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Measurement of net global warming potential in three agroecosystems

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Abstract

When appraising the impact of food and fiber production systems on the composition of the Earth's atmosphere and the 'greenhouse' effect, the entire suite of biogenic greenhouse gases – carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) – needs to be considered. Storage of atmospheric CO_2 into stable organic carbon pools in the soil can sequester CO_2 while common crop production practices can produce CO_2, generate N_2O, and decrease the soil sink for atmospheric CH_4. The overall balance between the net exchange of these gases constitutes the net global warming potential (GWP) of a crop production system. Trace gas flux and soil organic carbon (SOC) storage data from long-term studies, a rainfed site in Michigan that contrasts conventional tillage (CT) and no-till (NT) cropping, a rainfed site in northeastern Colorado that compares cropping systems in NT, and an irrigated site in Colorado that compares tillage and crop rotations, are used to estimate net GWP from crop production systems. Nitrous oxide emissions comprised 40–44% of the GWP from both rain-fed sites and contributed 16–33% of GWP in the irrigated system. The energy used for irrigation was the dominant GWP source in the irrigated system. Whether a system is a sink or source of CO_2, i.e. net GWP, was controlled by the rate of SOC storage in all sites. SOC accumulation in the surface 7.5 cm of both rainfed continuous cropping systems was approximately 1100 kg CO_2 equivalents ha^{-1} y^{-1}. Carbon accrual rates were about three times higher in the irrigated system. The rainfed systems had been in NT for >10 years while the irrigated system had been converted to NT 3 years before the start of this study. It remains to be seen if the C accrual rates decline with time in the irrigated system or if N_2O emission rates decline or increase with time after conversion to NT.

Introduction

The purpose of mitigating greenhouse gas emissions is to minimize the increase of greenhouse gases in the atmosphere which contribute to increasing radiative forcing. Our goal is to mitigate radiative forcing, generally referred to as global warming potential (GWP), in agricultural systems by increasing soil organic carbon (SOC) storage, by decreasing CH_4 emissions or promoting soil CH_4 oxidation, and by decreasing N_2O emissions, while maintaining sustainable crop production. Food and fiber production is a main human-induced contributor to the emissions of CH_4 and N_2O to the atmosphere (IPCC 2001). When appraising the impact of agricultural production on the composition of earth's atmosphere, the entire suite of biogenic greenhouse gases, CO_2, CH_4 and N_2O, needs to be considered (e.g. Robertson and Grace 2004). Likewise, sources and sinks of all three gases should be considered when designing CO_2 stabilization portfolios (Caldeira et al. 2004).

Storage of atmospheric CO_2 into stable organic carbon pools in the soil can sequester CO_2, while commonly used crop production practices generate CO_2 and N_2O and decrease the soil sink for atmospheric CH_4. The overall balance between the net exchange of these gases constitutes the net GWP of a crop or livestock production system. Methane is produced mainly through enteric fermentation by livestock and through the handling of livestock and poultry manure in anaerobic lagoon systems. Typically agricultural soils are minor emitters of CH_4 and generally small sinks for atmospheric CH_4 (Bronson and Mosier 1993). Nitrous oxide, the principal non-CO_2 greenhouse gas emitted from soils, is produced naturally in the soil through nitrification and denitrification. Nitrogen fertilizer input to facilitate crop production augments this production. It is the relationship of soil C changes to N_2O emissions that typically regulate net GWP (Robertson et al. 2000).

Past and current increases in atmospheric N_2O are related to increased N-fixation in synthetic fertilizer and legume crops. Strategies which increase N fertilizer use efficiency will typically reduce emissions of N_2O, ammonia (NH_3) and nitric oxide (NO) (Kroeze et al. 1999). In general, gaseous N emissions can be decreased by management practices which optimize the crop's natural ability to compete with processes whereby plant-available N is lost from the soil–plant system. If fertilizer N is used more efficiently by the crop, then less N will be needed to meet the plant's demand, less N will be lost, less N_2O will be produced and CO_2 fixation is optimized for maximum production at low environmental cost.

The undesirable effects of N-fertilizer use on increased N_2O production can be mitigated by agronomically sound agricultural management without decreasing production. Carbon dioxide emissions from fossil fuel combustion contribute approximately 50% of total GWP globally, while CH_4 (16%) and N_2O (5%) contribute about 20% to GWP from all sources (IPCC 2001). Globally, anthropogenic sources of N_2O and CH_4 are dominated by agriculture and sum to 7.7 Pg CO_2-equivalents y^{-1} (Robertson 2004); this is close to the annual global atmospheric loading rate for CO_2 of 8.4 Pg CO_2 y^{-1} (IPCC 2001). In the US, CO_2 emitted from farming ($\sim$ 50 Tg), N_2O emitted in crop and livestock production ($\sim$ 300 Tg), CH_4 emitted from livestock production ($\sim$ 160 Tg), and increased soil C storage (~ -60 Tg), sum to approximately 450 Tg of CO_2 equivalents annually (USEPA 2002). Tillage and fertilizer N additions are known to have decreased soil consumption of atmospheric CH_4 by $>50\%$ compared to uncultivated soils (CAST 2004). Agricultural soils have the potential to greatly reduce this amount by changing management to increase soil organic matter content (Follett 2001) and decrease N_2O emissions (Kroeze et al. 1999). Changing from conventional tillage (CT) to no-till (NT) practices typically leads to increased SOC content in the surface 7 cm of soil with little change observed below that depth (West and Post 2002).

A goal of this paper is to address the issue of net GWP and to consider the potential tradeoffs and/or synergisms between tillage and cropping practices aimed at C sequestration and mitigation of N_2O and CH_4 emissions. To accomplish this goal, we present the results from three studies that were conducted in rainfed systems in Colorado and Michigan and in an irrigated system in Colorado.

Materials and methods

Site descriptions

Michigan

Beginning in 1991, a series of replicated field sites were sampled for fluxes of N_2O and CH_4, changes in soil carbon, and other sources of radiatively active gases in field crops. The sites were located in southwest Michigan in the northern part of the US corn belt at the W.K. Kellogg Biological Station (KBS), located at 42°24′ N, 85°24′ W. All sites are on a soil series similar to Kalamazoo loam (fine-loamy, mixed, semiactive, mesic Typic Hapludalf) derived from glacial till deposited about 14,500 y BP. Mean annual temperature is 9 °C and annual precipitation is approximately 900 mm distributed evenly through the year. Native vegetation is eastern deciduous forest with pockets of oak savannah likely maintained intentionally with fire since initial human settlement about 1300 y BP.

The sites sampled are part of the KBS Long-term Ecological Research (LTER) site and can be arranged along a management intensity gradient. They include four annual cropping systems, two perennial cropping systems, and four midsuccsessional (native vegetation) communities at different times since last disturbance. From these studies three systems are used. The annual cropping systems are corn–soybean–wheat rotations managed either (1) with CT and inputs as called for by local best management practices, (2) NT with conventional inputs, and (3) and continuous alfalfa (*Medicago sativa* L.). Sites are described in greater detail in Robertson et al. (2000) and at www.lter.kbs.msu.edu.

Sites were sampled in 1988 for various soil properties including SOC contents (Robertson et al. 1997) and again for organic C in 1999, providing a 10-year record of SOC change in the 0–7.5 cm soil horizon. Deeper C sampling to 1 m is currently underway, but is not expected to alter our conclusions as West and Post (2002) found that approximately 85% of the SOC sequestered in soil with a change from CT to NT occurs in the top 7 cm.

Gas fluxes were measured using a static chamber technique (Livingston and Hutchinson 1995) in which headspace samples are taken four times over a 90 min period from an 11 l box placed temporarily on a stainless steel collar removed only for agronomic operations. Samples are removed to the laboratory for analysis of N_2O and CH_4 by gas chromatography. Flux boxes are placed in four replicate plots of each treatment on the same mornings 2–4 times per month when soils were not frozen (usually March–December). Other GWP sources (fuel, fertilizer, lime) were calculated from agronomic records. None of the sites were irrigated.

Colorado dryland

In May 2002, a study to quantify net GWP within an established dryland agricultural management project was begun in northeastern Colorado, USA. This project, 'The Sustainable Dryland Agroecosystem Management Project' was established in 1985 in a field that had been used for dryland winter wheat (*Triticum aesitivum* L.) production using a conventionally tilled, wheat–fallow system for the previous 50 years. Cropping systems were established in the fall of 1985 with the planting of winter wheat. Cropping systems include all phases of each rotation each year with two replications of wheat–fallow (WF), wheat–corn (*Zea mays* L.) –fallow (WCF), wheat–corn–millet (*Panicum milaceum* L.)–fallow (WCMF), opportunity cropping (continuous cropping) (OC), and planted prairie grass mixture. At the end of 12 years, all cropping systems were back to their starting phase and a change in treatments was made. The WF system was replaced with a three phase system of wheat–corn–soybean/millet without any summer fallow. The WCMF cropping system was replaced by a four phase rotation with summer fallow of wheat–wheat–corn–soybean (*Glycine max* Merr.)/millet. It is located at an elevation of 1340 m and a longitude of 40°22′12″ N and a latitude of 103°7′48″ W, and the average annual precipitation is 420 mm (Peterson et al. 1993). The study site was positioned along a catenary sequence of soils that are common to the geographic area. The OC system was in a forage legume in 2000, wheat in 2001 and was cropped to corn in 2002. The 2002 corn in both OC and WCF was fertilized with 112 kg N ha^{-1} as a solution of urea and ammonium nitrate.

We selected WCF, OC, and perennial grass (Grass) for quantification of net GWP based on previous observation of the greatest differences in SOC storage. Sherrod et al. (2003) and Peterson et al. (1993) provide a complete site description. For trace gas measurements, we selected the midslope and toeslope position of the catenary sequence. Midslope and toeslope soils are loam soils classified as Fine-loamy, mixed, mesic Aridic Argiustoll and Fine-loamy, mixed mesic Pachic Argiustolls, respectively.

Fluxes of CO_2, CH_4 and N_2O were measured one or two times per week, year-round, midmorning of each sampling day. Ten centimeter high vented rectangular aluminum chambers were installed in a water channel on permanently fixed anchors (78.6 cm × 39.3 cm × 10 cm). Anchors were set perpendicular to the corn row so that the corn row and interrow were contained within each chamber. Anchors were oriented the same way in grass plots. Gas samples from inside the chambers were collected by syringe at 0, 15 and 30 min after installation (Mosier and Mack 1980; Hutchinson and Mosier 1981; Mosier et al. 1991). Four anchors were established within each replicate treatment and slope position so that eight total observation points within each of the six treatment by slope position combinations were used. Gas samples were injected into 12-ml evacuated tubes that were sealed with butyl rubber septa and transported to the laboratory in Fort Collins for analysis by a gas chromatograph that is equipped with thermoconductivity, flame ionization and electron capture detectors to quantify CO_2, CH_4 and N_2O, respectively (Mosier and Mack 1980; Mosier et al. 1991). Soil temperature and volumetric soil water content of each sampling site was recorded at each gas flux measurement period.

The annualized change in SOC content between 1986 and 1997 (Sherrod et al. 2003) was used as SOC input into the GWP calculation. In addition to annual N_2O emission, CH_4 consumption and SOC change, the CO_2 equivalents used for farm operations such as planting and herbicide production and application (Farm Operations) were estimated from information in West and Marland (2002). The energy used to produce (0.82 kg CO_2-C kg^{-1} N) and apply (45.5 kg CO_2 ha^{-1}) the N fertilizer were estimated according to Follett (2001) and West and Marland (2002).

Colorado irrigated

Greenhouse gas and soil carbon measurements were initiated in the spring of 2002, on selected plots of an irrigated cropping systems study established in 1999 near Fort Collins, CO (40°39′ N; 104°59′ W). The study is located at the Agricultural Research, Development, and Education Center operated by Colorado State University on a Fort Collins clay loam soil (fine montmorillonitic, mesic Aridic Argiustoll). A sprinkler irrigation system is used to apply water. Cropping systems in which trace gas fluxes and net GWP measurements were made include: NT-continuous corn (NT-CC); NT-corn–soybean (NT-CS); and CT-continuous corn (CT-CC). Continuous corn plots were fertilized at rates of 0, 134, and 202 kg N ha^{-1}. Gas flux measurements were made in the NT-CS treatments fertilized at rates of 0 and 202 kg N ha^{-1}. The N treatments are arranged in a completely randomized design with three replications. Total N and C uptake were measured and the amount of residue N and C returned to the soil was determined. Inputs required for each of the cropping systems were recorded to estimate fossil fuel consumption and costs. Herbicides were used for weed control in all systems. Urea–ammonium nitrate-N (UAN, 32%) was banded about 5 cm below the soil surface just prior to planting corn in the NT and CT systems. A subsurface band application of phosphorus (0-46-0) was applied at a rate of 56 kg P ha^{-1} prior to planting the 1999 crops in both tillage systems. Liquid starter fertilizer containing P_2O_5 and K_2O with a very low concentration of N was applied to the seed row at planting in 2000 and 2002.

Biomass samples were collected in mid to late September for determination of residue production. Grain yields were measured at physiological maturity in late October each year by collecting the ears from two 7.6 m long rows per plot. The corn grain yields are expressed at 15.5% water content. Soil samples (0–7.5 cm depth is used in this paper for Michigan and Colorado irrigated sites) were collected for SOC and NO_3-N analysis after grain harvest. Soil analyses revealed that SOC changes below 15 cm depth were not significantly different ($P > 0.05$) between CT and NT soils (unpublished data), but are significantly greater in NT soils ($P < 0.05$) at the 0–7.5 cm and 7.5–15 cm depths.

The measurement of trace gas (CH_4, CO_2, N_2O) fluxes began in late April 2002, and were made one to three times per week, year round, until mid-April 2003. The measurements employ the same anchor/chamber system used at the Colorado Dryland site. Anchors were removed for tillage and planting operations and reinstalled near the initial locations. Duplicate flux measurements are made within each replicate of each treatment for a total of six measurements per treatment. Soil water content and soil and air temperature are monitored continuously at selected sites and at each trace gas sampling event. Other details of the study are provided by Halvorson et al. (2004).

Results and discussion

Michigan

In the Michigan CT treatment the total GWP impact was 1140 kg CO_2 equivalents ha^{-1} averaged over three rotation cycles (Table 1). About half of the system's GWP was attributable to N_2O flux, with the remainder partitioned N-fertilizer production, lime use, and to a lesser extent, farm operations. Methane oxidation provided about 40 kg CO_2 equivalents ha^{-1} of mitigation.

Table 1. Net GWP in rain-fed cropping systems at Kellogg Biological Station, Hickory Corners, Michigan (Robertson et al. 2000) in units of kg CO_2 equivalents ha^{-1} y^{-1}.

Treatment	Irrigation	Farm operations	Lime	N fertilizer	N_2O	CH_4	SOC	Net GWP
CT	0a	160a	230a	270a	520a	−40a	0a	1140a
NT	0a	120b	340b	270a	560a	−50a	−1100b	140b
Alfalfa	0a	80c	880c	0b	590a	−60a	−1610c	−200c

CT = conventional tillage; NT = no-till.

Farm operations = fuel use for plowing and secondary tillage (mainly disking) for CT, and planting, herbicide application, liming, and harvesting for both CT and NT.

Lime = dissolution of agricultural lime (dolomitic limestone: $CaMg(CO_3)_2$) applied to counteract soil acidity; assumes complete conversion to CO_2; 1 MT dolomitic limestone = 474 kg CO_2.

N-fertilizer production = 45.5 kg CO_2 ha^{-1} for application + 3.0 kg CO_2 per kg N applied (Follett 2001).

N_2O = N_2O emission from linear integration of flux measurements, 1 kg N_2O ha^{-1} = 296 kg CO_2 ha^{-1}.

CH_4 = CH_4 emission from average of flux measurements, 1 kg CH_4 ha^{-1} = 23 kg CO_2 ha^{-1}.

SOC = annual loss of soil organic C content in 0–7.5 cm depth increment by difference in SOC between 1988 and 1999. Negative sign indicates increase in SOC.

Values within the same column followed by different letters are significantly different from one another at $P < 0.05$.

In the Michigan NT system, N_2O and CH_4 fluxes were equivalent to those in the conventionally managed rotation, as was GWP from fertilizer use. Farm operations required about 25% less fuel owing to less tractor traffic on the NT fields, resulting in an equivalent modest reduction in GWP as compared to the CT system. Soil carbon storage in the NT system, on the other hand, provided substantial reduction in GWP; about 1100 kg CO_2 equivalents ha^{-1} were mitigated in this system by soil organic matter gain, providing a net GWP for the system of 140 kg CO_2 equivalents ha^{-1}.

Alfalfa, with a net GWP of −200 kg CO_2 equivalents ha^{-1}, provided a net global warming mitigation potential. This was due to a combination of factors: although N_2O and CH_4 fluxes were similar to those in the conventionally managed rotation, GWP savings accrued from the lack of N-fertilizer, about 50% less fuel use, and somewhat higher SOC accretion than in the NT system probably owing to perennial root growth. Had lime not been applied, the net GWP would have even been much lower at −1000 kg CO_2 equivalents ha^{-1}.

Estimates of net GWP in the Michigan annual cropping systems are conservative relative to more intensively managed annual field crops. In a continuous corn or corn–soybean rotation net GWP would be higher because of more intensive fertilizer use and correspondingly higher N_2O fluxes. Wheat received about half as much N fertilizer as corn in these rotations, and because wheat is sown in the fall it is actively growing in early spring and therefore competes with soil microbes for available soil N, which is consequently lower in the spring of wheat years. The Michigan site is also managed for average yield goals rather than maximum, which means, for example, that during corn years N fertilizer is added at rates of 120 kg N ha^{-1} rather than at rates closer to 180 kg N ha^{-1}, which is not uncommon in the region. A more aggressive management regime with a simpler (non-wheat) rotation, then, might have up to twice the net GWP of that measured in this study.

These GWP estimates are also tempered by our assumptions about the fate of agricultural lime. Lime is added to soil to counteract acidity generated mainly by nitrifying bacteria and by excess cation removal in harvested biomass. Nitrifying bacteria are stimulated by inputs of N other than nitrate, including urea, UAN, anhydrous ammonia, manure, and other forms of N fertilizer as well as by N_2 fixation in soybean and alfalfa. Acidity is also generated by excess cation removal from ecosystems, which occurs faster when harvests include total aboveground biomass as in alfalfa. When lime (most commonly calcite [$CaCO_3$] or dolomite [$CaMg(CO_3)_2$]) comes in contact with a strong acid it generates CO_2 that is then released to the atmosphere. If, on the other hand, lime is dissolved by a weak acid it generates HCO_3^-, which remains in the soil solution and can be leached to groundwater storage; in fact this latter reaction involves additional moles of CO_2, leading to a potential for net mitigation (Hamilton and Robertson, unpublished). The calculations in Table 1 assume that lime is dissolved mainly by strong acids such as nitric acid generated by nitrate production; if, on the other hand, it is generated by reaction with weak acids then the GWP-cost of lime is overstated. The actual fate of lime in these systems is under investigation.

Colorado dryland

Between September 2001 and near the end of July 2002, only 70 mm of precipitation was measured at the site. As a result of the dry conditions, corn production in 2002 was minimal (Peterson et al. unpublished data). Nitrous oxide fluxes from the dryland cropping systems were small and did not differ by slope position or cropping system. Fluxes from the annually fertilized treatments were approximately two fold greater than from the unfertilized perennial grass (Figure 1). Nitrous oxide fluxes typically increase following rain events and above background fluxes were observed following rain events in late July and August 2002 (Mosier et al. unpublished data).

Average CH_4 uptake rates were higher in the cropped soils than in the soils planted to perennial grass but did not differ by slope position. Soil water content (0–15 cm) was generally higher in the corn treatments than in the grass because of the low productivity of the drought-stressed corn (data not shown). Estimates of net GWP are dominated by the CO_2 emissions from fertilizer production, N_2O emissions and SOC accumulation (Table 2). Since N_2O fluxes did not differ between cropping systems or slope position net GWP was lower in the continuously cropped soils because SOC accumulation was greater in soils that did not have fallow in their rotation. The CWF systems were net sources of GWP while the OC systems were net sinks.

Although we have only one year of trace gas flux data, and growing season precipitation was unusually low for much of the cropping season, the data suggest that crop management can dramatically affect net GWP. Incorporating fallow into the cropping sequence maintains lower SOC content than continuous cropping. The difference would be even greater if a conventionally tilled wheat-fallow system had been available for comparison (Del Grosso et al. 2002; Sherrod et al. 2003). SOC storage was directly related to above ground biomass production. Eliminating the fallow part of the cropping sequence led to increased SOC stabilization (Sherrod et al. 2003). Neither N_2O nor CH_4 fluxes differed by slope position or cropping system. The only difference observed was between grass where CH_4 uptake and N_2O efflux was lower than in either crop rotation. Lower gas flux rates in the grass treatments are probably due

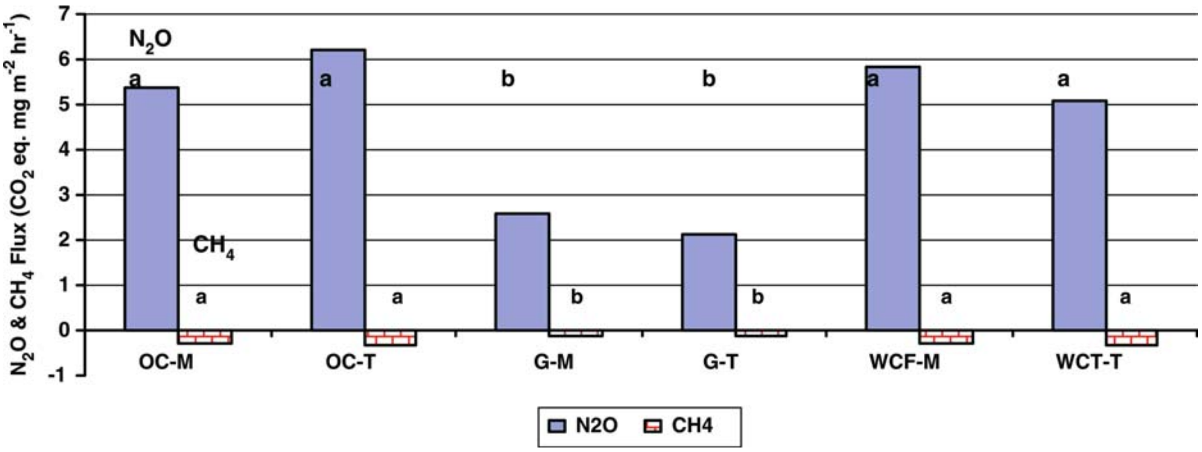

Figure 1. Methane consumption and N_2O emissions in perennial grass, NT continuously cropped, and wheat–corn–fallow rotations in a dryland agroecosystem in northeastern Colorado. OC = opportunity or continuous cropping, G = perennial grass, WCF = wheat–corn–fallow rotation, mid = midslope of field catena, toe = toe slope position of field catena. Flux measurements represent the mean of flux measurements made one to two times per week during the time from mid-May 2002 until mid-May 2003. Methane consumption rates having the same letter below the flux rate bar are not significantly different ($P \geq 0.1$). Nitrous oxide flux rates having the same letter above the rate bar are not significantly different ($P \geq 0.1$).

Table 2. Estimate of net GWP in a North eastern Colorado NT dryland cropping system (GWP units in kg CO_2 equivalents ha^{-1} y^{-1}) (Peterson et al. 1993; Sherrod et al. 2003).

Treatment	Annualized biomass (kg ha^{-1} y^{-1})	Farm operations	N fertilizer	N_2O	CH_4	SOC	Net GWP
		(kg CO_2 equivalents ha^{-1} y^{-1})					
WCF-M	2060	85	383	334*	25*	−476	311a
WCF-T	2705	85	383	334	25	−590	197a
OC-M	2880	85	383	334	25	−1100	−313b
OC-T	3790	85	383	334	25	−1467	−683c
Grass-M	803	0	0	165	11.4	−653	−480bc
Grass-T	1569	0	0	165	11.4	−968	−803dc

WCF = wheat-corn-fallow rotation; M = midslope field position; T = toeslope field position.

OC = opportunity or continuous cropping; Grass = perennial grass treatment.

The IPCC (2001) conversion of N_2O and CH_4 emissions to CO_2 equivalents on a 100 year time frame is 296 and 23, respectively.

Annualized biomass is the 1986–1997 biomass production calculated on a yearly basis (Sherrod et al. 2003).

Farm operations = planting, harvesting, herbicide applications (Sherrod et al. 2003).

N-fertilizer production = 45.5 kg CO_2 ha^{-1} for application + 3.0 kg CO_2 per kg N applied (Follett 2001).

Estimates are based on average observed flux calculated for the year, May 2002–May 2003.

Soil organic C (SOC) is based on average annual loss in soil organic C content for the 0–5 cm depth between 1986 and 1997 (negative sign indicates increase in SOC).

The net GWP values followed by the same letter are not significantly different at $P = 0.1$.

*N_2O and *CH_4 fluxes were not significantly different (analysis of variance) by crop rotation or by slope position so flux rates were averaged across treatment (Figure 1). Fluxes of N_2O and CH_4 from grass treatments were not significantly different at the different slope positions so are averaged (Figure 1).

N_2O = N_2O emission from linear integration of flux measurements from May 2002–May 2003, 1 kg N_2O ha^{-1} = 296 kg CO_2 ha^{-1} IPCC (2001).

CH_4 = CH_4 emission from average of flux measurements, 1 kg CH_4 ha^{-1} = 23 kg CO_2 ha^{-1}.

to the fact that soil water content (Mosier et al. unpublished data) was generally lower in the grass plots than in the corn. Very dry soils tend to produce less N_2O and oxidize less CH_4 soils than more moist soils (Mosier et al. 1996). Re-establishment of CH_4 oxidation and N_2O emission rates in the grass plots that are near those of a native grassland will likely require several decades. Studies within the shortgrass steppe indicate that it may take 50 years before grassland systems equilibrate following plowing (Mosier et al. 1997).

Colorado irrigated

The irrigated corn field soils were a net source of CH_4 during the year (Figure 2) and no treatment differences were observed. We suspect this is because of the large amount of irrigation water that was required to moisten the root zone. Since little precipitation occurred during the 2001–2002 winter and spring so the soil profile was very dry when the corn was planted in late-April 2002. As a result of the frequent irrigation needed to recharge the soil profile, surface soil remained near field capacity much of the time and low rates of CH_4 emission resulted. Nitrous oxide emissions increased with increased N fertilizer addition ($P < 0.05$ for CT and $P < 0.1$ for NT). N_2O emissions tended to be lower from the NT plots, but were not significantly different from those from CT plots ($P = 0.31$, for the 202 N rate). Nitrous oxide emissions from the soils that were planted with soybeans in 2001 were significantly higher than from either CT-CC or NT-CC soils fertilized with the same 0 and 202 kg N ha^{-1} fertilizer rates ($P < 0.05$).

Tillage and resulting lack of SOC storage in the CT plots (Halvorson et al. 2004) directly impacted net GWP (Table 3). CT-CC soils were net sources of GWP while NT-CC soils were net sinks for GWP, mainly due to the sequestration of C. The decreased SOC storage in the CS rotations that were fertilized at the 202 kg N ha^{-1} rate and relatively higher N_2O emissions created a net source for GWP. The energy required for pumping irrigation water was the largest single source of GWP with GWP for fertilizer production and N_2O emissions contributing greatly to the total (Table 3).

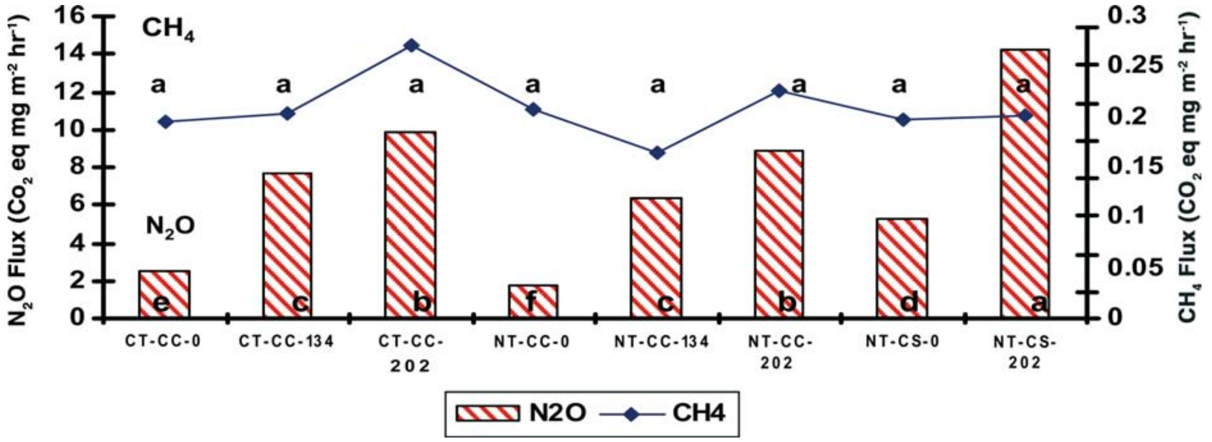

Figure 2. Methane and N_2O fluxes in CT-CC and NT-CC and in NT-CS rotation. N fertilization rates of 0, 134 and 202 kg N ha^{-1} were used. Flux measurements represent the mean flux rate for measurements made one to three times per week from late-April 2002 until late-April 2003. The (a) over each methane flux rate bar indicates that the CH_4 emission rate averages are not significantly different ($P \geq 0.1$). For N_2O emission rate averages, rate bars having the same letter above them are not significantly different ($P \geq 0.1$).

Table 3. April 2002–April 2003 Net GWP in Irrigated Corn near Fort Collins, CO: Effect of tillage, N rate and crop rotation in units of kg CO_2 equivalents ha^{-1} y^{-1}.

Treatment	Irrigation	Farm operations	N-fertilizer	N_2O	CH_4	SOC	Net GWP
CT-CC-0	1052	273	0	148	20	154	1647c
CT-CC-134	1052	273	448	419	21	154	2383b
CT-CC-202	1052	273	653	567	29	154	2763a
NT-CC-0	1052	114	0	114	30	−3076	−1766f
NT-CC-134	1052	114	448	311	24	−3076	−1125de
NT-CC-202	1052	114	653	408	32	−3076	−815de
NT-CS-0	1052	114	0	279	26	−2413	−942de
NT-CS-202	1052	114	653	730	28	−2413	−164d

CT = conventional tillage; NT = no-till; CC = continuous corn; CS = corn–soybean rotation; 0, 134, 202 = fertilizer rate kg N ha^{-1}.

Irrigation = West and Marland (2002) estimate of 598 kg C ha-m^{-1} H_2O applied (applied 0.48 m H_2O).

Farm operations = plowing, disking, harrowing, leveling, etc. for CT and planting, herbicide application, harvesting and herbicide application only for NT.

N-fertilizer production = 45.5 kg CO_2 ha^{-1} for application + 3.0 kg CO_2 kg^{-1} N applied (Follett 2001).

N_2O = N_2O emission from linear intergration of flux measurements from April 2002–April 2003, 1 kg N_2O ha^{-1} = 296 kg CO_2 ha^{-1} (IPCC 2001).

CH_4 = CH_4 emission from average of flux measurements, 1 kg CH_4 ha^{-1} = 23 kg CO_2 ha^{-1}.

SOC = annual loss in soil organic C content in 0–7.6 cm depth estimate by linear regression of all plots between 1999 and 2002 (negative sign indicates increase in SOC).

GWP numbers followed by the same letter are not significantly different ($P > 0.1$). Analysis of variance, LSD value = 330.

Impact of tillage on N_2O, CH_4 and SOC in cropped soils

No-till management has been promoted as a practice that off-sets the GWP from emissions of N_2O and CH_4 in crop production because of its ability to sequester carbon in the soil (Cole et al. 1997). In a recent analysis of available field data, Six et al. (2004) found that newly converted NT systems increased GWP relative to CT practices in both humid and dry climates. Only in humid climates did longer maintainance of NT, >10 years, significantly reduce GWP. Mean, cumulative GWP over a 20-year period was also reduced under continuous NT in dry areas. Emissions of N_2O drive much of the trend in net GWP. The number of data sets that are available for such analyses is limited, and the high uncertainty associated with the N_2O flux data, dictate a high uncertainty to the GWP data. The decrease in N_2O flux with time that a system has been in NT in the Six et al. (2004) analysis is attributed to increased soil aggregation and improved aeration status. During the first few years of NT, soil bulk density in the top 30-cm may increase, but as SOC accumulates over time, soil structure improves as more stable aggregates develop, and soil aeration improves concomitantly (Six et al. 2004). The resulting effect is a decrease in net GWP over time in dry and humid climate soils.

A very different picture of the effect of time under NT on GWP is given in a modelling study (Del Grosso et al. 2002). Using the DAYCENT ecosystem model, they observed that during the first few years of NT, the soil may have decreased net GWP and over time, as the rate of increase in SOC declines and N_2O emissions increase, the net GWP increases. Simulating US Great Plains cropping systems, baseline soil conditions were developed using 100 years of historical land use, followed by 50 years of improved management, i.e. conversion to NT. The 50 years was divided into 12-year segments and the change in SOC after each 12 years was assumed to represent net C exchange between the atmosphere and the soil–plant system over that 12 years. The estimated soil–atmosphere exchange of N_2O and CH_4 over each 12 year period were converted to CO_2 equivalents. Production of each gram of N fertilizer was assumed to require 2.9 g of CO_2. Net greenhouse gas was calculated by summing the change in SOC and the CO_2 equivalents of N_2O, CH_4 and N fertilizer production.

This simulation suggests that the impact of NT on net GWP decreases over time in a dry agroecosystem. During the first 12-year period, the change in SOC is greatest and N_2O emissions are lowest (Del Grosso et al. 2002). Over time, the rate of C-sequestration declines and N_2O emissions increase because the rate of immobilization of inorganic N declines. The model predicts that the small soil CH_4 sink declines under NT because of higher soil water content. Changes in CH_4 consumption are small, however, and have little impact on net GWP estimates as demonstrated by the Robertson et al. (2000) field study. The DAYCENT model does not account for changes in soil structure following conversion to NT but does allow uniform conditions for all comparisons. The data used in the Six et al. (2004) evaluation are, in contrast, from a variety of studies that were likely conducted using a variety of methodologies. As a result, the relative importance of improved soil structure on decreasing N_2O emission suggested by the array of field studies and the DAYCENT model projection of increased N_2O emissions over time cannot be fully evaluated at this time.

Nitrous oxide fluxes were higher in NT than in CT in the studies in England and Canada, discussed in Six et al. (2004), but were not different in the Nebraska and Michigan studies. Soil moisture was likely continually higher at the sites where N_2O emissions were higher in NT, but these sites had been converted to NT less than 10 years before the studies were conducted. Tillage had little effect on soil CH_4 consumption or N_2O emissions in the semiarid wheat-fallow system in Nebraska or the crop rotation studies in more humid Michigan. These sites had been converted to NT 20 and 10 years, respectively, before the gas flux measurements were made.

Conclusions

In our studies N_2O emissions comprised 40–44% of the CO_2 equivalent emissions from both rain-fed sites. Nitrous oxide emissions contributed 16–33% of GWP in the irrigated system. The energy used for irrigation was the dominant GWP source in the irrigated system. The sign of net GWP was controlled by the rate of soil SOC storage in all sites. SOC accumulation in the surface 7.5 cm of both rainfed continuous cropping systems was approximately 1100 kg CO_2 equivalents ha^{-1} yr^{-1}. Carbon accrual rates were about three times higher in the irrigated systems. The rainfed systems had been in NT for >10 years while the irrigated system had been converted to NT 3 years before the start of this study. It remains to be seen if the SOC accrual rates decline with time in the irrigated system or if several years of trace gas flux measurements reveal different trends than suggested by the first year of the two Colorado studies.

Soil organic C storage, energy use in fertilizer production, and field N_2O emissions are the main contributors to net GWP in the rain-fed cropping systems. The energy required for irrigation is a major part of GWP in the irrigated systems. In all sites, differences in SOC storage dictated whether the system was a net source or sink for CO_2 equivalents.

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