

Nitrogen fertilizer management for nitrous oxide (N₂O) mitigation in intensive corn (Maize) production: an emissions reduction protocol for US Midwest agriculture

Neville Millar · G. Philip Robertson · Peter R. Grace ·
Ron J. Gehl · John P. Hoben

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Abstract Nitrous oxide (N₂O) is a major greenhouse gas (GHG) product of intensive agriculture. Fertilizer nitrogen (N) rate is the best single predictor of N₂O emissions in row-crop agriculture in the US Midwest. We use this relationship to propose a transparent, scientifically robust protocol that can be utilized by developers of agricultural offset projects for generating fungible GHG emission reduction credits for the emerging US carbon cap and trade market. By coupling predicted N₂O flux with the recently developed maximum return to N (MRTN) approach for determining economically profitable N input rates for optimized crop yield, we provide the basis for incentivizing N₂O reductions without affecting yields. The protocol, if widely adopted, could reduce N₂O from fertilized row-crop agriculture by more than 50%. Although other management and environmental factors can influence N₂O emissions, fertilizer N rate can be viewed as a single unambiguous proxy—a transparent, tangible, and readily manageable commodity. Our protocol addresses baseline establishment, additionality, permanence, variability, and leakage, and provides for producers and other stakeholders the economic and environmental incentives necessary for adoption of agricultural N₂O reduction offset projects.

Keywords Agriculture · Baseline · CO₂ equivalents · Cap and trade · Crop yield · Emission reduction credits · Leakage · Nitrogen management · Nitrous oxide · Offset market

N. Millar (✉) · G. P. Robertson · P. R. Grace

W. K. Kellogg Biological Station, Michigan State University, 3700 E. Gull Lake Drive,
Hickory Corners, MI 49060, USA
e-mail: millarn@msu.edu

G. P. Robertson · J. P. Hoben

Department of Crop and Soil Sciences, Michigan State University, East Lansing, MI 48824, USA

P. R. Grace

Institute for Sustainable Resources, Queensland University of Technology, Brisbane, Australia

R. J. Gehl

Department of Soil Science, North Carolina State University, Mills River, NC 28759, USA

1 Introduction

The greatest alteration of the global nitrogen (N) cycle brought about by human activities is the change associated with the huge increase in biologically available or reactive N (Galloway et al. 2003). The rate at which reactive N enters into the biosphere each year has increased dramatically through the intensification of anthropogenic pathways (Robertson and Vitousek 2009). Fixation of N_2 , both biological and industrial, now far outpaces historical rates of denitrification and is the principal reason why N has become a major modern pollutant. Since the late 1950s, global synthetic N fertilizer consumption has increased from ~ 10 to ~ 100 Tg N in 2008 (Robertson and Vitousek 2009), with the global N input into agricultural systems from synthetic fertilizer increasing more than 40 fold since 1930 (Mosier et al. 1999). Currently the US is the third largest global producer and consumer of fertilizer N (8.2 and 14.5 Gg of N, respectively; FAO 2009). The need to feed and provide energy for a growing population drives the increase in demand for fixed N, which also results in increased emission of nitrous oxide (N_2O). Human induced emissions of N_2O are currently increasing by ~ 150 Tg N year⁻¹ (Mosier 2002), with current global concentrations of N_2O in the atmosphere around 320 ppbv vs. a pre-industrial concentration of 270 ppbv (Forster et al. 2007).

Nitrous oxide has important effects both on the climate system and on stratospheric ozone (Wuebbles 2009). It is a potent greenhouse gas (GHG) produced in the soil predominantly by the microbial processes of nitrification (ammonia oxidation) and denitrification (nitrate reduction) (Robertson and Groffman 2007). It is the major GHG emitted by US agricultural activities, with annual estimated emissions from cropland ~ 500 Gg in 2007 (EPA 2009). In 2007, agriculture in the US was responsible for around 7% of total GHG emissions, with soil management activities such as fertilizer N application accounting for almost 80% of total emissions of N_2O from this sector. The majority of N_2O emissions from agriculture in the US are associated with field crop production (CAST 2004; EPA 2009).

Processes that control N_2O production in soil include those that regulate denitrification and nitrification—available carbon, inorganic nitrogen, and oxygen as affected by soil moisture, porosity, and aggregate structure (Robertson and Groffman 2007). Management practices that can influence emissions of N_2O from agricultural soils include fertilizer N (rate, type, timing and application method), crop, tillage, residue management, and irrigation (Parkin and Kaspar 2006). Given that N_2O in agricultural soil is produced predominantly through the microbial transformations of inorganic N, the potential to produce and emit N_2O increases with the increasing availability of N (Bouwman et al. 1993). Due to the strong influence of available soil N on N_2O emissions, some emissions of N_2O seem to be an unavoidable consequence of maintaining highly productive cropland (Mosier 2002). However, anthropogenic activities that lower the input of N into cropland agriculture or reduce N availability can reduce emissions of N_2O .

Nitrogen is generally the most limiting nutrient in intensive crop production systems (Robertson and Vitousek 2009), and N fertilizer is commonly applied to corn, wheat and other non-leguminous crops. Knowledge of the trade-offs between N_2O emissions, N fertilizer management practice, and crop yield is therefore an essential requirement for informing management strategies that aim to reduce the agricultural N_2O burden without compromising productivity and economic returns. A number of management technologies have been proposed to reduce agricultural N_2O emissions (e.g., Mosier et al. 2001; Oenema et al. 2001; CAST 2004; Follett et al. 2005).

There is currently great interest in developing and implementing agricultural GHG reduction protocols for offset projects that can be included in cap and trade markets. Nitrous oxide, with its global warming potential (GWP) of 298 (vs. 1 for CO₂), is a major target for these endeavors due to the high payback associated with its emission prevention.

We propose here an N₂O reduction protocol suitable for a cap and trade offset market. In the pages that follow we introduce terms and definitions that focus our protocol development. We then present arguments for inclusion in the protocol a limited number of specific N management practices that alter N₂O emissions. This is followed by a summary of the evidence, and the development and presentation of a quantitative methodology for N₂O emission reduction. Finally, we illustrate the potential for N₂O mitigation with a worked example calculating N₂O emission reductions from a simple project scenario, prior to a discussion of project adoption issues such as baseline setting, additionality and leakage. In the [Appendix](#) we present a set of questions and answers to help inform guidelines and requirements that must be considered in order for an N₂O reduction protocol to be utilized in offset projects suitable for current cap and trade markets.

1.1 Scope

Our objective is to evaluate the current relevance and suitability of particular agronomic N practices for inclusion in an N₂O emissions reduction protocol. We discuss producer management practices as factors that influence emissions of N₂O, specifically focusing on those related to fertilizer N input to row-crop agriculture in the US Midwest, a region that has a major impact on US agricultural N₂O emissions. This narrowed focus is important for establishing protocol transparency for all stakeholders and acknowledges the logistics necessary to allow for ease of use in the validation, monitoring, and verification processes required for an N₂O reduction protocol and associated offset projects. The benefits of utilizing a simple, scientifically robust N management practice as an N₂O mitigation surrogate will far outweigh the cost of adoption if the practice gains producer confidence and can be initiated with little associated financial or social expense. Although row-crop agriculture in seven US Midwest states is highlighted, the factors that influence emissions of N₂O within this region and the methodology itself could be applicable to other agricultural regions globally.

1.2 Definitions

1.2.1 US Midwest

In our study, the US Midwest (Midwest) constitutes the seven states of Iowa, Illinois, Indiana, Michigan, Minnesota, Ohio and Wisconsin. This region is characterized by extensive crop cultivation and is the major producer of US corn and soybean, and half of the nation's wheat. The major Land Resource Region in the Midwest is Central Feed Grains and Livestock, more commonly known as the Corn Belt, which extends across all of these states. Agricultural GHG emissions in the Midwest are over 100 Tg of carbon dioxide equivalent (CO₂e), the fifth largest GHG-emitting sector, accounting for 7% of total regional emissions. Nitrous oxide is the major agricultural GHG across nearly all Midwestern states, reflecting the dominance of corn and other N fertilizer-intensive crops (Larsen et al. 2007).

1.2.2 Row-crop agriculture

Our protocol discussion concentrates on the two major row crops in the Midwest, namely corn and soybean. The corn–soybean rotation is a representative agricultural ecosystem widely found in the region and in eastern and central North America in general. For example, in 2007 corn and soybean combined comprised 78% and 95% of all harvested cropland in Ohio and Illinois, respectively (USDA NASS 2009a, b). Corn is an N intensive crop, typically receiving large additional N inputs to the soil, whereas soybean is a nitrogen fixing crop that adds N to the soil and requires little or no additional N input. Alterations to the N management of these crops therefore have a major impact on agricultural N₂O emissions from the Midwest. To augment the studies in the Midwest region, we also discuss research from other row-crop systems and from other regions of North America (from humid temperate climates, typical of the Midwest, where possible).

1.2.3 Fertilizer nitrogen sources

For our purposes, sources of fertilizer N are considered to be any readily soluble synthetic (e.g., single or multi-nutrient) or organic (e.g., animal manure, compost, sewage sludge) fertilizer containing N that is deliberately and directly applied to the soil as an external source. Other potential N input sources that are included in the Intergovernmental Panel on Climate Change (IPCC) inventories (IPCC 2006) such as crop residues and atmospheric deposition are not directly considered here. Readily soluble synthetic N fertilizers are the most commonly used synthetic fertilizers in corn–soybean rotations and predominate in the literature. In developing the protocol, all of the above inputs are considered equal on a nitrogen mass basis irrespective of their source, as per IPCC national GHG inventory protocols (IPCC 2006)

1.2.4 Nitrous oxide emissions

Emissions of N₂O that result from fertilizer N inputs to the soil can occur through both direct and indirect pathways. Direct emissions of N₂O are considered emissions from the soil that occur as a direct result of additional fertilizer N application to that same soil (e.g., a producer's field within a defined boundary). Indirect emissions of N₂O are considered to be those produced off-site (beyond the boundary) and include, but are not limited to, N₂O produced in receiving waters or soils as a result of NO₃⁻ leaching (IPCC 2006). Due to the limited data available on indirect emissions of N₂O in Midwest row-crop systems, only direct emissions of N₂O are considered in the context of this protocol development.

2 Factors influencing N₂O emissions

In the following sections we review individual fertilizer N management practices that can influence emissions of N₂O in row-crop agriculture in the Midwest. These practices are fertilizer type, timing, placement, and rate. For each direct N management practice we determine whether there is sufficient evidence to support its inclusion in the proposed N₂O reduction methodology. If so, we then develop a quantitative relationship that links the practice to changes in the emissions of N₂O.

2.1 Fertilizer N type

Readily soluble N fertilizers such as urea, anhydrous ammonia, urea ammonium nitrate, ammonium nitrate and ammonium sulfate are the most commonly used synthetic fertilizers in row-crop agriculture. In some soils, N₂O production can be affected by the form of fertilizer applied. On a silt loam in Minnesota, for example, Venterea et al. (2005) found that emissions of N₂O were 2–4 times greater from plots amended with anhydrous ammonia than from those amended with urea ammonium nitrate and broadcast urea. On an Ontario silt loam, Tenuta and Beauchamp (2003) found that the relative magnitude of total N₂O emitted was greater from urea than from ammonium sulfate, which in turn was greater than from calcium ammonium nitrate. On four varying soils in Saskatchewan under canola, flax and wheat, Hultgreen and Leduc (2003) found no significant differences in N₂O emissions between urea and anhydrous ammonia treatments over a 3 year sampling period.

In a global review of N₂O emission measurements from mineral soils in agricultural fields, Bouwman et al. (2002a) found that nitrate based fertilizers resulted in significantly lower emissions of N₂O than ammonium based fertilizers. However, they also warned against applying any estimates from their summarized data to individual fields because estimates represent gross relative differences among fertilizer types. Moreover, in many studies fertilizer N source effects are confounded with placement and other variations in methodology, thus further complicating (and often invalidating) comparisons of N source effects. Using an expansion of the data set used by Bouwman et al. (2002a), Stehfest and Bouwman (2006) found that after balancing for other factors, differences among fertilizer types all but disappeared. On the other hand, there is growing evidence that enhanced—efficiency fertilizers such as slow and controlled release and stabilized N fertilizers can enhance crop recovery of fertilizer N and minimize nutrient losses to the environment (Snyder et al. 2007). Their potential to reduce N₂O emissions is however, unclear; few investigations have documented abatement (Halvorson et al. 2008).

Overall, current evidence suggests that for the purposes of protocol development, synthetic fertilizer N type is unreliable as a single factor for abating N₂O emissions, and we therefore do not include it in this N₂O reduction protocol.

2.2 Fertilizer N timing

Synchronous timing of fertilizer N application with plant N demand is an important factor in determining soil N availability and, potentially, emissions of N₂O from row-crop agriculture. Crop N uptake capacity is generally low at the beginning of the growing season, increasing rapidly during vegetative growth, and dropping sharply as the crop nears maturity. Autumn fertilizer N application prior to spring crop planting, results in increased soil N with no plant uptake, and therefore greater potential for increased N₂O emissions. About 30% of the US area cropped to corn is fertilized in autumn (CAST 2004), such that large emissions of N₂O could potentially be avoided with spring rather than autumn fertilization. Although data from Midwest studies quantifying these potential N₂O emission differences are sparse, in Saskatchewan Hultgreen and Leduc (2003) showed that emissions of N₂O were lower following spring N fertilizer application than following autumn application. Also, in wheat and canola plots in Alberta with 100 kg N ha⁻¹ application rates, Hao et al. (2001) found that autumn fertilizer N application resulted in significantly greater N₂O emissions than did spring fertilizer N application.

Although circumstantial evidence suggests that Midwest N_2O fluxes should be lower in spring—than in fall—fertilized crops, predictive quantitative evidence for the Midwest is lacking. Until evidence suggests otherwise, then, we cannot justify including it in the current protocol. However, we believe this lack of information should be considered a high research priority.

2.3 Fertilizer N placement

The placement of synthetic fertilizer into the soil and near the zone of active root uptake may both reduce surface N loss and increase plant N use, resulting in less N that can be emitted as N_2O (CAST 2004). For example, in Colorado on a fine loam, Liu et al. (2006) found that injection of liquid urea ammonium nitrate at deeper levels in the soil profile (10 and 15 cm) resulted in 40–70% lower emissions of N_2O as compared to shallow injection (5 cm) or surface application. In contrast, on a clay loam in Ontario, Drury et al. (2006) found that emissions of N_2O were on average 26% higher from treatments with a deep (10 cm) injection of ammonium nitrate than from shallow (2 cm) injection in various tillage practices. In Saskatchewan, Hultgreen and Leduc (2003) determined that there was a weak trend for higher emissions of N_2O when urea was broadcast rather than banded, and when fertilizer N was placed mid-row, rather than side-banded.

In the absence of more consistent findings, and in particular for Midwest soils, it is difficult to justify including a fertilizer N placement strategy in an N_2O reduction protocol.

2.4 Fertilizer N rate

Numerous field studies conducted on N input gradients in row-crop agriculture have found that emissions of N_2O correlate well with fertilizer N rate (e.g., MacKenzie et al. 1998; Bouwman et al. 2002a; McSwiney and Robertson 2005; Mosier et al. 2006; Drury et al. 2008; Dusenbury et al. 2008; Halvorson et al. 2008; Hoben et al. 2010, in review; Millar et al. 2010, in review). In all of these studies, increasing the amount of N added to soil resulted in increasing emissions of N_2O . This is the foundation for current IPCC (2006) greenhouse gas inventory calculations.

2.5 Summary of evidence

Roberts (2007) argues that the basis of good N fertilizer management in cropland agriculture is using the right source, at the right rate, at the right time, and with the right placement. With regards to predicting emissions of N_2O from row-crop agriculture in the Midwest, evidence suggests that the right fertilizer rate is the most important factor. This finding and our consequent protocol development strategy is consistent with Tier 1 methodologies endorsed by the IPCC (2006). The IPCC approach is based upon extensive reviews and meta-analyses (e.g., Bouwman et al. 2002a; Akiyama et al. 2005; Novoa and Tejeda 2006; Stehfest and Bouwman 2006), and uses anthropogenic N addition as the primary controlling factor for estimating country-wide emissions of N_2O from managed land (IPCC 2006). Other management practices as well as land cover, soil type and climatic conditions are not taken into account with Tier 1 methodologies. Our summary therefore focuses on using fertilizer N rate as a quantitative proxy to calculate reductions in emissions of N_2O . Fertilizer N application rate as a management tool also has the advantage of allowing flexibility in its alteration, a major requirement for inclusion within any N_2O reduction protocol.

The majority of studies investigating emissions of N_2O from varying management practices in row-crop agriculture in North America examine only one fertilizer N (test) rate with or without a zero (control) rate (e.g., Drury et al. 2008; Parkin and Kaspar 2006; Hao et al. 2001). To calculate an emission factor requires sampling N_2O emissions from more than one test rate (e.g. MacKenzie et al. 1997; Mosier et al. 2006; Dusenbury et al. 2008; Halvorson et al. 2008). In these North American studies a maximum of three test rates were investigated in addition to a control, and all studies documented a linear relationships between fertilizer N rate and N_2O emissions, consistent with IPCC Tier 1 directives.

In the development of our protocol we therefore propose to utilize an IPCC Tier 1 linear approach for estimating fertilizer-based N_2O mitigation potentials in row-crop systems in the Midwest.

This linear approach may however, be unsuitable for most Midwest row-crop systems. Evidence from high resolution N fertilizer gradients in Michigan (McSwiney and Robertson 2005; Hoben et al. 2010, in review; Millar et al. 2010, in review) suggest that N_2O emissions increase exponentially with increasing fertilizer N rate, particularly at high rates that exceed the ecosystem (crop+soil) N uptake capacity (Grant et al. 2006). In a 3 year continuous corn experiment with nine fertilizer N rates from 0 to 291 kg N $ha^{-1}yr^{-1}$, McSwiney and Robertson (2005) discovered a non-linear relationship between N rate and emissions of N_2O , with fluxes remaining low and relatively stable at low N rates, and rapidly increasing at N rates beyond which crop yield was maximized. In the same study, McSwiney and Robertson (2005) calculated fertilizer induced emission factors of 2–7% at fertilizer rates of 134–291 kg N $ha^{-1}yr^{-1}$, the lowest value of which is greater than the IPCC default value of 1.0%. This non-linear relationship was corroborated at the same site with six fertilizer N rates (0–246 kg N $ha^{-1}yr^{-1}$) under winter wheat (Millar et al. 2010, in review) and at five commercial (on-farm) corn crop sites in Michigan with six fertilizer N rates (0–225 kg N $ha^{-1}yr^{-1}$) by Hoben et al. (2010; Fig. 1). Non-linear relationships have also been found in corn and wheat systems in Ontario and Alberta, (Grant et al. 2006; Ma et al. 2009). Emissions of N_2O may therefore exhibit a threshold response related to crop N requirement and the magnitude of N input (Erickson et al. 2001). Meta-analysis of the literature also provides support for the use of a non-linear relationship; Bouwman et al. (2002b) noted that the “calculated (N_2O) emission increases more than proportional with the N application rate.”

To the best of our knowledge, the Michigan field studies are the only Midwest studies to specifically investigate long-term N_2O emission responses to a large number of fertilizer N rate treatments in corn cropping systems. The sites used in the development of the non-linear N_2O flux model for Michigan (Hoben et al. 2010) are broadly representative of crop rotations and conditions throughout the Midwest. During years with normal precipitation, crop yields at these sites are typical of the region as a whole (Smith et al. 2007).

Nevertheless, these N gradient datasets are geographically limited and further studies of N_2O emissions responses from multiple N gradients throughout the Midwest would provide greater confidence for applying the non-linear relationship Hoben et al. (2010, in review) documented for Michigan. However, these gradient studies provide the only detailed information of their kind, and the non-linearity of N_2O emissions has significant consequences when comparing N_2O emissions reductions with the very general IPCC Tier 1 approach. This approach also offers an evidence-based, less complex solution to estimating N_2O emissions, when compared to the typically non-transparent Tier 3 approaches (e.g., Del Grosso et al. 2006). In the absence of evidence to the contrary we assume that these N gradient experiments are representative of the soil and corn cropping systems throughout the Midwest.

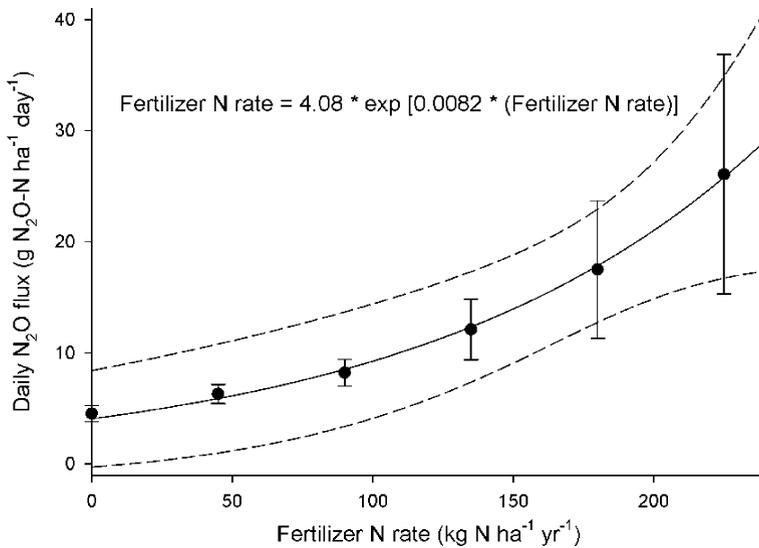


Fig. 1 Relationship between fertilizer N rate ($\text{kg N ha}^{-1} \text{ yr}^{-1}$) and N_2O fluxes ($\text{g N}_2\text{O-N ha}^{-1} \text{ day}^{-1}$) across five Michigan farm sites in 2007–2008. Regression for daily flux was performed on 48 data points representing 8 site year averages at 6 fertilizer N rates (4 replicate strips at each N rate per site). The upper and lower 95% confidence intervals of the average are shown with dashed lines. Error bars represent one standard error. From Hoben et al. 2010

For this protocol we therefore also propose the non-linear relationship determined from the Michigan field sites as an alternative, regional specific approach for estimating direct N_2O emissions from row-crop systems in the Midwest. This non-linear approach is consistent with IPCC (2006) Tier 2 methodological guidelines, where modified IPCC equations can be used with regionally relevant emission factors to calculate N_2O emissions.

3 Trade-offs between emissions, N rate and crop yield

Nitrogen is often the co-limiting factor in crop growth and N_2O production. Crop yield is related to crop N requirement, with higher yields typically requiring increased N inputs. When the availability of N in the soil exceeds the requirements of competing biota, fluxes of N_2O may be substantial and exhibit threshold responses according to the magnitude of N input (Erickson et al. 2001).

Greater than 50% of the major cropland area in the US is rated as having high N balances, resulting in soils highly susceptible to losses of N_2O to the atmosphere. CAST (2004) estimated that promoting the efficient use of fertilizer N inputs could reduce agricultural N_2O emissions in the US by 30–40%. If, as we have found, fertilizer N rate is a robust proxy for estimating N_2O emissions from Midwest row-crop agriculture, then reducing this rate is a readily accessible strategy for mitigating N_2O production in these systems. However, any reduction must be balanced against the potential economic cost of lost crop productivity. Since fertilizer N has typically been relatively inexpensive in comparison with other farm costs and remains low relative to corn and wheat prices (Robertson and Vitousek 2009), over-fertilization (application in excess of plant needs) is common, as producers' hedge against a perceived risk of insufficient N.

Prior to 1975, most crop N rate recommendations were based on soil-specific criteria and /or on crop management variables such as rotation and manure application. Since the 1970s, yield based N rate recommendations have been used in most Midwest states, primarily as a result of the landmark paper by Stanford (1973). In this approach, a yield goal value (e.g., 200 bushel [bu] acre⁻¹) is multiplied by an N yield factor (commonly 1.2 lb N bu⁻¹) to obtain a fertilizer N rate recommendation (e.g., 240 lb N acre⁻¹) that can be adjusted for N contributions from other sources, such as prior leguminous crops or manure. More recently, this yield-based approach to N rate recommendations has been questioned, primarily due to the poor relationship between recommendations and the economic optimum N rate (EONR) as observed in numerous N rate response trials (e.g., Vanotti and Bundy 1994). This has led to a newly developed Midwest regional approach to optimize crop yield (Iowa State University Agronomy Extension 2004). In this approach, current N rate research data from field trials in corn–soybean rotations and continuous corn are used to determine economically profitable N inputs, expressed as a range of N rates around the maximum return to N (MRTN) at different fertilizer nitrogen and corn prices (Nafziger et al. 2004).

In the MRTN approach a number of steps, as detailed in Sawyer et al. (2006), are used to calculate the MRTN rate and the economically profitable N rate range (PNRR) for corn in each rotation for each Midwest state. In brief, the steps are: 1) yield data are collected at replicated N rates from numerous fertilizer N rate trials; 2) curves are fitted and equations calculated for each yield response to N rate data set for each crop rotation at each site; 3) from the response curve equation at each site, the yield increase (amount above yield at zero fertilizer N rate), gross dollar return at that yield increase (corn grain price times yield), fertilizer cost (fertilizer N price times fertilizer N rate), and net return to N (gross dollar return minus fertilizer N cost) are calculated at each 1 lb (0.45 kg) fertilizer N rate increment from zero to 240 lb N acre⁻¹ (214 kg N ha⁻¹); 4) for each incremental N rate, the net return is averaged across all sites in the dataset for each rotation in each state. The N rate with the largest average net dollar return to N is the MRTN for corn in each crop rotation in each state. The net return will vary depending upon fertilizer N and corn prices, and it is their ratio that directly influences the net return and point of maximum net return.

From the MRTN analysis, the net economic return to N in each state is found to be similar at fertilizer N rates just below and just above the point of maximum net return (i.e., the MRTN). A range of N rates around the MRTN rate can therefore be considered to provide comparable economic return, and as such, a fertilizer N rate can be defined to be within the PNRR when it results in a net return to N within ±US\$ 1.00 acre⁻¹ (US\$ 2.45 ha⁻¹) of the MRTN (Sawyer et al. 2006). The specific N rates that result in a net return to N of US\$ 1.00 acre⁻¹ (US\$ 2.45 ha⁻¹) higher and lower than the MRTN rate can be defined as the *high* and *low* profitable N rate, respectively for corn in each crop rotation in each state.

The MRTN method is attractive for a number of reasons as outlined in Sawyer et al. (2006), including: 1) data can be utilized from a large number and variety of N response trials, and new trials can easily be added to the analysis; 2) specific responses of each site are considered in the determination of optimum N and net return, rather than average response; 3) risk assessment can be included, and 4) calculations are straightforward and likely economic outcomes at different N rates can be easily determined with different N and corn prices. These and other advantages help bridge the gap between research and practical N rate guidelines.

For protocol development we utilize the fertilizer MRTN approach in the seven Midwest states where sufficient data is available, in conjunction with the linear Tier 1 approach and

the non-linear Tier 2 approach, to calculate potential reductions in N₂O emissions from corn–soybean and continuous corn systems. Very different calculated reductions in N₂O emissions can result from identical reductions in fertilizer N rate, depending on the form of the relationship between N rate and N₂O emissions. This has significant environmental and economic implications regarding the generation of N₂O emission reduction credits and the incentives for adopting reduced fertilizer N rate strategies.

Any reduction in fertilizer N rate below a pre-determined baseline rate could be considered to generate producer credits, due to the concomitant decrease in N₂O emissions. As an exercise to demonstrate our protocol, we define the baseline N rate as the *high* profitable N rate for corn in each crop rotation in each state, with N₂O emission reduction credits generated by the reduction in fertilizer N rate from this *high* profitable N rate to the *low* profitable N rate for corn in each crop rotation in each state. This conservative approach assumes that producers who, given the choice of an N rate to apply within an economically profitable application range, would choose to apply the highest rate within this range in order to hedge against perceived inadequate N supply.

In Table 1, we present data from these seven states to show the reduction in N₂O emissions achievable in both continuous corn and corn–soybean rotations as a result of the management practice alteration that applies the *low*, rather than the *high* profitable fertilizer N rate in the PNRR, at a fertilizer N to corn price ratio of 0.10—a realistic ratio in current markets.

Previously recommended N rates for maximizing crop yields, based on yield goal calculations, exceeded 250 kg N ha⁻¹ (223 lb N acre⁻¹) in many parts of the Midwest (Vitosh et al. 1995). This rate is substantially higher than the *high* profitable N rate of 196 kg N ha⁻¹ (175 lb N acre⁻¹) averaged across the seven states. If a producers' baseline N rate is above that of the *high* profitable N rate for that state, as is still common practice, then the credits generated from an N rate reduction from the *high* to the *low* profitable N rate are additional to those generated from an N rate reduction from the producer's baseline N rate to the *high* profitable N rate. Therefore, greater N₂O emission reductions than those calculated in Table 1 will occur.

We suggest that this incentive for N₂O emission reduction, to apply the lower N rate within a profitable range, ultimately expressed as financial remuneration through a carbon or nutrient market, would bring about economic and environmental advantages that would far outweigh any marginal productivity benefits achieved in applying the higher N rate. For this reason, we believe this straightforward, transparent methodology has great potential to be accepted by the various stakeholders involved.

4 Nitrous oxide emission reduction protocol

In this section we present the equations required to calculate annual direct emission reductions of N₂O and CO₂e emissions from a continuous corn system and the corn component of corn–soybean rotation brought about by reductions in fertilizer N rate.

4.1 Equations

Emission reductions of N₂O brought about by reducing the annual fertilizer N rate can be calculated from:

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

Table 1 Annual reductions in N₂O emissions (kg N₂O ha⁻¹ yr⁻¹) and carbon dioxide equivalents (CO₂e, Mg CO₂ ha⁻¹ yr⁻¹) in seven Midwestern states under two cropping systems (continuous corn (C-C) and corn-soybean (C-S)). The reductions in emissions are calculated from the reductions in fertilizer N rate from a baseline N rate, equivalent to the *high* profitable N rate for each rotation in each state, to the *low* profitable N rate for each rotation in each state, as determined by the MRTN approach, using the IPCC default fertilizer induced emission factor for N₂O of 1.0% (Linear, Tier 1) and the varying fertilizer induced emission factor for the Midwest (Non-linear, Tier 2). The fertilizer N to corn price ratio used is 0.10, expressed as US\$ per pound of applied N divided by \$ per bushel of corn yield. The ‘metric ratio’ following conversion to units of kg of applied N and Mg (metric ton) of corn yielded is 1.79

State	System	PNRR		Linear (Tier 1)		Non-linear (Tier 2)	
		<i>low</i> ^A	<i>high</i> ^A	N ₂ O reductions ^B (kg N ₂ O ha ⁻¹ yr ⁻¹)	CO ₂ e reductions ^C (Mg CO ₂ ha ⁻¹ yr ⁻¹)	N ₂ O reductions ^B (kg N ₂ O ha ⁻¹ yr ⁻¹)	CO ₂ e reductions ^C (Mg CO ₂ ha ⁻¹ yr ⁻¹)
Iowa	C-C	184	212	0.44	0.13	2.63	0.78
Illinois ^D	C-C	185	217	0.51	0.15	3.12	0.93
Minnesota	C-C	152	173	0.32	0.09	1.46	0.44
Ohio	C-C	206	237	0.48	0.14	3.36	1.00
Wisconsin ^E	C-C	145	166	0.33	0.10	1.46	0.44
Iowa	C-S	128	155	0.42	0.13	1.66	0.49
Illinois ^D	C-S	174	205	0.49	0.15	2.77	0.83
Indiana ^F	C-S	180	207	0.42	0.13	2.45	0.73
Michigan ^F	C-S	135	160	0.41	0.12	1.67	0.50
Minnesota	C-S	110	133	0.37	0.11	1.25	0.37
Ohio	C-S	180	212	0.49	0.15	2.91	0.87
Wisconsin ^E	C-S	113	137	0.37	0.11	1.28	0.38

^A The *high* and *low* Profitable Nitrogen Rate Range (PNRR) values for each system in each state are the fertilizer N rates that provide a net economic return to N of \$1.00 acre⁻¹ (\$0.40 ha⁻¹) above (*high*) and below (*low*) the maximum return to N (MRTN) fertilizer rate

^B N₂O and CO₂e reductions calculated using Eqs. 1 and 2 with EF₁ default value of 0.01 (see text)

^C N₂O and CO₂e reductions calculated using Eqs. 1 and 2 with EF₂ regional value of 0.012 × exp [0.00475 × (F_{SN}+F_{ON})] (see text)

^D Data for Central region of Illinois

^E Data for high to very high yield potential soils in Wisconsin

^F Data for corn-soybean rotation only in Indiana and Michigan

Where:

N₂O_R Reduction in N₂O emissions brought about by fertilizer N rate reduction, kg CO₂e ha⁻¹ yr⁻¹

N₂O_{+N(B)} Direct N₂O emissions following N fertilizer input before fertilizer N rate reduction, kg CO₂e ha⁻¹ yr⁻¹

N₂O_{+N(A)} Direct N₂O emissions following N fertilizer input after fertilizer N rate reduction, kg CO₂e ha⁻¹ yr⁻¹

Equation 2 is used for estimating N₂O emissions from both the linear (Tier 1), and non-linear (Tier 2) N₂O response scenarios, with the emission factor terms EF₁ and EF₂ used for Tier 1 and Tier 2 calculations, respectively. The subscripts (B) or (A) represent the scenario before or after the fertilizer N rate reduction, respectively. Factors without these subscripts are unchanged for both scenarios:

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

Where:

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

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. The emission factor of 1.0% represents an annual direct loss of N_2O-N of $1.0\ kg\ N\ ha^{-1}$ for every $100\ kg\ N\ ha^{-1}$ of fertilizer N applied in that same year.

EF_2 : The value of the regional Tier 2 emission factor (EF_2) determined from the N fertility gradient on-farm field sites in Michigan (Hoben et al. 2009) is sensitive to N rate and can be expressed as:

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

To account for background anthropogenic N_2O emissions (Bouwman 1996), N_2O emissions from a zero fertilizer N rate control (N_2O_{0N}) scenario are included. The regional value for these background emissions determined from the N gradient sites in Michigan is $1.47\ kg\ N_2O-N\ ha^{-1}yr^{-1}$ (Hoben et al. 2009). When N_2O emissions are compared between Tier 1 and Tier 2 approaches, this value for N_2O emissions from the zero fertilizer rate control is applied to both equations.

The conversion of N_2O-N (the mass of the nitrogen component of the nitrous oxide molecule) to N_2O (N_2O_{MW}) is performed by multiplication of the ratio of the molecular weight of N_2O to the atomic weight of the two N atoms in the N_2O molecule, i.e., $N_2O = N_2O-N \times 44/28$.

The GWP value of 298 for N_2O used in the protocol (N_2O_{GWP}) is the 100-year value used in the most recent IPCC Fourth Assessment Report (Forster et al. 2007), and is the direct GWP for one molecule of N_2O on a mass basis for a 100 year time horizon, relative to one molecule of CO_2 , which is ascribed a value of 1 by convention. This means that a molecule of contemporary N_2O released to the atmosphere will have 298 times the radiative impact of a molecule of CO_2 released at the same time. Thus, an agronomic activity such as reduction in fertilizer N rate that reduces N_2O emissions by $1\ kg\ ha^{-1}$ is equivalent to an activity that sequesters $298\ kg\ ha^{-1}\ CO_2$ as soil C (Robertson and Grace 2004).

Fertilizer N additions to the soil during a whole crop cycle are included in the yearly fertilizer N rate irrespective of when N is applied during the calendar year or whether N application is split between calendar years for a single crop. The period for yearly fertilizer N rate would thus commence with the first application of fertilizer N dedicated to the particular crop and continue for 12 months.

4.2 Worked example

Below, we outline a simple scenario for a potential project utilizing the non-linear N_2O response approach to calculate reductions in emissions of N_2O and CO_2e brought about by an alteration in fertilizer N rate management practice.

Figure 2 shows the relationship between fertilizer N rate and emissions of N_2O derived from a) the IPCC linear Tier 1 approach and b) the non-linear Tier 2 approach using the data described in the worked example below. With the linear IPCC approach the annual direct N_2O-N emissions from zero N inputs (background anthropogenic emissions, N_2O_{0N}) is taken to be the same as the N_2O emissions determined from the zero N input treatment from the fertilizer N gradient studies.

Scenario A producer in Michigan with land under a corn–soybean rotation proposes to reduce his N rate input to corn from a previously verifiable average of 160 kg N ha^{-1} ($143 \text{ lb N acre}^{-1}$) corresponding to the *high* profitable N rate for the rotation in the state, to 135 kg N ha^{-1} ($123 \text{ lb N acre}^{-1}$), the *low* input N rate of the profitable range. This N rate reduction corresponds to a yield reduction from 99 to 98% of the maximum agronomic yield with no change in expected profitability (Iowa State University Agronomy Extension 2004). The N:corn price ratio for this scenario is 0.10.

Using Eqs. 2 and 3, the direct N_2O emissions before fertilizer N rate reduction are:

$$\begin{aligned} N_2O_{+N(B)} &= [(160 \times (0.012 \times \exp(0.00475 \times 160))) + 1.47] \times 44/28 \times 298 \\ &= 2617 \text{ kg CO}_2\text{e ha}^{-1} \text{ yr}^{-1} \end{aligned}$$

And the direct N_2O emissions after fertilizer N rate reduction are:

$$\begin{aligned} N_2O_{+N(A)} &= [(135 \times (0.012 \times \exp(0.00475 \times 135))) + 1.47] \times 44/28 \times 298 \\ &= 2121 \text{ kg CO}_2\text{e ha}^{-1} \text{ yr}^{-1} \end{aligned}$$

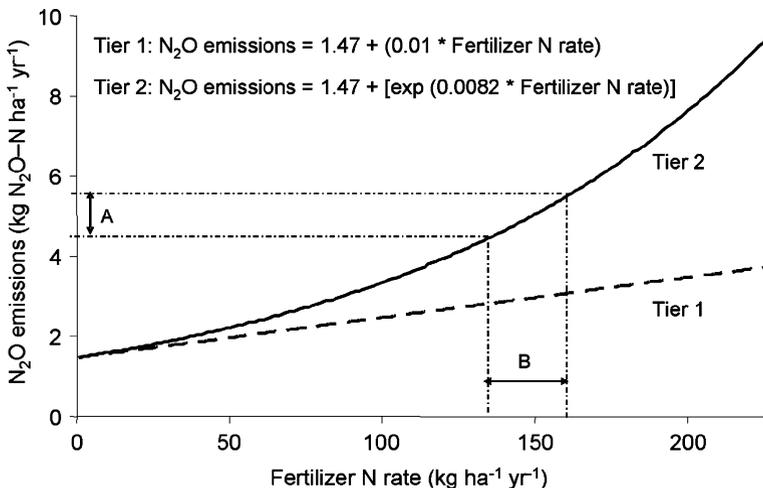


Fig. 2 Relationship between annual direct emissions of N_2O ($\text{kg N}_2\text{O-N ha}^{-1}\text{yr}^{-1}$) and fertilizer N application rate ($\text{kg N ha}^{-1}\text{yr}^{-1}$) determined from the linear default (Tier 1, dashed line) and non-linear regional (Tier 2, solid line) approach. The regional value for background emissions determined from the N gradient sites is $1.47 \text{ kg N}_2\text{O-N ha}^{-1}\text{yr}^{-1}$ and is applied to both Tier 1 and Tier 2 approaches. The potential N_2O emission reduction of $\sim 1.1 \text{ kg N}_2\text{O-N ha}^{-1}\text{yr}^{-1}$ (A) brought about using the Tier 2 approach with a reduction in N rate from 160 to $135 \text{ kg N ha}^{-1}\text{yr}^{-1}$ (B) is shown (arrows and dash-dot lines). The equivalent emission reduction using the Tier 1 approach (not shown for clarity) is $\sim 0.3 \text{ kg N}_2\text{O-N ha}^{-1}\text{yr}^{-1}$

Emission reductions of N₂O brought about by reducing the annual fertilizer N rate can be calculated from:

$$\begin{aligned} \text{N}_2\text{O}_R &= (2617 - 2121)\text{kg CO}_2\text{e ha}^{-1} \text{ yr}^{-1} \\ &\approx 0.5 \text{ Mg CO}_2\text{e ha}^{-1} \text{ yr}^{-1} \end{aligned}$$

If we compare this potential reduction in CO₂ emission equivalents to, for example, the current conditions for awarding contracts for employing agricultural conservation tillage practices in Michigan from the Chicago Climate Exchange (CCX), we find that our value of 0.5 Mg CO₂e ha⁻¹yr⁻¹ (0.2 metric tons CO₂e acre⁻¹yr⁻¹) from fertilizer N rate reduction is of similar magnitude to the 0.4–0.6 metric tons CO₂e acre⁻¹ yr⁻¹ rate for conservation tillage (0.6 metric tons CO₂e is the highest CCX credited rate of C sequestration in the US).

However, producers are currently still fertilizing at N rates based on yield goal recommendations that can significantly exceed this starting N rate of 160 kg N ha⁻¹. For example, the same producer with a typical corn yield goal of 180 bu acre⁻¹ (11.3 Mg ha⁻¹) would be recommended to apply 190 lb N acre⁻¹ (~213 kg N ha⁻¹) to the corn component of the corn–soybean rotation (Vitosh et al. 1995). At the same N:corn price ratio of 0.10, a reduction from 213 kg N ha⁻¹ to 135 kg N ha⁻¹ would yield a credit of 1.86 Mg CO₂e ha⁻¹yr⁻¹ (0.75 metric tons CO₂e acre⁻¹ yr⁻¹). Additionally, as discussed below and different from soil C sequestration, the avoided emissions of N₂O are permanent, i.e., not subject to possible release at a later date.

5 Protocol considerations

The inclusion of the agriculture sector in a cap and trade program has remained controversial since the Kyoto Protocol negotiations (Johnson 2008) and at present only a few governments regulate credits from agriculture. Many of the major areas of concern regarding agricultural offsets and allowances are relevant to the potential adoption of projects associated with a N₂O reduction protocol. Some are pragmatic—related to measurement and verification for the large number of producers and landowners, and others ideological—related to granting too much flexibility in how emission reductions are met, which could undermine overall mitigation goals. The major issues include permanence and duration; measurement and accounting variability; additionality; effectiveness; and leakage. We outline each of these concerns below and discuss some specific implications for the implementation of N₂O emission reduction projects.

5.1 Permanence and duration

The permanence or duration of a project helps to determine the amount of ‘new’ N₂O emissions prevented from entering the atmosphere. The longer the duration of a project that reduces the fertilizer N rate, the greater the magnitude of avoided N₂O emissions when compared to a previous practice with a higher N rate. Based upon our N rate reduction approach, these avoided emissions occur immediately, are irreversible and are thus permanent. This is similar to other agricultural management practices such as methane capture in confined animal feeding operations, but differs from others such as the adoption of no-till to sequester C in soil, where a reversal of practice back to conventional tillage may release sequestered C brought about as a result of project implementation.

5.2 Measurement and accounting variability

Emissions of N_2O are inherently variable at different temporal and spatial scales, and are unlikely to be measured directly at specific project sites. Reliable and robust quantification of the fertilizer N rate proxy for N_2O emission calculation is therefore essential. Using nitrogen fertility gradients to quantify the relationship between fertilizer N rate and N_2O emissions is an accurate, simple, and transparent tool for helping to predict N_2O emission reductions in continuous corn and corn–soybean rotations in the Midwest and potentially beyond.

5.3 Additionality

Additionality occurs when it can be demonstrated that steps have been taken to reduce N_2O emissions from a standard or previously common agricultural practice. Specifically, additionality can result from the continuing maintenance and augmentation of avoided N_2O emissions below any regulatory or other specified requirement. The emission reduction credit associated with the adoption of a project should be the only or primary incentive for the alteration or change in the producer management practice. Project reductions also need to be proven additional to other environmental goals or programs which would have taken place irrespective of project implementation, so that ‘double-counting’ does not occur. Our approach, as outlined in the worked example above, provides potential for substantial reduction in N_2O emissions when compared to pre-existing ‘business-as-usual’ practices.

5.4 Effectiveness

The effectiveness and therefore success of any project in mitigating N_2O emissions from row-crop agriculture will depend on many factors other than those related to the scientific robustness of the reduction mechanism associated with the adopted practice. These include practical considerations such as how well the practice is implemented and managed by the producer or landowner, and how well the practice can be verified, overseen and enforced by the relevant bodies. In addition to the economic and environmental consequences, other more intangible aspects such as gaming and psychological and social factors including stakeholder perception, tradition, and comfort will also play a role in determining effectiveness. Some of these factors are addressed in the [Appendix](#) below.

5.5 Leakage

Leakage can be defined as the net change of N_2O emissions that occur outside a project boundary, but which are measurable and directly attributable to the project activities. This can include increases in N_2O emissions outside the project area due to the displacement of pre-project activities and the potential for increased indirect emissions of N_2O . In cropland management alteration, such as N_2O reduction projects, these leakage risks will likely be negligible as the land will have been actively maintained for commodity production for many years prior to any project implementation. Adoption of N rates based on MRTN will not result in average yield reductions, an additional potential source of leakage since reduced yields would be compensated for elsewhere, presumably with additional N fertilizer use.

5.6 General comments

In developing this agricultural N₂O emission reduction protocol we have deliberately focused our attention on a small number of synthetic fertilizer N management practices that can influence emissions of N₂O from corn based row-crop systems in the US Midwest. Although other management and environmental factors influence N₂O emissions, fertilizer N rate can be viewed as an unambiguous proxy—a transparent, tangible, and readily manageable commodity within a future N₂O credit framework. We believe that utilizing the regional, field-based MRTN approach introduces the necessary economic component to the protocol framework and promotes producer confidence in the process. For these reasons, we believe our protocol has merit and potential to be utilized in future offset projects developed for carbon cap and trade markets.

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Appendix

Here we present a number of basic questions that may be posed by the various stakeholders during the development of a N₂O reduction protocol. We provide answers for these questions based upon our protocol methodology and other sources, in particular recent documentation from the Voluntary Carbon Standard (VCS) and the Chicago Climate Exchange (CCX).

Permanence and duration

Is there a minimum contractual time commitment for the project? The project crediting period is considered the time for which the net N₂O emission reductions will be verified, which under the VCS is equivalent to the project lifetime. Under the VCS, the project crediting period for agricultural land management (ALM) projects focusing exclusively on emissions reductions of N₂O will not exceed 10 years, renewable at most two times. Basic CCX specifications for soil carbon management offsets from conservation tillage stipulate a minimum 5 year contractual commitment.

Will N₂O reductions be readily reversible? Variable economic and environmental conditions may cause individual producers to temporarily alter their management practices, thereby potentially reversing previously accumulated credits for reductions that are reversible. This is of particular concern in the agricultural sector. Currently carbon contracts with the CCX require full accountability for any reversal of practice and maintain an implicit reserve level of 20% of the credit during the contract period. Similar precautions may be envisaged for any future N₂O reduction projects. However, as N₂O emissions are avoided as a result of fertilizer N rate reductions, with no transformation or sequestration of N, at worst a reversal of practice would likely involve simply a return to previous baseline practices. A further counter for any

potential reversal would be the requirement for an aggregation of producers, which would tend to provide a collective persistence of credits, as not all producers would likely make changes to their credit practice at the same time.

Measurement and accounting variability

Is the non-linear approach sufficiently robust for quantification of N₂O reduction credits? Recent VCS documentation (VCS 2007) stipulates that measurement of cropland soil management projects can include activity-based model estimates or direct measurement approaches or a combination of both. There are three tiers of flux estimation method as outlined in the IPCC 2006 Guidelines for National Greenhouse Gas Inventories. Tier 1 methods involve the use of IPCC equations and emission factors specified for broadly defined climate, soil and land use and management conditions, which include the 1.0% factor used in comparison with our non-linear Tier 2 approach that uses a more rigorously established, regionally relevant emission factor. Our Tier 2 approach also meets VCS requirements that “measurements to estimate project-specific N₂O emissions factors should be based on scientifically defensible measurements of sufficient frequency and duration to determine emissions for a full annual cycle.”

Additionality

What is the N₂O emission baseline for a project? The emission baseline (pre-project) can be considered the amount of N₂O that would have been emitted to the atmosphere during the crediting period of the project under the N management practice that would have been in place had the project not been implemented. The offset issuance for N₂O reductions will be based on the difference between ‘with-project’ and ‘without project’ emissions.

How is an N₂O emissions baseline for a project established? Proposed project activities will consider current and previous management practices. The project proponent must provide evidence of baseline N management practices, with minimum baseline estimates for N₂O emissions based on verifiable management records. These may include synthetic fertilizer purchase and application rate records, as well as manure application rate and N content data averaged over at least 5 years prior to the project establishment. Information on crop yield in this 5 year period is also desirable, particularly if varying yield has previously been associated with varying N fertilizer rate.

How many offsets does a project proponent receive? Agricultural N₂O offsets are issued on the basis of N₂O emissions that are avoided as a result of the introduction of the project. The amount of N₂O emissions (and ultimately CO₂e) avoided are derived from Eqs. 1 and 2 in the text above. Currently the commodity traded on the CCX is the carbon financial instrument (CFI) contract, each of which represents 100 metric tons (100 Mg) of CO₂ emission equivalents. The currency of carbon offsets generated under the VCS system, are voluntary carbon units (VCUs), each of which represent one metric ton (1 Mg) of CO₂ emission equivalents.

How will ‘annual’ N₂O emissions reductions (offsets) be defined? Crop production and agricultural GHG offset projects cannot be directly compared to typical existing industrial credit projects, due to (among other issues) stability, point source measurement, and spatial and temporal variability. It is reasonable to suggest that agricultural N₂O emission reductions

should be determined from the reduction in fertilizer N rate applied during either a whole annual cropping cycle or a multiyear rotation, irrespective of when fertilizer is applied throughout the calendar year or rotational cycle. This approach would encompass potential split applications of fertilizer N in two calendar years for one crop and applications to multiple crops grown at the same site during a 12 month period following initial application.

Effectiveness

How will potential fertilizer N rate reductions impact other GHG emissions and soil C stock estimates within the project boundary, and will these be considered during the project crediting period? Projects targeting N₂O emission reductions need to account for, where significant, increases in CO₂ and CH₄ emissions and reductions in soil C stocks. Guidelines for VCS Agriculture, Forestry and Other Land Use (AFOLU) projects (VCS 2007) stipulate that GHG sources that account for less than 5% of the total CO₂e emissions generated by the project are considered “insignificant.” Increases in CH₄ and CO₂ emissions or decreases in soil C stocks brought about by a reduction in fertilizer N rate are very unlikely to exceed this threshold during project crediting periods, and may well contribute to further project emission reductions.

Assuming that no direct monitoring of N₂O emissions from the project site will take place, what practical measures are available to project verifiers to ensure contractual compliance and prevent and detect ‘gaming’? Options for project acceptance to aid in verification during the crediting period may include a requirement for the establishment of crop ‘test strips’ to which zero and excess fertilizer N are applied, and from which visual and / or soil and plant sample comparisons can be made with the project crop area. Specific monitoring techniques that could be utilized to help verify ‘correct’ N application could include pre-season and late spring soil nitrate tests, late season stalk nitrate tests, handheld chlorophyll meter readings, remote sensing of soil and crop canopy properties, site-specific data from yield monitors, and soil electrical conductivity maps. A prerequisite for project acceptance will involve access to previous and current producer management records, as well as potential cross-checks with fertilizer suppliers, and other verification measures.

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Erratum to: Nitrogen fertilizer management for nitrous oxide (N₂O) mitigation in intensive corn (Maize) production: an emissions reduction protocol for US Midwest agriculture

Neville Millar · G. Philip Robertson · Peter R. Grace · Ron J. Gehl · John P. Hoben

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There was a typographical error in the Introduction section in Lines 10–11 of the original article. The sentence currently reads:

‘Currently the US is the third largest global producer and consumer of fertilizer N (8.2 and 14.5 Gg of N, respectively; FAO 2009).’

This should read:

‘Currently the US is the third largest global producer and consumer of fertilizer N (8.2 and 14.5 Tg of N, respectively; FAO 2009).’

The online version of the original article can be found under <http://dx.doi.org/10.1007/s11027-010-9212-7>.

N. Millar (✉) · G. P. Robertson · P. R. Grace
W. K. Kellogg Biological Station, Michigan State University, 3700 E. Gull Lake Drive,
Hickory Corners, MI 49060, USA
e-mail: millarn@msu.edu

G. P. Robertson · J. P. Hoben
Department of Crop and Soil Sciences, Michigan State University, East Lansing, MI 48824, USA

P. R. Grace
Institute for Sustainable Resources, Queensland University of Technology, Brisbane, Australia

R. J. Gehl
Department of Soil Science, North Carolina State University, Mills River, NC 28759, USA