. (2005). Briefly, a 20-mL aliquot of air was withdrawn and compressed to 12-mL vial. When outside air temperatures were below  $0^\circ\text{C}$ , the sample vials were kept in an insulated container (i.e., a beverage cooler) with a hot pack to prevent compromising the septum seal and sample leakage.

**Table 2. Cropping operations from three management systems.**

	Business as usual	Max. C sequestration	Overall greenhouse gas benefit
Crop rotation	Corn–soybean	Corn–soybean–wheat/alfalfa–alfalfa	Corn–soybean–wheat/alfalfa–alfalfa
Crop varieties	Dekalb 'DK4446' (corn), Pioneer '91B33' (soybean)	Dekalb 'DK4446' (corn), Pioneer '91B33' (soybean), 'Wrangler' (alfalfa), 'Alsen' (wheat, 2004 and 2006), 'Oklee' (wheat, 2005)	Dekalb 'DK4446' (corn), Pioneer '91B33' (soybean), 'Wrangler' (alfalfa), 'Alsen' (wheat, 2004 and 2006), 'Oklee' (wheat, 2005)
Post-harvest tillage	Moldboard plow (after corn) Chisel plow (after soybean)	Mole knife strip tillage (after corn and alfalfa)	Mole knife strip tillage (after corn and alfalfa)
Spring tillage	Field cultivator	None	None
Starter fertilizer	11–17–0 (kg N and P $\text{ha}^{-1}$ ) (corn all years, beans 2004 and 2005)	11–17–0 (kg N and P $\text{ha}^{-1}$ ) (corn all years, beans 2004 and 2005)	None
Side-dress N to corn	Side-dress $132 \text{ kg N ha}^{-1}$ $\text{NH}_4\text{NO}_3$ (2004 and 2005), anhydrous $\text{NH}_3$ in 2006	None	None
Broadcast	None	78–15–28 (kg N–P–K $\text{ha}^{-1}$ ) (wheat phase only)	None

Typically, samples were collected midmorning to minimize diurnal variation by collecting flux measurements to reflect mean daily temperature (Parkin and Kaspar, 2003; Parkin and Venterea, 2010). A Traceable Flip-Stick thermometer (Control Company, Friendswood, TX) was used to measure soil temperature in the surface 0 to 15 cm, and a Stevens Hydra Probe (Stevens Water Monitoring Systems Ltd., Portland, OR) was used to measure volumetric moisture (0–5 cm) adjacent to the collars when the ground was not frozen (data not shown). On several sample dates that the BAU system was slightly drier than either MAXC or OGGB, these differences did not correspond to flux differences. Measured temperatures adjacent to the collars had a nearly 1:1 relationship to average daily air temperatures, which suggests fluxes were collected at temperatures near the daily mean temperature (data not shown). A gas chromatograph with a thermal conductivity detector, electron capture detector, and flame ionization detector was used to detect CO<sub>2</sub>, N<sub>2</sub>O, and CH<sub>4</sub>, respectively. Flux was calculated for each chamber using the nonlinear method proposed by Pedersen (2000) for samples taken at nonequal time intervals, or by linear regression similar to Liu et al. (2005). Cumulative emission was estimated with linear interpolation between sampling dates and subsequent numerical integration of the area under the resulting curve using the trapezoidal rule. Temperature coefficient Q<sub>10</sub> corrections were not performed on the flux rates. Nitrous oxide flux did not correlate with mean air temperature or measured volumetric soil moisture (data not shown). Cumulative emission was converted to CO<sub>2</sub> equivalents using 298 for N<sub>2</sub>O and 25 for CH<sub>4</sub> based on the Intergovernmental Panel on Climate Change's Fourth Assessment Report values (Solomon et al., 2007). The mass of C from CO<sub>2</sub> flux, kilograms of C in soil organic carbon, or change in kilograms of C in soil organic C or plant biomass C was converted to the mass of CO<sub>2</sub> equivalents.

## Soil Sampling

In 2002, soil from the surface 30 cm was characterized for texture, total C, inorganic C, and pH. In fall 2003 and 2007, additional soil samples were collected after grain harvest but before tillage at 0 to 5, 5 to 10, 10 to 15, 15 to 30, and 30 to 60 cm for total, organic, and inorganic C analysis. A 5.3-cm-diameter hydraulic probe was used for the 10- to 15-, 15- to 30-, and 30- to 60-cm increments, three pooled cores taken

per plot. The residue was brushed aside before inserting the hydraulic probe or rings. Hand pounded rings (4.9 cm diam.) were used for the 0- to 5- and 5- to 10-cm increments, one per plot. Bulk density was calculated from cores dried at 105°C. Soil for chemical analysis was dried at 37°C. Soil was passed through a 2-mm sieve, so all but large pieces of plant debris may be included. Additionally, soil cores were collected each spring before planting to a depth of 60 cm to determine side-dress N fertilizer requirements (Archer et al., 2007).

## Analyses

Plant tissue and soil samples were analyzed for total N and total C using a LECO TRU-SPEC CN analyzer (LECO Corporation, St. Joseph, MI). Soil inorganic C was determined by measuring pressure rise of a soil sample acidified with 6 M HCl stabilized with FeCl<sub>2</sub> in a closed constant volume, constant temperature container (Wagner et al., 1998) and soil organic C calculated by difference. Soil C content was calculated from concentration and bulk density. Total plant C was calculated by multiplying concentration by total biomass. Soil pH was determined in a 1:2 soil to 0.01 M CaCl<sub>2</sub> slurry (Thomas, 1996). Particle-size analysis was determined by the hydrometer method (Day, 1956).

## Farm Operations and Global Warming Potential

The average annual contribution of production inputs to global warming potential was calculated using field records from 2003 to 2006 and based on estimated fuel use for field operations and grain drying and on actual fertilizer and pesticide use. Fuel use for field operations and grain drying were estimated using the CARE crop budget generator (USDA–NRCS, 1993). Drying fuel use was calculated based on grain moisture content measured at harvest, assuming grain would be dried using liquid propane-to-moisture contents of 155, 130, and 135 g kg<sup>-1</sup> for corn, wheat, and soybean, respectively. Fuel, fertilizer, and pesticide inputs were converted to CO<sub>2</sub> equivalents using global warming potential emission factors from West and Marland (2002) and Lal (2004).

Annual global warming potential was calculated using two methods similar to Mosier et al. (2006). The first method is based on the difference between soil plus root respiration and measured plant biomass C (total aboveground and root biomass C, Table 3):

**Table 3.** Three-year (2004, 2005, and 2006) average biomass produced in business as usual (BAU), maximum C sequestration (MAXC), and optimum greenhouse gas benefit (OGGB) systems.

Crop	Total aboveground			Total unharvested			Root (60 cm)		
	BAU	MAXC	OGGB	BAU	MAXC	OGGB	BAU	MAXC	OGGB
	Mg ha <sup>-1</sup>						kg ha <sup>-1</sup>		
Corn	15.8a†	14.8a	12.2b	8.86a	8.68a	7.20b	863	964	760
Soybean	4.17	4.30	3.82	1.99	2.17	1.92	137	192	170
Alfalfa	NR‡	9.38a	6.66b	NR	1.72	1.50	NR	1250	1170
Wheat	NR	7.34a	5.12b	NR	4.97	3.65	NR	393	348
Rotation mean	10.0a	8.96a	6.95b	5.43a	4.38ab	3.57b	500	699	612
	Mg CO <sub>2</sub> equivalents ha <sup>-1</sup> yr <sup>-1</sup>								
Rotation	16.5a	14.6a	11.3b	8.85a	8.85a	5.72b	0.81	1.12	0.99

† Values with a measured parameter and row with different letters in a row are significantly different at  $P \leq 0.05$ . Letters were omitted if no differences were detected among systems.

‡ NR, not reported; alfalfa and wheat were not included in the BAU system.

§ Average rotation biomass converted to Mg CO<sub>2</sub> equivalents ha<sup>-1</sup> yr<sup>-1</sup> using measured C concentration.



$$(\text{Soil CO}_2 - \text{total biomass C}) + (\text{production inputs} + \text{N}_2\text{O} + \text{CH}_4) = \text{global warming potential} \\ (\text{all units Mg CO}_2 \text{ equivalents ha}^{-1} \text{ yr}^{-1}) \quad [1]$$

A second method, similar to that used by Mosier et al. (2006) and Robertson et al. (2000), calculated global warming potential from the change in soil organic C (Table 4):

$$\text{Production inputs} + \text{change in soil organic C} + \text{N}_2\text{O} + \text{CH}_4 = \text{global warming potential} \\ (\text{all units Mg CO}_2 \text{ equivalents ha}^{-1} \text{ yr}^{-1}) \quad [2]$$

Mosier et al. (2006) calculated greenhouse gas intensity from global warming potential divided by grain yield, which related global warming potential to crop production. Similarly, global warming potential (Eq. [2]) divided by harvested biomass (Table 3) calculated emission relative to productivity as shown in Eq. [3]:

$$[\text{Global warming potential (Mg CO}_2 \text{ equivalents ha}^{-1} \text{ yr}^{-1})] \div [(\text{total aboveground biomass} - (\text{total unharvested biomass} - \text{root biomass}))(\text{Mg ha}^{-1} \text{ yr}^{-1})] \\ = \text{Mg CO}_2 \text{ equivalents Mg yield}^{-1} \quad [3]$$

## Statistical Analysis

The Mixed Procedure of SAS software, Version 9.1.3 (SAS, 2002), was used to detect differences among systems. System was considered a fixed effect and replication was considered a random effect. Pair-wise *t*-test comparisons of system least-squares means were performed, and significance differences are reported at the 0.05 level unless otherwise indicated (SAS, 2002). The probability that differences in measured parameters

between 2007 and 2003 were statistically different from zero was tested using an univariate Student's *t* test (SAS, 2002).

## Results

### Biomass Production

Plant biomass was reported as total aboveground biomass (grain plus residue), total unharvested biomass (which includes roots), and root biomass (Table 3). The 3-yr average, annual production of corn total aboveground biomass was similar between BAU and MAXC but was approximately 17% less in the unfertilized OGGB system (Table 3). The 3-yr average total soybean biomass ( $\sim 4.1 \text{ Mg ha}^{-1}$ ) was comparable among all three systems. The 3-yr average total alfalfa biomass and wheat total biomass were approximately 30% greater in the MAXC compared with OGGB. The 3-yr total aboveground biomass averaged across rotation was similar between BAU and MAXC, and both exceeded the OGGB by at least 10%. The largest amount of unharvested biomass returned to the land was in the BAU system, which was approximately 30% greater compared with the OGGB system, with the MAXC system intermediate to the other systems (Table 3). Root biomass in the surface 0.6 m provides a relative comparison of root growth among the three systems (Table 3). Even though corn and alfalfa have more than twice the root biomass of wheat or soybean, there were no differences for the 3-yr rotation average root biomass among systems.

### Greenhouse Gas Emission

Annual average CO<sub>2</sub> flux rates differed among systems, with the greatest fluxes typically occurring in MAXC and OGGB, which included wheat- and alfalfa-shoot respiration (Table 5).

**Table 4.** The mass per area of total C content and soil organic C from soil collected in 2003 and 2007 from three management systems: business as usual (BAU), maximum carbon sequestration (MAXC), and optimum greenhouse gas benefit (OGGB). Changes were calculated as the difference between 2007 and 2003; a positive value indicates an increase and a negative value a decrease in soil C.

Depth	2007			2003			Change (2007 – 2003)		
	BAU	MAXC	OGGB	BAU	MAXC	OGGB	BAU	MAXC	OGGB
Soil total C Mg ha <sup>-1</sup>									
0–5	21.17b†	24.98a	22.48b	18.50b	21.95a	20.37ab	2.68a**	3.03a**	2.10a**
5–10	19.74	21.46	20.45	19.66	21.33	19.98	0.08	0.13	0.48
10–15	22.08	23.28	21.50	23.66	23.99	22.56	–1.57	–0.72	–1.06
15–30	68.90a	66.29a	57.92b	69.62ab	71.66a	60.48b	–0.72	–4.56‡	–2.56
30–60	149.5	118.7	118.5	132.7	127.2	123.4	16.81	–8.44	–4.97
0–60	281.4	251.6	240.8	264.1	266.1	246.8	17.28	–10.03	–6.02
SE§ 0–60	20.88	15.25	14.77	19.62	13.87	13.88	12.96	10.37	10.14
Soil organic C Mg ha <sup>-1</sup>									
0–5	18.27c	23.57a	21.55b	16.66b	20.42a	19.59a	1.62‡	3.16**	1.96**
5–10	17.01b	19.88a	19.63a	17.87	19.78	19.14	–0.86	0.10	0.49
10–15	18.83	21.36	20.43	21.51	22.07	21.38	–2.67**	–0.71	–0.95
15–30	50.45	56.49	51.69	56.74	60.82	52.60	–6.28*	–4.23*	–0.91
30–60	43.16	46.13	37.37	45.70	49.55	44.08	–2.54	–3.43	–6.72*
0–60	147.7	168.1	150.7	158.5	172.6	156.8	–10.74‡	–4.55	–6.12
SE 0–60	9.20	6.72	6.50	7.99	5.65	5.65	6.14	4.48	6.12

\* Significant at the 0.05 probability level for the change over time being different from zero within a system.

\*\* Significant at the 0.01 probability level for the change over time being different from zero within a system.

† Differences among systems are designated within a grouping with different letters in a row are significantly different at  $P \leq 0.05$ . Letters were omitted if no differences were detected among systems.

‡ Significant at the 0.10 probability level for the change over time being different from zero within a system.

§ Standard error for 0–60 profile.

Occurrence of plants within flux chambers did not affect N<sub>2</sub>O or CH<sub>4</sub> emission. Nitrous oxide emission differed significantly among systems only in the 2005–2006 crop years, where the BAU system released significantly more N<sub>2</sub>O than either MAXC or OGGB systems (Table 5). In general, there was net CH<sub>4</sub> oxidation, but there were no differences among systems. The total greenhouse gas emission was 17.0, 24.2, and 23.7 Mg CO<sub>2</sub> equivalents ha<sup>-1</sup> yr<sup>-1</sup> from the BAU, MAXC, and OGGB systems, respectively.

## Bulk Density and Soil Carbon Content

Bulk density was measured to identify any differences due to management, particularly since tillage differed among systems (Table 6). Within years, bulk density was comparable among management systems, except in 2003, where there was a trend ( $P = 0.10$ ) for BAU to be less than MAXC and OGGB in the surface 10 cm. The change in bulk density between sample years did not differ among systems. The bulk density significantly increased 16% in the surface 0 to 5 cm, 10% at 5- to 10-cm depth, and 5% at the 30- to 60-cm depth increment of the BAU system. Bulk density significantly increased over time by 7 and 8% at 0 to 5 and 5 to 10 cm, respectively, for the MAXC and OGGB systems.

Soil C concentration and soil bulk density were used to calculate mass and change in mass of total soil C and soil organic C (Table 4). In 2003, the content of total C in the surface 0 to 5 cm differed among systems. The MAXC had 18% and OGGB had 10% more total soil C compared with the BAU system.

Similarly, the MAXC system had 22.5% and the OGGB had 17.6% more soil organic C compared with the BAU system. In 2007, the MAXC system had 18% and the OGGB system had 6% more total soil C compared with the BAU system. Similarly, the MAXC had 23% and the OGGB had 18% more total soil C compared with the BAU system. Relative differences among systems did not change between 2003 and 2007. Total soil C and soil organic C amounts were similar in the 0–60-cm depth for all three systems in both 2003 and 2007. Soil inorganic C content did not differ among systems at any depth increment (data not shown).

Changes in total soil C between 2003 and 2007 did not differ among systems (Table 4). All systems had about a 10% increase in total soil C in the surface 0 to 5 cm. In contrast, measurable decreases in soil organic C occurred at 10 to 15 cm and 15 to 30 cm for the BAU system, at 15 to 30 cm for MAXC system, and at 30 to 60 cm for the OGGB system. When integrated over the 0- to 60-cm soil profile, soil organic C decreased in all systems; this decrease was significant at  $P = 0.09$  for the BAU system.

## Global Warming Potential

All three systems had a positive global warming potential (Fig. 1), regardless of the method used to approximate CO<sub>2</sub> contribution (Eq. [1] or Eq. [2]). Approximating the CO<sub>2</sub> contribution from the difference in measured biomass C and soil plus root respiration (Eq. [1]), the apparent global warming potential was greater for the MAXC and OGGB

**Table 5. Annual and average of 3-yr emission of CO<sub>2</sub>, N<sub>2</sub>O, and CH<sub>4</sub> along with calculated CO<sub>2</sub> equivalents; from Business as usual (BAU), Maximum carbon sequestration (MAXC) and Optimum greenhouse gas benefit (OGGB) management systems.**

Year	Carbon dioxide			Nitrous oxide			Methane		
	BAU	MAXC	OGGB	BAU	MAXC	OGGB	BAU	MAXC	OGGB
	— Mg C ha <sup>-1</sup> from CO <sub>2</sub> —			— kg N ha <sup>-1</sup> from N <sub>2</sub> O —			— kg C ha <sup>-1</sup> from CH <sub>4</sub> —		
2004–2005	4.42	5.59	5.57	4.89	5.30	5.56	–0.60	–0.35	–0.31
2005–2006	3.65b†	4.77ab	5.16a	5.47a	4.57b	4.64b	–0.12	–0.06	0.07
2006–2007	3.95b	7.60a	6.78a	4.25	4.55	4.92	–0.43	–0.49	–0.49
Mean	4.01b	5.99a	5.84a	4.87	4.81	5.04	–0.38	–0.30	–0.24
	— Mg CO <sub>2</sub> equivalents ha <sup>-1</sup> yr <sup>-1</sup> —								
Mean	14.7b	22.0a	21.4a	2.28‡	2.25	2.36	–0.013	–0.010	–0.008

† Different letters following a value within a row and within a gas indicate significant differences at  $P \leq 0.05$  among systems. Letters were omitted if no differences were detected among systems.

‡ Assuming a 100-yr global warming potential of 298 for N<sub>2</sub>O and 25 for CH<sub>4</sub> (Solomon et al., 2007).

**Table 6. Soil bulk density and the change in bulk density between 2003 and 2007 in each of the three management systems: business as usual (BAU), maximum C sequestration (MAXC), and optimum greenhouse gas benefit (OGGB).**

Depth cm	2007			2003			Change† (2007 – 2003)		
	BAU	MAXC	OGGB	BAU	MAXC	OGGB	BAU	MAXC	OGGB
	— Mg m <sup>-3</sup> —								
0–5	1.21‡	1.20	1.20	1.04	1.12	1.12	0.17**	0.08**	0.08**
5–10	1.18	1.22	1.25	1.07	1.12	1.15	0.11*	0.10**	0.10**
10–15	1.32	1.35	1.37	1.33	1.29	1.32	–0.01	0.07	0.05
15–30	1.31	1.33	1.34	1.34	1.36	1.35	–0.02	–0.02	–0.01
30–60	1.44	1.44	1.41	1.37	1.42	1.40	0.07*	0.02	0.01

\* Significant at the 0.05 probability level for the change in bulk density from 2003 to 2007 within a system of being different from zero using a  $t$  test.

\*\* Significant at the 0.01 probability level for the change in bulk density from 2003 to 2007 within a system of being different from zero using a  $t$  test.

† A positive value indicates bulk density was greater in 2007 compared with 2003.

‡ Values for systems within a grouping (e.g. 2007) with different letters in a row are significantly different at  $P \leq 0.05$ . Letters were omitted if no differences were detected among systems.

systems compared with the BAU system (Fig. 1a). This method reflects the uncorrected bias of shoot and root respiration from wheat and alfalfa. In contrast, when global warming potential was calculated based on the changes in soil organic C (Eq. [2]), there were no differences among systems (Fig. 1b). Annual change in soil organic C was the largest fraction (52%) of global warming potential for the BAU system, but the largest fraction (68 and 63%, respectively) of global warming potential came from N<sub>2</sub>O emission in the MAXC and OGGB systems (Fig. 1b).

Global warming potential relative to dry crop yield relates greenhouse gas emission and productivity (Eq. [3]). The global warming potential relative to dry crop yield was 1.04, 0.92, and 1.24 CO<sub>2</sub> equivalents Mg<sup>-1</sup> crop yield for BAU, MAXC, and OGGB. Compared with the BAU system, the MAXC had an 11% decrease in Mg CO<sub>2</sub> equivalents Mg<sup>-1</sup> crop yield, but the OGGB system had nearly a 20% increase.

## Discussion

A goal of this study was to identify management systems that reduce global warming potential without negatively impacting plant productivity. The MAXC system maintained similar productivity (Table 3) compared with the BAU systems with lower global warming potential (Fig. 1b); thus, fewer CO<sub>2</sub> equivalents per unit dry yield (Eq. [3]) were observed in the MAXC system. However, economic analysis indicated greater economic return with the BAU system compared with the MAXC system (Archer et al., 2007). Therefore, without additional economic incentive, producers are not likely to adopt a MAXC system.

Eliminating fertilizer from the OGGB system was predicted to reduce N<sub>2</sub>O flux and global warming potential, but this was not observed. We speculate this may have been due to applying N based on spring soil tests and using a split N application in the BAU, which may have reduced the opportunity for N<sub>2</sub>O formation (Johnson et al., 2010). An increase in N<sub>2</sub>O emission was observed following N-fertilizer application in corn and wheat (Johnson et al., 2010). However, greatest N<sub>2</sub>O fluxes always occurred during spring thaw and not in direct response to N-fertilizer application. Presumably, there was sufficient C and N substrate provided in the soil organic matter to drive N<sub>2</sub>O production during spring thaw even in the OGGB system (Johnson et al., 2010). These results suggest additional comparisons on efficacy of N-fertilizer management to avoid N<sub>2</sub>O emission are needed.

Soil organic C was sequestered at the 0- to 5-cm depth (Table 4). However, comparing the 0- to 60-cm profile muted system impacts in part due to summing the noise of sampling variability. Other researchers (e.g., Gregorich et al., 2005; Baker et al., 2007) have also reported a lack of measurable change in soil organic C in response to eliminating tillage especially if soil was sampled deeper than 30 cm. In the 0- to 60-cm profile, bulk density (Table 6), total soil C, and soil organic C values (Table 4) were consistent with other reports on Mollisols (Lal et al., 1998; Liebig et al., 2006). Within a sampling year, the coefficient of variance was 10% or less, but the variability for the change over time was >50% even though the change over time was determined on a plot-by-plot basis. The depth of the

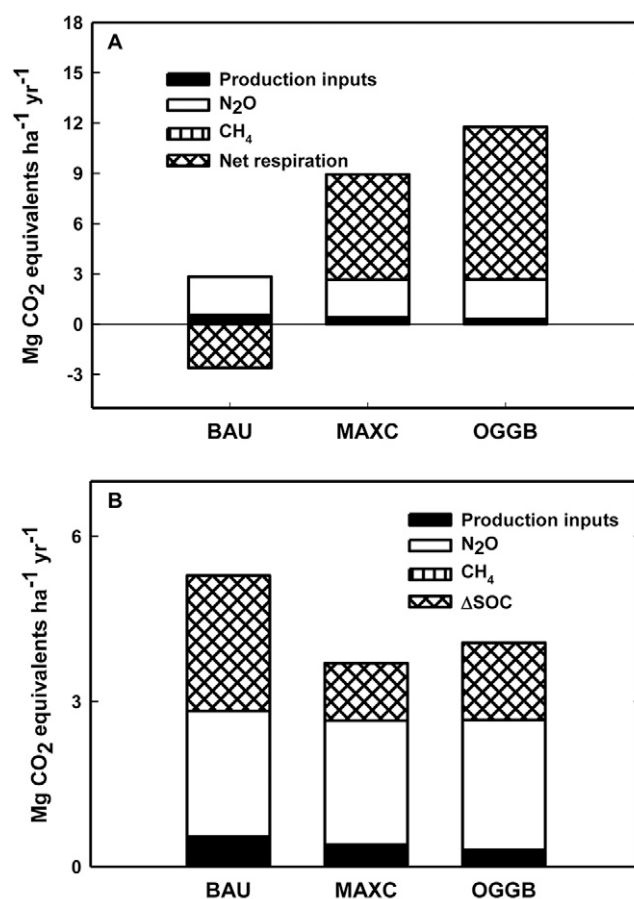


Fig. 1. Global warming potential (Mg CO<sub>2</sub> equivalents ha<sup>-1</sup> yr<sup>-1</sup>) from business as usual (BAU), maximum carbon sequestration (MAXC) and optimum greenhouse gas benefit (OGGB) management systems based on (A) net respiration as the difference between total biomass C returned and measure CO<sub>2</sub> flux (Eq. [1]) and (B) change in soil organic C (SOC) (Eq. [2]). Methane contribution is not visible at this scale. Negative values indicate a CO<sub>2</sub> equivalent sink, and positive values indicate a source.

mollic epipedon in these glacial till soils is highly variable with a highly calcareous subsoil (Soil Survey Staff, 2008), which contributes to the observed variability. Thus, a small difference in the amount of subsoil included in a soil core may impact the soil C measurements.

Similar to Mosier et al. (2006), two methods were used for calculating the total global warming potential for systems. The first method (Eq. [1]) estimated the net CO<sub>2</sub> flux portion of global warming potential by comparing measured CO<sub>2</sub> flux and biomass production. Measured CO<sub>2</sub> flux reflects soil and root respiration in all crops, thereby overestimating soil CO<sub>2</sub> flux. In addition, because the 26-cm-diameter chambers did not fit between wheat or alfalfa rows, CO<sub>2</sub> flux was overestimated even more by also including shoot respiration. Thus, this method is inherently biased and is not appropriate when soil CO<sub>2</sub> flux cannot be separated from shoot and root respiration. Furthermore, as previously discussed by Johnson et al. (2010), a long chamber deployment time (≥25 min), which was necessary for detecting N<sub>2</sub>O and CH<sub>4</sub> emission, was not ideal for measuring CO<sub>2</sub> flux. Ideally, Eq. [1] would include all photosynthetically fixed C. However, even including root biomass C underestimated total biomass C, as it was not possible to



collect all root biomass and because it neglects rhizodeposition. Roots including rhizodeposition may represent 60% or more of the total aboveground biomass (Allmaras et al., 2004; Johnson et al., 2006). The other method (Eq. [2]) of calculating global warming potential relied on measuring the change in soil organic C over time but excluded labile pools (e.g., standing biomass). Soil organic C is the primary way C is sequestered, although perennial roots can also contribute to long-term storage (ESA, 2000; West and Post, 2002). Alfalfa was only maintained for 2 yr in the rotation; therefore, its roots would decompose similar to annual rather than perennial species (Johnson et al., 2007a). Measuring the change in soil organic C is an accepted method for estimating CO<sub>2</sub> exchange (Robertson et al., 2000), even though it can be hampered by large spatial and temporal variability and requires long-term monitoring (Mosier et al., 2006). Furthermore, even long-term studies may not detect changes in soil C mass (West and Post, 2002; Gregorich et al., 2005). However, due to the artifacts and biases introduced by the CO<sub>2</sub> flux measurement, the change in soil organic C is the better method for estimating global warming potential.

The data suggested that all three cropping systems were a net source of CO<sub>2</sub> equivalents (Fig. 1b). Reducing tillage and adopting a 4-yr rotation did not result in differences in N<sub>2</sub>O or CH<sub>4</sub> flux. However, global warming potential per unit biomass harvest was reduced in the MAXC system, while it was increased in the OGGB system compared with the BAU system. The desired reduction global warming potential was not achieved and yield was decreased, making OGGB an undesirable alternative system. Continued implementation of the MAXC system, however, could result in sufficient soil C sequestration to offset greenhouse gas emission, especially if the alfalfa phase of the rotation were lengthened to allow time for additional secondary root growth and rhizodeposition. Additional research is needed, but the data suggest N<sub>2</sub>O emission may be reduced through N-fertilizer management. Long-term studies that monitor change in soil C and N<sub>2</sub>O emission are necessary to identify management systems that might reduce the global warming potential from agriculture and maintain soil productivity, thereby addressing dual societal challenges of climate change and providing food for an expanding population.

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