Nitrogen fertilizer rate management as a nitrous oxide mitigation strategy: Development of a nitrous oxide emission reduction protocol (NERP)

Neville Millar[A], G. Philip Robertson[A,B], Peter R. Grace[A,C], Ron J. Gehl[D], and John P. Hoben[B]

[A]W. K. Kellogg Biological Station, Michigan State University, Hickory Corners, MI, USA, Email millarn@msu.edu
[B]Department of Crop and Soil Sciences, Michigan State University, East Lansing, MI, USA, Email robertson@kbs.msu.edu
[C]School of Natural Resource Sciences, QUT, Brisbane, QLD, Australia, Email pr.grace@qut.edu.au
[D]Department of Soil Science, North Carolina State University, Mills River, NC, USA, Email Ron_Gehl@ncsu.edu

Abstract
Nitrous oxide (N_2O) is a potent agricultural greenhouse gas (GHG). More than 50% of the global anthropogenic N_2O flux is attributable to emissions from soil, primarily due to large fertilizer nitrogen (N) applications to corn and other non-leguminous crops. Quantification of the trade–offs between N_2O emissions, fertilizer N rate, and crop yield is an essential requirement for informing management strategies aiming to reduce the agricultural sector GHG burden, without compromising productivity and producer livelihood. There is currently great interest in developing and implementing agricultural GHG reduction offset projects for inclusion within carbon offset markets. Nitrous oxide, with a global warming potential (GWP) of 298, is a major target for these endeavours due to the high payback associated with its emission prevention. In this paper we use robust quantitative relationships between fertilizer N rate and N_2O emissions, along with a recently developed approach for determining economically profitable N rates for optimized crop yield, to propose a simple, transparent, and robust N_2O emission reduction protocol (NERP) for generating agricultural GHG emission reduction credits. This NERP has the advantage of providing an economic and environmental incentive for producers and other stakeholders, necessary requirements in the implementation of agricultural offset projects.

Key Words
Agriculture, cap and trade, N_2O mitigation.

Introduction
The rate at which reactive N enters into the biosphere each year has increased dramatically through the intensification of anthropogenic pathways. Global synthetic fertilizer N consumption has increased from ~10 Tg N in the late 1950s to ~100 Tg N in 2008 (Robertson and Vitousek 2009). The need to feed and provide energy for a growing population drives this increase in demand for fixed N, but also results in increased emissions of N_2O. Human induced emissions of N_2O are increasing by ~150 Tg N/y, with the current global atmospheric concentration of N_2O ~322 ppbv, compared with a pre–industrial concentration of ~270 (Forster *et al*. 2007). Annual agricultural emissions of N_2O are estimated at ~2.8 Gt CO_2 equivalents (CO_2e) (Smith *et al*. 2007), the vast majority attributable to field crop management activities (EPA 2009). As N_2O in agricultural soil is produced predominantly through microbial transformations of inorganic N, the potential to produce and emit N_2O increases with increasing N availability. With the strong influence of available N on N_2O emissions, some emissions of N_2O are an unavoidable consequence of maintaining highly productive cropland. However, management technologies that lower N input or reduce N availability without compromising crop productivity have great potential for reducing emissions of N_2O (e.g., Follett *et al*. 2005).

Manipulating N input, is a readily accessible management tool for altering crop N availability, with fertilizer N rate a crucial parameter for estimating both crop yield and N_2O emissions. Quantification of the trade–offs between N_2O emissions, crop yield and fertilizer N rate is essential for proposing strategies which optimize productivity at economically and environmentally favorable N inputs. Increasing fertilizer N rate typically increases N_2O emissions. As a result of extensive reviews and meta–analyses (e.g., Bouwman *et al*. 2002), anthropogenic N addition is used in IPCC Tier 1 methodologies as the primary controlling factor for estimating country–wide emissions of N_2O from managed land (IPCC 2006).

Our paper focuses on using fertilizer N rate as a quantitative proxy to calculate reductions in N_2O emissions from cropland. This narrowed focus is important in establishing protocol transparency for all stakeholders and is cognizant of the practical undertakings necessary to allow for ease of use in the validation, monitoring, and verification process required for a NERP. The benefits of utilizing a simple, scientifically robust N management practice as a N_2O mitigation surrogate will far outweigh the cost of adoption if the practice gains producer confidence and is initiated with minimal associated financial or social expense.

IPCC Tier 1 methodology relies on a linear relationship between fertilizer N rate and N_2O emissions, i.e., the N_2O emission factor (EF) is constant (1.0%) irrespective of fertilizer N rate. This linear approach however, may be too conservative. Evidence from high resolution N fertilizer gradient studies in the US Midwest (McSwiney and Robertson 2005; Hoben *et al*. 2010; Millar *et al*. 2010a) suggest that N_2O emissions can increase exponentially with increasing fertilizer N rate, particularly at rates which exceed ecosystem (crop + soil) N uptake capacity. In these studies, N_2O emissions were substantially increased at fertilizer N rates above where crop yield was optimized when compared to emissions at rates that were insufficient for optimization. This non–linearity translates into an increasing EF value as N rate increases. Consequently, identical reductions in fertilizer N rate occurring above the threshold fertilizer N rate for optimized productivity result in very different calculated reductions in N_2O emissions, dependant on the form of the relationship. This has significant environmental and economic implications regarding the generation of N_2O emission reduction credits and the incentives for adopting reduced fertilizer N rate strategies.

Protocol development

We developed our N_2O reduction protocol (NERP) for calculating reductions in direct N_2O emissions from row–crop agricultural systems in the US Midwest (Midwest). We compared the IPCC Tier 1 linear methodology (constant EF) with our Tier 2 regional non–linear calculation (variable EF) and coupled these with a recently developed approach for determining economically profitable N rates for optimized crop yield to construct a simple, robust NERP for generating agricultural GHG emission reduction credits resulting from fertilizer N rate reduction (Millar *et al*. 2010b). For our purposes, the Midwest comprises the states of Iowa, Illinois, Indiana, Michigan, Minnesota, Ohio and Wisconsin. The region is characterized by extensive crop cultivation and is the major US producer of corn, soybean, and wheat. The corn–soybean rotation is the representative agricultural ecosystem in the Midwest, as well as in eastern and central North America generally.

Fertilizer N rate recommendations

Recently, the yield–based approach for crop N rate recommendations has been questioned, primarily due to the poor relationship between the recommendations and the economic optimum N rate (EONR). This has lead to a newly developed Midwest approach to optimize crop yield (Sawyer *et al*. 2006), which utilizes current N rate research data from field trials in corn–soybean rotations and continuous corn in the seven Midwest states to determine economically profitable N inputs. These inputs are expressed as a range of N rate around the maximum return to N (MRTN) at different N and corn prices, defined to be at or within ± \$1.00 $acre^{-1}$ of the MRTN (i.e., + or - \$1.00 $acre^{-1}$ is the *high* or *low* N rate, respectively).

Baseline and credit

Any reduction in fertilizer N rate below a previous baseline (common practice) level can be considered to generate emission reduction credits, due to the concomitant decrease in N_2O emissions. For our purposes these credits are provided by the reduction in N from the *high* to the *low* profitable MRTN rate (Figure 1; Table 1), i.e., we assume that producers who, given the choice of an N rate to apply within an economically profitable input range, would choose to apply the highest rate within this range in order to hedge against a perceived inadequate N supply.

Equations

Emission reductions of N_2O from a reduction in fertilizer N rate can be calculated from:

$$N_2O_R = N_2O_{+N\,(B)} - N_2O_{+N\,(A)} \quad (1)$$

Where:

N_2O_R — Reduction in N_2O emissions brought about by fertilizer N rate reduction, Mg CO_2e/ha/y;

$N_2O_{+N\,(B)}$ — Direct N_2O emissions following N fertilizer input before fertilizer N rate reduction, kg CO_2e/ha/y;

$N_2O_{+N\,(A)}$ — Direct N_2O emissions following N fertilizer input after fertilizer N rate reduction, kg CO_2e/ha/y;

The subscripts $_B$ and $_A$ represent the scenario before and after the fertilizer N rate reduction, respectively. Emissions of N_2O under these scenarios can be calculated from:

$$N_2O_{+N\,(B/A)} = [((F_{SN} + F_{ON})_{(B/A)} \times EF_n) + N_2O_{0N\,(B/A)}] \times N_2O_{MW} \times N_2O_{GWP} \quad (2)$$

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Where:

$N_2O_{+N\ (B\ /\ A)}$	Direct N_2O emissions following N fertilizer input, kg CO_2e/ha/y;
$N_2O_{0N\ (B\ /\ A)}$	Direct N_2O emissions following zero fertilizer N input, kg N_2O–N/ha/y;
$F_{SN\ (B\ /\ A)}$	Mass of N applied from synthetic fertilizer, kg N/ha/y;
$F_{ON\ (B\ /\ A)}$	Mass of N applied from organic fertilizer, kg N/ha/y;
EF_n	Emission factor for N_2O emissions from N inputs, kg N_2O–N (kg N input)$^{-1}$ (n = 1 or 2 for Tier 1 or Tier 2 approaches, respectively);
N_2O_{MW}	Ratio of molecular weight of N_2O to N (44/28), kg N_2O (kg N)$^{-1}$;
N_2O_{GWP}	Global Warming Potential for N_2O (298), kg CO_2e (kg N_2O)$^{-1}$;

EF_1: The IPCC Tier 1 default emission factor (EF_1) has a value of 0.01 or 1.0% (IPCC 2006), and is insensitive to fertilizer N rate.

EF_2: The value of the regional Tier 2 emission factor (EF_2) determined from the N fertility gradient field sites in the Midwest (Figure 1; Hoben *et al*. 2010) is sensitive to N rate and can be expressed as:

$$EF_2 = 0.012 \times \exp\,[0.00475 \times (F_{SN} + F_{ON})] \qquad (3)$$

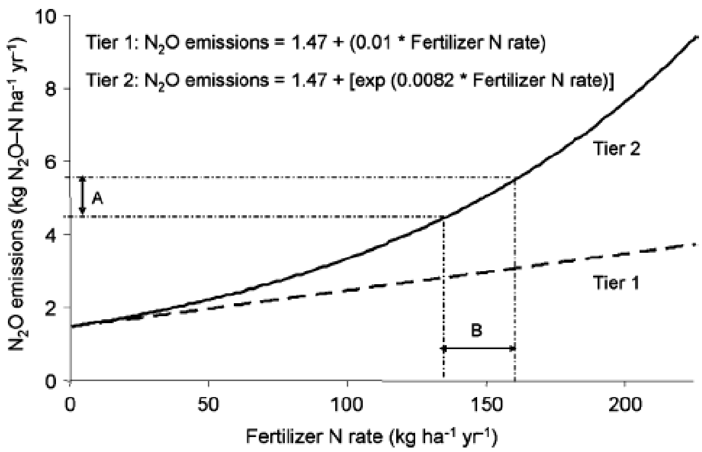

Figure 1. Relationship between direct emissions of N_2O (kg N_2O–N/ha/y) and fertilizer N rate (kg N/ha/y) determined from a linear (Tier 1, dashed line) and non–linear (Tier 2, solid line) approach. The Midwest background emission value (1.47 kg N_2O–N/ha/y) determined from the N gradient sites is included in Tier 1 and Tier 2 approaches. The N_2O emission reduction A (~ 1.1 kg N_2O–N/ha/y), results from an N rate reduction B (160 to 135 kg N/ha/y) using the Tier 2 approach (dash–dot lines). The equivalent reduction using the Tier 1 approach (not shown for clarity) is ~ 0.3 kg N_2O–N/ha/y.

Table 1. Annual reductions in N_2O emissions (CO_2e; Mg CO_2/ha/y) in Midwest states (selected data) under two cropping systems (continuous corn (C–C) and corn–soybean (C–S)) resulting from reductions in fertilizer N rate, calculated using the IPCC linear (Tier 1) and the regional non–linear (Tier 2) approach. The fertilizer N to corn price ratio used is 0.10, expressed as $ per pound of applied N divided by $ per bushel of corn yield.

State	System	PNRR *low*†	PNRR *high*†	Linear (Tier 1)	Non linear (Tier 2)
		N rate (kg N/ha)		CO_2e reductions ‡ (Mg CO_2/ha/y)	CO_2e reductions ‡ (Mg CO_2/ha/y)
Iowa	C–C	184	212	0.13	0.78
Illinois #	C–C	185	217	0.15	0.93
Indiana	C–S	180	207	0.13	0.73
Michigan	C–S	135	160	0.12	0.50
Minnesota	C–C	152	173	0.09	0.44
Ohio	C–C	206	237	0.14	1.00
Wisconsin ¤	C–C	145	166	0.10	0.44

† The Profitable Nitrogen Rate Range (PNRR) is the N rate values at a $1.00 / acre ($0.40 / ha) net return range (*low* and *high*) around the maximum return to N (MRTN). ‡ CO_2e reductions calculated using equations 1 and 2 above. # Data for Central region of Illinois. ¤ Data for high to very high yield potential (6.3-13.8 Mg/ha) soils in Wisconsin.

From equations 1 and 2 we calculate an N_2O emission reduction of 0.5 Mg CO_2e/ha/y for the corn component of a corn-soybean rotation in Michigan (using EF_2) as a result of reducing fertilizer N rate from the *high* (160 kg N/ha) to the *low* (135 kg N/ha) N rate of the profitable range (Figure 1). However, many producers are currently still fertilizing at N rates based on yield goal recommendations that can significantly exceed 160 kg N/ha. For example, a reduction from a starting N rate of 200 kg N/ha to 135 kg N/ha would yield an emission reduction credit of 1.5 metric tons CO_2e/ha/y.

Summary

In developing the NERP we have deliberately focused on fertilizer N rate. Other management and environmental factors influence N_2O emissions, however as an unambiguous proxy, fertilizer N rate can be viewed as a transparent, tangible, and readily manageable commodity within a future N_2O credit framework. We believe that utilizing the Midwest field based MRTN approach introduces the necessary economic component to the protocol framework and promotes producer confidence in the process. Although row crop agriculture in the Midwest is highlighted, this protocol could be applicable to other agricultural regions globally. For these reasons, we believe our protocol has merit and potential to be utilized in future agricultural offset projects developed for the carbon offset markets.

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