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Short Communication

The contribution of maize cropping in the Midwest USA to global warming: A regional estimate

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ABSTRACT

Agricultural soils emit about 50% of the global flux of N_2O attributable to human influence, mostly in response to nitrogen fertilizer use. Recent evidence that the relationship between N_2O fluxes and N-fertilizer additions to cereal maize are non-linear provides an opportunity to estimate regional N_2O fluxes based on estimates of N application rates rather than as a simple percentage of N inputs as used by the Intergovernmental Panel on Climate Change (IPCC). We combined a simple empirical model of N_2O production with the SOCRATES soil carbon dynamics model to estimate N_2O and other sources of Global Warming Potential (GWP) from cereal maize across 19,000 cropland polygons in the North Central Region (NCR) of the US over the period 1964–2005. Results indicate that the loading of greenhouse gases to the atmosphere from cereal maize production in the NCR was 1.7 Gt CO_2e, with an average 268 t CO_2e produced per tonne of grain. From 1970 until 2005, GHG emissions per unit product declined on average by 2.8 t CO_2e ha^{-1} annum^{-1}, coinciding with a stabilisation in N application rate and consistent increases in grain yield from the mid-1970's. Nitrous oxide production from N fertilizer inputs represented 59% of these emissions, soil C decline (0–30 cm) represented 11% of total emissions, with the remaining 30% (517 Mt) from the combustion of fuel associated with farm operations. Of the 126 Mt of N fertilizer applied to cereal maize from 1964 to 2005, we estimate that 2.2 Mt N was emitted as N_2O when using a non-linear response model, equivalent to 1.75% of the applied N.

1. Introduction

The North Central Region (NCR) of the USA encompasses 12 Midwestern states (North Dakota, South Dakota, Nebraska, Kansas, Minnesota, Iowa, Missouri, Wisconsin, Illinois, Michigan, Indiana and Ohio), is the major producer of maize and soybean, and produces half of the nation's wheat. The major Land Resource Region in the NCR is Central Feed Grains and Livestock, more commonly known as the Corn Belt, which extends across all of these states. Donigan et al. (1994) have estimated that the Corn Belt has lost half of its soil organic carbon (SOC) stores since cultivation began in the mid-nineteenth century. Crop residues are essential for sustainable cereal maize productivity for both bioenergy and food production in this region (Wilhelm et al., 2007; Robertson et al., 2008). Our study informs the bioenergy vs. food security debate in that it directly examines the historical impact of cereal maize production in the NCR over the past 40 years on greenhouse gas emissions, including the maintenance of SOC for continued productivity.

Average maize yields in the NCR increased nearly threefold (from 3.6 to 9 t ha^{-1}) from 1964 to 2005, with a 25% increase in the harvested area (Fig. 1) since the introduction of post-Green Revolution maize varieties in the mid-1960's (United States Department Agriculture (USDA) – National Agricultural Statistics Service (NASS), http://nass.usda.gov). Recommended N application rates in the NCR for maximum yields exceed 250 kg N ha^{-1} in some states (Vitosh et al., 1995).

Cost-effective and large scale greenhouse gas (GHG) mitigation interventions in agriculture can be identified only if all emissions are evaluated. Whilst the sequestration of atmospheric CO_2 into stable SOC pools has been demonstrated through reduced tillage

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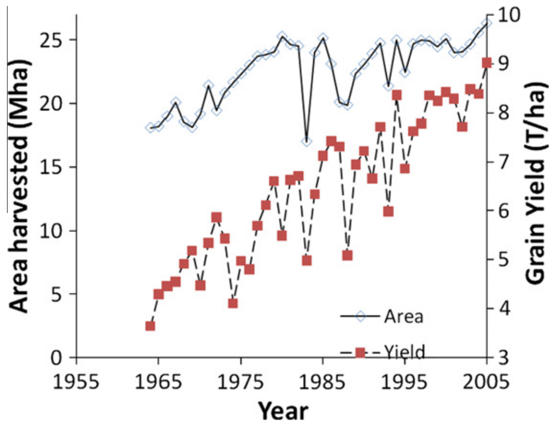

Fig. 1. Grain yield and harvested area of cereal maize in the North Central Region from 1964 to 2005 (USDA/NASS).

and improved grazing management (Lal, 2004), agricultural systems in the NCR remain net sources of CO_2 and N_2O and consume a reduced amount of atmospheric CH_4 relative to unmanaged ecosystems (Robertson et al., 2000).

The total global flux of N_2O attributable to human activity is approximately 1.2 Pg C-equivalents annually (Prinn, 2004; Robertson, 2004). The current loading of CO_2 to the atmosphere is 4.1 Pg C y^{-1} (Canadell et al., 2007), therefore in comparison, N_2O represents a major area for both concern and mitigation (IPCC, 2007a). About 85% of the global flux of N_2O from human sources is from agriculture (IPCC, 2007b), with about 50% of the global flux from denitrification and nitrification in agricultural soils.

The overall balance of CO_2, N_2O, and CH_4 constitutes the net Global Warming Potential (GWP) impact of the agricultural production system (Robertson and Grace, 2004). Primary influences on SOC dynamics and losses of N_2O from soils are climate (temperature and precipitation), soil type, and the quantity and quality of organic material and nitrogen returned to the soil. In concert, climate and soil type have a major impact on N_2O loss, with clay soils more conducive to water logging and denitrification (Bouwman et al., 2002).

Regional assessments of SOC change and N_2O loss require the synergy of biology, modeling, and geographic data management. A Modeling Applications Integrative Framework (MASIF) (Gage et al., 2001) has been specifically developed to assemble and process the large amounts of spatiotemporal climate, land use, yield, and soil data necessary for regional scale simulation experiments. Here we use MASIF to couple the SOCRATES terrestrial carbon dynamics model (Grace et al., 2006b) with an empirical N_2O calculator to estimate the net GWP impact of maize production in the North Central Region (NCR) since the advent of the Green Revolution in the mid-1960's (Duvich and Cassman, 1999).

2. Materials and methods

2.1. Soil organic carbon simulation

We used the USDA/Natural Resources Conservation Service (NCRS) STATSGO soils database (USDA, 1994) to develop a base map of textural properties across the NCR. Each of the STATSGO mapping units was assigned a dominant pre-settlement vegetation type (forest or grassland) based on the potential natural vegetation dataset of Kuchler (1964). The National Land Cover Data (NLCD) (Vogelmann et al., 2001) was then overlaid, producing nearly 19,000 separate cropland polygons across the 1056 counties of the NCR.

Surface soil bulk density (BD) and cation exchange (CEC) values were assigned to each cropland polygon based on their relationships with soil clay content (Grace et al., 2006a). Annual precipitation (mm) and mean temperature (°C) was assigned to each map unit by overlaying an interpolated 4 km climate surface created by the PRISM climate mapping system (http://www.ocs.orst.edu/prism/). Litter inputs for each land use type were estimated using the net primary production (NPP) algorithm from the Miami model (Leith, 1975). The partitioning of NPP into the carbon input from leaf, branch, stem and roots components is described in Grace et al. (2006b).

Pre-cultivation (1850), 1964, and post-1964 soil organic carbon (SOC) concentrations (0–10 cm) were generated by SOCRATES for each soil polygon using a similar procedure to that outlined in Grace et al. (2006b) to simulate SOC changes in all croplands of the NCR assuming conventional tillage practices. In determining the initial pre-cultivation SOC content, each polygon was assigned a nominal topsoil (0–10 cm) organic carbon value of 0.5% prior to running the SOCRATES model for a minimum of 2000 years to generate steady-state SOC values based on the dominant pre-cultivation vegetation. In these simulations, 3% of the initial SOC was considered to be protected microbial biomass and the remaining SOC considered tobe in the relatively stable humus pool, with the decomposable and resistant plant material pools initialized at 0 and 1 t C ha^{-1} respectively. Based on Buyanovsky and Wagner (1998), a minimal crop residue return of only 12% of NPP was used to simulate C inputs from 1850 to 1949, with full residue return thereafter.

The change in SOC under cereal maize production for the period 1964–2005 in the NCR was estimated using the actual grain yield (to account for changes in cultivars) and the annual area of maize harvested for each county for each individual year as reported by the USDA/NASS. A harvest index of 50% of aboveground biomass was used to determine residue production (Bennet et al., 1989), with all of the non-harvested biomass returned to the soil as a result of conventional tillage.

Using FAO/UNESCO data summarized in Kern (1994), we developed an SOC distribution profile for extrapolating the 0–10 cm estimate to any depth in the profile, in this case 0–30 cm. Excluding organic soils (Histosols), the FAO data maintains that the 0–10 cm layer represents, on average, 43% of the SOC in the top 30 cm.

2.2. Nitrous oxide estimation

A simple empirical model of N_2O production was linked to SOCRATES for estimating annual emissions from the NCR croplands through both nitrification and denitrification pathways as a function of the annual input of N fertiliser applied to the crop on an area basis. Whilst the current default protocols developed by the Intergovernmental Panel for Climate Change (IPCC) estimate direct N_2O emissions as a simple proportion (1%) of N inputs, there is increasing evidence that once N demands are met for plant growth, gaseous N loss may significantly increase (Robertson et al., 2000; Mosier et al., 2002; Grant et al., 2006; Zebarth et al., 2008; Kim and Hernandez-Ramirez, 2010). Increased N loss (in general) with higher yields has been reported by Kanampiu et al. (1997) and increased N_2O emissions specifically have been measured by Sehy et al. (2003), McSwiney and Robertson (2005), Ma et al. (2009) and Hoben et al. (2010). In all cases a non-linear curve best describes the N_2O flux response to increasing amounts of N, with small increases in applied N resulting in proportionately higher N_2O fluxes at higher N application rates.

Detailed experimental data linking annual climate variability, crop yield, a range in N application rates and soil types, and N_2O emissions is extremely limited in the Midwest. Over 2 years, Hoben et al. (2010) measured N_2O flux along a six point N fertilizer gradient (0–225 kg N ha^{-1}) in continuous maize at four sites in

Michigan to test the hypothesis that N_2O fluxes respond to N inputs in a non-linear manner. The N rates employed in Hoben et al. (2010) were within the range commonly required for optimum corn grain production and recommended for the US Midwest (Sawyer et al., 2006; Vitosh et al., 1995). The sites were specifically chosen to ensure a wide range of soil types, textures, and grain yields generally found across the NCR. Average N_2O fluxes were relatively low (8 g N_2O–N ha^{-1} d^{-1}) at 90 kg N ha^{-1}, with N_2O fluxes more than trebling at 225 kg N ha^{-1}. Emission factors reported in Hoben et al. (2010) ranged from 0.6% to 1.5% of applied N and are considered to be representative of agricultural soils within the US Midwest planted to corn.

The average daily flux of N_2O in response to N application across all eight site-years (including the non-growing season and background fluxes), was best described using a simple exponential function:

$$\text{Average daily } N_2O \text{ flux } (\text{g } N_2O\text{—N ha}^{-1}) = 4.55 * \exp(0.0064 * \text{annual N fertiliser application } (\text{kg N ha}^{-1}))$$

Annual maize production and N fertilizer application statistics for all 1056 counties within the NCR from 1964 to 2005 were obtained from the USDA/NASS. Annual fertilizer induced N_2O emissions from cereal maize production in each county were estimated as the product of total harvested area of grain in any year, total N applied, total number of days in respective years (365 or 366), and the average daily N_2O flux as detailed in Hoben et al. (2010) after correcting for background emissions. A comparison of N_2O flux using the IPCC Tier 1 default emission factor of 1% of applied N fertilizer (IPCC, 2007b) was determined using N fertilizer statistics reported by the USDA/Economic Research Service (ERS) (http://www.ers.usda.gov/Data/FertilizerUse/).

2.3. Other emissions

Carbon emissions from agricultural machinery and inputs (149 kg C ha^{-1} yr^{-1}) (West and Marland, 2002), were taken into account in developing net GWP estimates for the period 1964–2005. A GWP of 296 was used to convert N_2O emissions from N fertilization to CO_2 equivalents (IPCC, 2007a).

3. Results and discussion

We estimate the loss of SOC from the top 30 cm of cropping soils in the NCR under cereal maize from 1964 to 2005 to be nearly 52 Mt (Table 1), approximately 1.2 Mt C $annum^{-1}$ with the largest losses occurring in the states of Iowa, Indiana and Illinois, which represented half of the cereal maize harvested in the Midwest during this time. To put this in perspective, carbon loss associated with the combustion of fuel in farming operations and ancillary inputs associated with cereal maize (154.5 Mt C) is three times the magnitude of the SOC loss. County specific SOC changes (0–30 cm) ranged from a loss of 183 kg C ha^{-1} $annum^{-1}$ to an overall sequestration of 101 kg C ha^{-1} $annum^{-1}$ with an overall average loss of 73 kg C ha^{-1} $annum^{-1}$ for the NCR. The only comparative study for the Midwest (Buyanovsky and Wagner, 1998), estimated an overall sequestration rate of 520 kg C ha^{-1} $annum^{-1}$ for cereal maize, but their estimate is based on only one long-term site where grain yields (and subsequent soil C inputs) were nearly double those actually reported by the NASS across the Midwest during the period 1961–1990. Our estimate of a relatively small rate of decline in SOC across the NCR is also well within the limits of either analytical (±20%) or model based uncertainty (±30%) and when aggregated across the region would be virtually undetectable over four decades. We have also used a proven simulation model (SOCRATES) which takes into account county specific differences in soil type, climate and yield on an annual basis.

Whilst the practice of conservation tillage has been promoted throughout the NCR since the early 1980's, it is only permanent no-tillage that has provided substantial evidence of increased SOC storage compared to conventional tillage (Conant et al., 2007; Dick et al., 1997; Paustian et al., 1997; Pierce et al., 1994; Reicosky, 1997). Ogle et al. (2003) report data from the Conservation Technology Information Center (CTIC) with the complete absence of long-term no-tillage practices in the greater Midwest in 1982, increasing to just 3% in 1997. Due to the low incidence of no-till cropping in the majority of years of our study, and the difficulties in accurately quantifying the impact of no-till cropping across a wide variety of soil types we have not included changes in tillage practices in our study. We do recognize the benefits of no-till on SOC storage and acknowledge our quantification of SOC loss is more so at the high end of estimates.

Of the 126 Mt of N fertilizer applied from 1964 to 2005, 2.2 Mt N was estimated to have been emitted as N_2O when using a non-linear N loss response model, equivalent to 1.75% of the applied N. The IPCC Tier 1 model estimated N_2O emissions from N applications to cereal maize across the NCR from 1964 to 2005 to be 1.3 Mt N_2O–N (Table 2). Our regional estimate of N_2O emitted from cereal maize cropping using a non-linear model is 75% greater than that predicted by the IPCC Tier 1 linear approach.

In terms of GWP, the total regional emission from cereal maize production from 1964 to 2005 is 1.7 Gt CO_2e, which is equivalent

Table 1
Estimated greenhouse gas emissions (Mt) from cereal maize production in the North Central Region of the USA from 1964 to 2005 using the SOCRATES soil C model and a non-linear N_2O loss function.

State	Soil	Fertilizer	Fuel	Soil	Fertilizer	Fuel	Total
	C loss (0–30 cm) (Mt)	N_2O–N (Mt)	C (Mt)	CO_2 (0–30 cm) (Mt)	CO_2e[a] (Mt)	CO_2 (Mt)	GWP CO_2e (Mt)
Illinois	10.3	0.53	26.7	37.8	239.6	97.9	375.3
Indiana	7.6	0.25	13.9	27.8	117.3	51.0	196.1
Iowa	8.4	0.43	29.8	30.8	201.4	109.1	341.3
Kansas	0.2	0.08	4.4	0.7	37.5	16.0	54.2
Michigan	3.7	0.07	5.3	13.5	31.8	19.4	64.7
Minnesota	4.1	0.17	14.7	14.9	79.8	53.8	148.5
Missouri	4.0	0.10	6.3	14.8	48.1	22.9	85.8
Nebraska	0.5	0.30	16.8	1.8	138.2	61.5	201.5
North Dakota	1.7	0.02	1.2	6.1	7.7	4.4	18.2
Ohio	5.0	0.16	8.4	18.5	72.2	30.9	121.6
South Dakota	3.6	0.04	7.1	13.2	19.9	26.1	59.2
Wisconsin	2.6	0.06	6.7	9.6	28.5	24.4	62.5
Total NCR	51.7	2.2	141.1	189.5	1021.7	517.4	1728.9

[a] GWP of 296 used to convert N_2O to CO_2 equivalents.

Table 2
Estimated N_2O–N emissions (Mt) from maize production in the North Central Region of the USA from 1964 to 2005 calculated using both a non-linear N_2O loss function and the default IPCC methodology.

	IL	IA	IN	KS	MI	MN	MO	ND	NE	OH	SD	WI	NCR
Non-linear	0.53	0.43	0.25	0.08	0.07	0.17	0.10	0.30	0.02	0.16	0.04	0.06	2.2
IPCC[a]	0.28	0.26	0.14	0.04	0.04	0.11	0.06	0.17	0.01	0.08	0.03	0.04	1.3

[a] Emission factor of 1% of applied N.

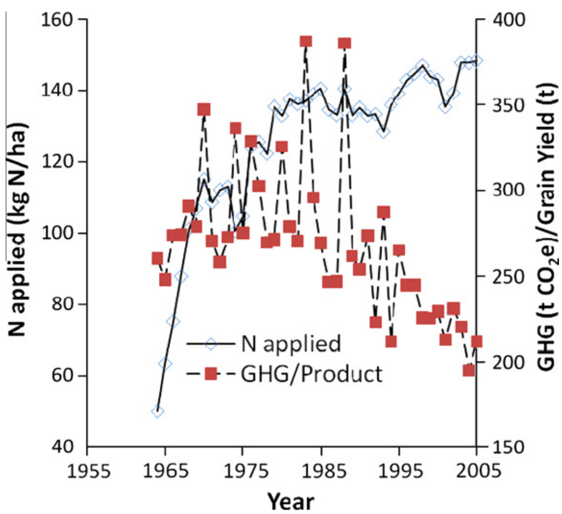

Fig. 2. Greenhouse gas emissions (t CO_2e) per unit product (t grain yield) and annual N application rates for cereal maize in the North Central Region from 1964 to 2005.

to four times the annual emissions from the US agricultural sector in 2008 (US EPA, 2010). Based on the non-linear model of N_2O loss, this GHG represents 59% of the total emissions from cereal maize cropping in the NCR since the introduction of Green Revolution varieties in the mid-1960's, and even with the more conservative IPCC Tier 1 approach, N_2O emissions represent 35% of total GWP from cereal maize cropping.

The average GHG emissions (CO_2e) per unit of product (grain yield) from 1964 to 2005 were estimated to be 268 t CO_2e t grain^{-1} (Fig. 2). The highest GHG emissions per annum (386 t CO_2e t grain^{-1}) occurring in both 1983 and 1988 when both the average grain yields and the total harvested area for cereal maize in the NCR were relatively low. From 1970 until 2005, GHG emissions per unit product declined on average by 2.8 t CO_2e ha^{-1} annum^{-1}, coinciding with a stabilisation in N application rate and consistent increases in grain yield from the mid-1970's.

Whilst we recognize that the N gradient dataset to develop the simple N_2O flux model is geographically limited, it does include temporal variability in soils, yield and N_2O emissions in response to climate and N management for a highly representative maize growing region of the NCR. The non-linear response is also entirely consistent with yield data from N rate trials from across the NCR (Sawyer et al., 2006) with a yield plateau in response to N fertilizer indicating reduced nitrogen use efficiency at higher rates of N. Whilst the dataset of Hoben et al. (2010) provides the only sufficiently detailed information of its kind for this region, its application clearly demonstrates the significant impact the non-linear response function has on regional estimates when compared with the very general IPCC Tier 1 approach. It also offers an evidence based, less complex, and integrated solution to estimating N_2O emissions compared to more detailed Tier 3 approaches based on process modeling (e.g. Del Grosso et al., 2006).

4. Conclusions

Total emissions of greenhouse gases from cereal maize production in the North Central Region from 1964 to 2005 were 1.7 Gt CO_2e, with N_2O production from nitrogen inputs representing 35–59% of these emissions, when using Tiers 1 and 2 approaches respectively. Using a non-linear (Tier 2) model linking N_2O loss and the rate of N application, an estimated 2.2 Mt N of the 126 Mt of N fertilizer applied to cereal maize in the NCR from 1964 to 2005 was emitted as N_2O–N, equivalent to 1.75% of the applied N.

We agree with Adviento-Borbe et al. (2007), that greenhouse gas emissions from agricultural systems can be kept low when planting, population, variety, tillage and fertilizer management is optimized. Nitrous oxide emissions have been clearly identified as a significant, if not, the main contributor to the overall GWP of cereal maize production in the NCR and increasing nitrogen use efficiency must be viewed as a major mitigation strategy in this region.

Millar et al. (2010) have proposed an N_2O mitigation protocol based on fertilizer N reduction. The rationale for their Tier 2 protocol is in part based on the non-linear relationship between N application rate and N_2O emissions. They couple predicted N_2O flux with the recently developed maximum return to N (MRTN) approach (Sawyer et al., 2006) for determining economically profitable N input rates for optimized crop yield as the basis for incentivizing N_2O reductions without affecting yield. Based upon the N rate reduction approach, these avoided emissions occur immediately, are irreversible and are thus permanent. This differs from other agricultural management practices such as the long-term adoption of no-till to sequester C in soil, where a reversal of practice back to conventional tillage may release sequestered C.

We hope our study has provided the impetus for the acquisition of N gradient datasets exploring the relationship between N application rate, N_2O emissions and yield from a broader range of soils and climates across the Midwest to refine these first estimates. This will enhance the development of robust empirical approaches and ensure growers can be provided with useful, easily assimilated extension material for reducing their own greenhouse gas footprint whilst maintaining productivity and profitability.

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