

# Challenges and opportunities for mitigating nitrous oxide emissions from fertilized cropping systems

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Nitrous oxide (N<sub>2</sub>O) is often the largest single component of the greenhouse-gas budget of individual cropping systems, as well as for the US agricultural sector as a whole. Here, we highlight the factors that make mitigating N<sub>2</sub>O emissions from fertilized agroecosystems such a difficult challenge, and discuss how these factors limit the effectiveness of existing practices and therefore require new technologies and fresh ideas. Modification of the rate, source, placement, and/or timing of nitrogen fertilizer application has in some cases been an effective way to reduce N<sub>2</sub>O emissions. However, the efficacy of existing approaches to reducing N<sub>2</sub>O emissions while maintaining crop yields across locations and growing seasons is uncertain because of the interaction of multiple factors that regulate several different N<sub>2</sub>O-producing processes in soil. Although these processes have been well studied, our understanding of key aspects and our ability to manage them to mitigate N<sub>2</sub>O emissions remain limited.

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The conflict between accelerating demand for agricultural crops and the ecological impacts of their production is most evident with respect to nitrous oxide (N<sub>2</sub>O) emissions, which are directly linked to applications of nitrogen (N) fertilizers and manures to soil (Davidson 2009). Several naturally occurring soil processes can convert N that is not used by crops into N<sub>2</sub>O gas, which then rapidly diffuses into the atmosphere.

Worldwide consumption of synthetic N fertilizers is expected to increase by ~2% per year through 2015 (FAO 2011). Consequently, fertilizer-derived N<sub>2</sub>O emissions are expected to increase by those same percentages (Crutzen *et al.* 2008).

Under a mandate from the 2008 US Farm Bill, the US Department of Agriculture is currently developing tools to help land managers estimate and manage N<sub>2</sub>O and total greenhouse-gas (GHG) emissions at the farm scale (Glauber 2011). The state of California is in the process of defining protocols to potentially compensate farmers for reducing their N<sub>2</sub>O emissions (CAR 2012). With the current focus on GHG impacts, the importance of N<sub>2</sub>O as the dominant anthropogenic, ozone-depleting substance is sometimes overlooked; even if fossil-fuel-driven GHG emission rates can be slowed in the coming decades, N<sub>2</sub>O-driven ozone depletion will remain an issue of concern (Ravishankara *et al.* 2009). Although considerable research gains have been made regarding soil N<sub>2</sub>O emissions over the past several decades, mitigation remains a research frontier since few practices have yet been proven to be reliable across locations, cropping systems, or growing seasons.

The fundamental challenge in reducing agroecosystem N losses in general is to maximize the amount of added fertilizer- or manure-N that is actually used by the crop – in other words, to optimize crop N-use efficiency (NUE). Although measures of NUE have increased over the past few decades in the US, the amount of applied N that is recovered in the aboveground biomass of major US crops is still typically below 40–50% (Cavigelli *et al.* 2012), owing to the difficulty of applying N cost-effectively to large land areas in a manner that is both temporally and spatially synchronized with crop N demands (Ribaud *et*

## In a nutshell:

- Reducing nitrous oxide (N<sub>2</sub>O) emissions from fertilized agroecosystems is particularly challenging due to the number and complexity of N<sub>2</sub>O production processes in soil and the tendency for emissions pulses to occur in response to climate and management events
- All other forms of reactive nitrogen (N) that are lost from agricultural ecosystems (eg nitrate, ammonia, and nitric oxide) can be converted to N<sub>2</sub>O once received by other terrestrial and/or aquatic ecosystems; this further complicates N<sub>2</sub>O mitigation but also enhances its potential benefits
- Ultimately, mitigating N<sub>2</sub>O emissions can only be achieved through the use of new methods of crop sensing, field mapping, fertilizer delivery, and other technologies that increase the proportion of added N that is assimilated by crops, as well as by reducing N-fertilizer inputs
- More studies are needed that focus on the specific soil biochemical processes most directly responsible for N<sub>2</sub>O emissions and on the management practices that affect these processes

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*al.* 2011). In this respect, efforts to mitigate N<sub>2</sub>O emissions face the same challenges as efforts to reduce agroecosystem losses of all forms of reactive N (Galloway *et al.* 2003). Nitrous oxide mitigation is even more difficult because of biophysical factors unique to this gas. Here, we discuss potential strategies and future research needs specific to N<sub>2</sub>O. We focus on the management of individual fertilized cropping systems but do not address animal production systems or larger structural issues, such as modifying the composition of traditional cropping systems or human dietary or food conservation practices (Cavigelli *et al.* 2012; Del Grosso and Cavigelli 2012; Reay *et al.* 2012). Nor is this intended to be a thorough review; a supplementary reading list (see WebReferences) is provided, but even that does not fully cover the literature on this topic.

### ■ Technical challenges for reducing N<sub>2</sub>O emissions

#### **Small N<sub>2</sub>O losses have large GHG impacts**

The primary challenge for N<sub>2</sub>O mitigation is directly associated with its high global-warming potential, which is ~300 times greater than that of carbon dioxide (CO<sub>2</sub>) and 12 times greater than that of methane (Forster *et al.* 2007). Thus, a negligible amount of N<sub>2</sub>O loss from an agronomic perspective can represent a substantial amount from a GHG perspective. For example, assuming that N fertilizer is applied at an areal rate of 150 kg N ha<sup>-1</sup>, a commonly observed N<sub>2</sub>O loss of only 1% of applied N translates to 0.7 metric tons of CO<sub>2</sub> equivalents (CO<sub>2</sub>eq) ha<sup>-1</sup> yr<sup>-1</sup>. This amount of CO<sub>2</sub> is equivalent to about 58% of the carbon (C) sequestration rates estimated for conversion from conventional to no-till management (Post *et al.* 2012). It is therefore possible to have relatively high crop NUE and still have substantial CO<sub>2</sub>eq GHG emissions.

#### **Improving NUE may not always reduce N<sub>2</sub>O emissions**

Recent studies have shown that N management practices that achieve the highest recovery of fertilizer N in crop biomass also result in the highest N<sub>2</sub>O emissions (Fujinuma *et al.* 2011; Gagnon *et al.* 2011). Although this may appear contradictory, it is reasonable given that most N losses occur in the form of ammonia (NH<sub>3</sub>) volatilization and/or nitrate (NO<sub>3</sub><sup>-</sup>) leaching, which commonly amounts to 10% and 30% of applied N, respectively, compared with N<sub>2</sub>O losses, which are generally < 3% (Mosier *et al.* 1998; De Klein *et al.* 2006). Thus, practices that improve NUE by reducing NH<sub>3</sub> and/or NO<sub>3</sub><sup>-</sup> losses may in effect make more N available in the soil for both N uptake in crops and N<sub>2</sub>O production via several N transformation pathways.

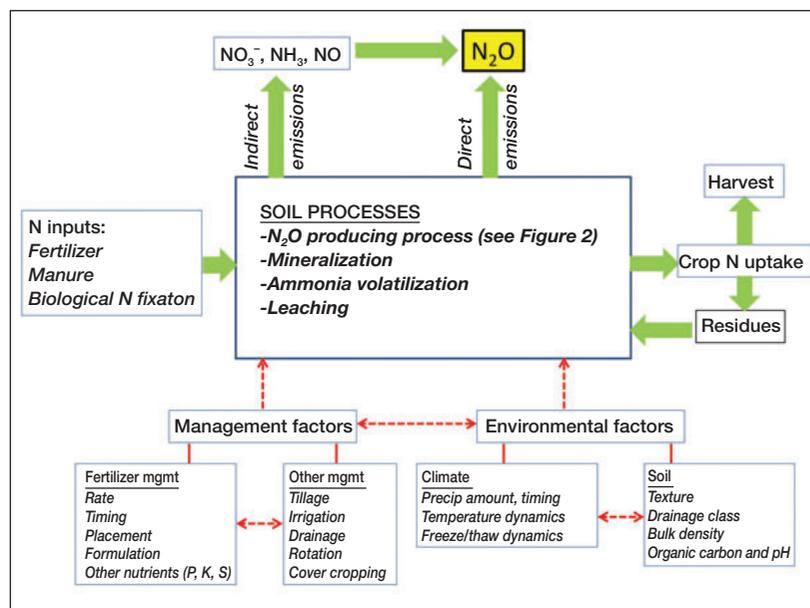
Improving temporal synchrony between crop-N demand and soil-N availability is a key strategy for improving NUE (Ribaudo *et al.* 2011). Most N fertilizers

are applied when the crop is not present or prior to the period of peak crop-N demand. In fact, in the US corn belt, a substantial amount of N fertilizer is applied during the fall, prior to the growing season (Bierman *et al.* 2012). Although shifting the timing of N application from fall to spring or from early to late spring may increase overall NUE, these practices have not consistently reduced N<sub>2</sub>O emissions (Phillips *et al.* 2009). In fact, fertilizer application in spring, as compared with fall application, has in some cases increased N<sub>2</sub>O emissions, possibly because warmer and/or wetter conditions at the time of application can stimulate larger pulses of N<sub>2</sub>O emissions (Hernandez-Ramirez *et al.* 2009). Use of alternative fertilizers, designed to release N gradually during the growing season, has reduced N<sub>2</sub>O emissions (Shoji *et al.* 2001) but not consistently, and the specific conditions where these products are effective still need to be defined.

Even if the timing of fertilizer application can be improved, optimizing the physical placement of fertilizer can still be a difficult challenge, because N fertilizers are added to soil, not directly to the crops. Incorporating fertilizer more deeply into the soil and/or placing it in concentrated bands instead of uniformly applying it to the soil surface may reduce NH<sub>3</sub> and NO<sub>3</sub><sup>-</sup> losses, improve root access to N, and increase overall NUE (Malhi *et al.* 2001). However, deep placement does not always reduce N<sub>2</sub>O emissions, and fertilizer banding can actually increase N<sub>2</sub>O emissions. Improving overall NUE will likely be effective in reducing N<sub>2</sub>O emissions in many cases, as well as in reducing all other forms of reactive N loss. Nevertheless, the key point here is that N<sub>2</sub>O mitigation will need to address not only overall NUE but also target the specific factors and processes that contribute directly to N<sub>2</sub>O emissions.

#### **High sensitivity of N<sub>2</sub>O emissions and crop yields to total N inputs**

The amount of N applied per area of field during a single growing season is commonly referred to in agriculture as the “N rate”. Reducing the N rate is perhaps the only practice that has broad consensus as being generally reliable for reducing N<sub>2</sub>O emissions. Emissions of N<sub>2</sub>O can increase linearly or exponentially with N rate (Hoben *et al.* 2011). However, because crop yields, and therefore farmers’ profits, are also highly sensitive to N rate, the feasibility of N-rate reduction as a strategy for mitigating N<sub>2</sub>O must consider economic impacts and other policy ramifications (Archer and Halvorson 2010). Simply reducing N rate without modifying other practices may also shift any lost crop production, and its associated N<sub>2</sub>O emissions, to another geographical location. Reducing N rate would certainly be possible when the current rate exceeds the economically optimal rate for a given cropping system (Millar *et al.* 2010). Van Groenigen *et al.* (2010) also showed that when N<sub>2</sub>O emissions increase exponentially with N rate, N<sub>2</sub>O emissions expressed on a



**Figure 1.** Multiple factors that influence direct and indirect N<sub>2</sub>O emissions from cropping systems. Vertical red arrows symbolize main effects on soil processes; horizontal red arrows symbolize potential interactions among these effects.

yield-scaled basis will be minimized at an intermediate (non-zero) N rate that may also be economically profitable. Fine-tuning of N rate to meet crop demand is inherently risky because both crop yields and N losses (eg NO<sub>3</sub><sup>-</sup> leaching) depend on annual weather variations. An N rate that supports optimum yield in a favorable weather year and also accounts for N losses may not be perceived by the farmer as an “over-application”. However, an N rate that is optimized for favorable weather is likely to exceed the economically optimal rate in some growing seasons (Babcock 1992). Policies that provide financial incentives may therefore be required to change farming practices (Ribauda *et al.* 2011).

Rather than using N-rate reduction as a stand-alone mitigation strategy, we argue that implementing other practices (eg improved fertilizer timing, placement, or source) that allow for N-rate reductions and that maintain (or even increase) yields could lessen the need for financial incentives. For example, if multiple N applications during the growing season can produce the same or a greater yield while using a lower total N rate, operating costs associated with multiple applications would be at least partly balanced by savings in fertilizer costs (and ideally also by yield increases). However, almost no studies have examined the combined effects of reduced N rate and improvements in other practices (eg timing) on N<sub>2</sub>O emissions. A related issue is that crop N demand can vary considerably (eg by 100 kg N ha<sup>-1</sup>) within a single field as a result of the spatially variable nature of soil N mineralization and N-loss potential (Scharf *et al.* 2005). Thus, instead of reducing N inputs uniformly across fields, targeting N rates to match within-field variations in crop requirements might allow for overall N-rate reductions without reducing yields, or perhaps even increasing them

(Scharf *et al.* 2011). To date, very little research has been performed to quantify the effect of within-field N-rate variation on N<sub>2</sub>O emissions.

### All N losses represent potential N<sub>2</sub>O emissions

In addition to direct emissions of N<sub>2</sub>O from fertilized fields, other forms of reactive N (eg nitric oxide [NO], NH<sub>3</sub>, and NO<sub>3</sub><sup>-</sup>), once emitted from the field, can subsequently be converted to N<sub>2</sub>O in downwind or downstream ecosystems (Figure 1; Mosier *et al.* 1998). So-called “indirect” emissions can complicate mitigation efforts because a given practice may affect both direct and indirect sources. Even if losses of all N forms could be quantified for a given practice, the proportion of each N form that is subsequently converted to N<sub>2</sub>O in a receiving ecosystem is subject to great uncertainty (Clough *et al.* 2006). Practices

that increase direct emissions while at the same time decreasing indirect emissions (or vice versa) are particularly difficult to assess, because in these cases the net impact on total N<sub>2</sub>O emissions will depend on the proportion of N that is converted to N<sub>2</sub>O elsewhere. Thus, the most effective N<sub>2</sub>O mitigation strategies will need to consider all reactive N losses; although this increases the difficulties of effective mitigation, it also creates the potential for other ecological benefits, including reduced total N loadings to aquatic and terrestrial ecosystems resulting from decreased N leaching and atmospheric N deposition (Galloway *et al.* 2003).

### Multiple soil production processes

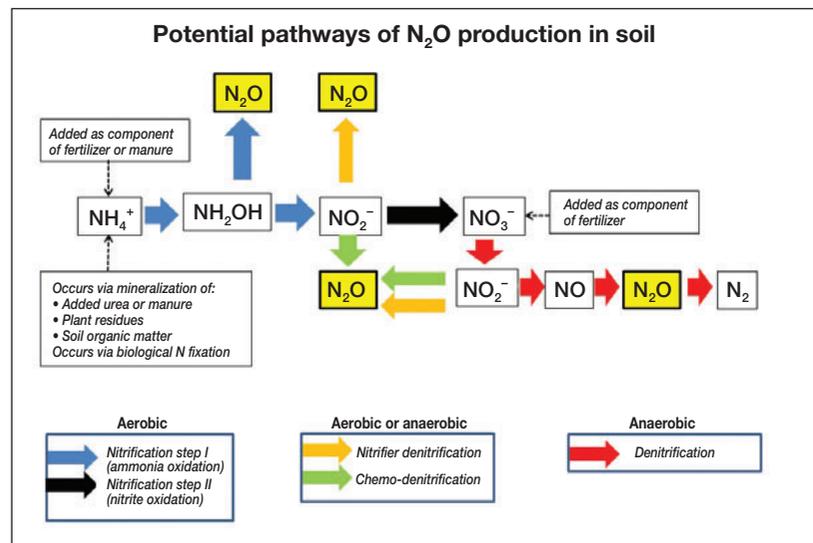
If a single process were responsible for all soil N<sub>2</sub>O production, managing N<sub>2</sub>O emissions might be considerably less problematic. However, there are at least four different processes that take place in soil and that lead to N<sub>2</sub>O production, including nitrification, nitrifier-denitrification, chemo-denitrification, and denitrification (Figure 2); furthermore, within each of these processes there may be more than one specific production pathway (Panel 1; WebReferences). Thus, once N enters the soil, there are numerous processes leading to conversion to N<sub>2</sub>O, and many agricultural activities tend to stimulate some or all of these processes. Fertilizers, manures, and biological N-fixation by legume crops provide the essential compounds (NH<sub>4</sub><sup>+</sup> and/or NO<sub>3</sub><sup>-</sup>) that initiate nitrification and/or denitrification, which in turn can promote nitrifier-denitrification and/or chemo-denitrification. Because these processes can occur under a range of soil conditions (eg from fully aerobic to anaerobic), optimization of specific soil conditions to reduce N<sub>2</sub>O production may be difficult.

### Tendency for large pulse events

It is common for a large proportion (> 65%) of annual N<sub>2</sub>O emissions to occur over time scales of hours to weeks in response to management practices (eg fertilization, tillage, irrigation) and climatic events (eg precipitation, soil thawing; Johnson *et al.* 2010). Reducing N<sub>2</sub>O responses to these events would greatly increase the mitigation benefits. Because these N<sub>2</sub>O pulse events have multiple sources, several modifications may be required. Potential strategies include the use of smaller and more frequent N applications, which would lessen fertilizer-induced pulses and could also reduce rainfall- or irrigation-induced pulses by maintaining lower levels of soil inorganic N (eg NO<sub>3</sub><sup>-</sup>). Pulses driven by decomposition of N-rich residues may be suppressed through the addition of C-rich residues that lead to short-term N immobilization or by conducting tillage under cool and dry conditions (Baggs *et al.* 2000). Thaw-induced N<sub>2</sub>O pulses may be the most difficult to control (and quantify) because this source is not well understood and is highly dynamic (Kariyapperuma *et al.* 2011). Manually sampling gas via flux chambers at frequencies of one to three times weekly may not adequately capture these pulse events, although more frequently deployed automated chamber systems are increasingly being used (Figure 3).

### Complexity of process controls

Soil N<sub>2</sub>O emissions are potentially sensitive to a wide range of management, environmental, and soil factors (Figure 1) that can affect N<sub>2</sub>O-producing processes (Figure 2). In addition to being highly dynamic and spatially variable within a single location, these properties tend to vary widely across geographic locations. A practice that reduces N<sub>2</sub>O emissions in one location or during



**Figure 2.** Processes that produce N<sub>2</sub>O in soil include nitrification (step I, NH<sub>4</sub><sup>+</sup> oxidation), nitrifier-denitrification, chemo-denitrification, and denitrification. See Panel 1 and WebReferences for further details.

one growing season may not be effective at other locations or times. Extrapolating research findings among locations is therefore a major challenge for N<sub>2</sub>O mitigation. Three examples are given below.

- (1) In irrigated systems under semi-arid climate conditions, controlled-release or stabilized fertilizers have reduced N<sub>2</sub>O emissions by up to 70% as compared with emissions produced through the use of conventional fertilizers (eg Shoji *et al.* 2001; Halvorson *et al.* 2011). However, studies conducted in humid areas not requiring irrigation showed no statistically significant benefits when alternative fertilizers were used (Sistani *et al.* 2011). Large rainfall events and/or wetter soil conditions in these regions may have decreased the effectiveness of the alternative fertilizers by stimulating more rapid N release that was not synchronized with crop N demand.
- (2) Application of anhydrous ammonia (AA) fertilizer at a shallower depth (0.1 m), as compared with the more conventional depth (0.2 m), decreased N<sub>2</sub>O emis-

#### Panel 1. N<sub>2</sub>O-producing processes in soil

Step I of nitrification (blue arrows in Figure 2) is the oxidation of NH<sub>4</sub><sup>+</sup> to hydroxylamine (NH<sub>2</sub>OH) and then to NO<sub>2</sub><sup>-</sup>. This process is carried out primarily by aerobic autotrophic bacteria that obtain their energy by using NH<sub>4</sub><sup>+</sup> as an electron donor, oxygen (O<sub>2</sub>) as an electron acceptor, and carbonates as a C source. The intermediate compound, NH<sub>2</sub>OH, although highly transient in soil, can produce N<sub>2</sub>O via reactions with manganese or NO<sub>2</sub><sup>-</sup> or through other, unknown reactions. Step 2 of nitrification (black arrow in Figure 2) is the subsequent oxidation of NO<sub>2</sub><sup>-</sup> to NO<sub>3</sub><sup>-</sup> by a specific class of autotrophic bacteria; while this process does not generate N<sub>2</sub>O directly, the NO<sub>3</sub><sup>-</sup> produced can then undergo denitrification (red arrows in Figure 2), which is the sequential reduction of NO<sub>3</sub><sup>-</sup> to NO, N<sub>2</sub>O, and then potentially to N<sub>2</sub>, a process performed by a wide range of heterotrophic bacteria and fungi that use these N compounds as electron acceptors under conditions of very low to non-existent O<sub>2</sub> levels. The same group of NH<sub>4</sub><sup>+</sup>-oxidizing bacteria that carry out nitrification step I can also use the product of this process (NO<sub>2</sub><sup>-</sup>) as an electron acceptor and reduce it to N<sub>2</sub>O in a process referred to as nitrifier-denitrification (orange arrows in Figure 2). This can occur under completely aerobic conditions but also appears to be promoted when O<sub>2</sub> concentrations decrease, even moderately, below ambient levels. The NO<sub>2</sub><sup>-</sup> produced during either nitrification step I or denitrification can react chemically with soil organic matter and/or possibly mineral constituents to form N<sub>2</sub>O in a variety of reactions, collectively referred to as chemo-denitrification (green arrows in Figure 2). This process most commonly occurs under aerobic conditions, when NO<sub>2</sub><sup>-</sup> produced from nitrification step I accumulates. References associated with this panel can be found in the WebReferences.



**Figure 3.** Measurement of soil-to-atmosphere N<sub>2</sub>O emissions by (a and c) manual sampling of gas flux chambers and (b and d) automated sampling systems.

sions by 28% in a clay loam soil (Breitenbeck and Bremner 1986) but increased N<sub>2</sub>O emissions by 100% in a loamy sand (Fujinuma *et al.* 2011), possibly due to a higher rate of denitrification in the clay loam substrate.

- (3) Some studies have found that reduced and no-till practices can reduce N<sub>2</sub>O emissions as compared with conventional tillage (Omonode *et al.* 2011), while other studies have shown the reverse (Baggs *et al.* 2003). A global meta-analysis concluded that climate regime, duration of practice, and N-fertilizer placement all influenced tillage effects on N<sub>2</sub>O emissions (Van Kessel *et al.* 2012).

### Process-level knowledge gaps

Nitrite (NO<sub>2</sub><sup>-</sup>) molecules are a potential or required precursor substrate for N<sub>2</sub>O produced by all four processes shown in Figure 2 and described in Panel 1. However, our understanding of the role of NO<sub>2</sub><sup>-</sup> in controlling N<sub>2</sub>O emissions is limited in two important respects: (1) what specific conditions lead to increased soil-NO<sub>2</sub><sup>-</sup> concentrations, resulting in increased N<sub>2</sub>O production, and (2) what specific reactions control NO<sub>2</sub><sup>-</sup>-driven N<sub>2</sub>O production. Some level of NO<sub>2</sub><sup>-</sup> accumulation tends to

occur during nitrification in soil, and appears to result from a lag in the growth of NO<sub>2</sub><sup>-</sup>-oxidizing bacteria (NOB) compared to NH<sub>4</sub><sup>+</sup>-oxidizing bacteria (AOB; Figure 4; Venterea and Rolston 2000a). This lag effect may be exacerbated by elevated levels of NH<sub>3</sub>; for example, when N fertilizers are placed in concentrated bands (Figure 5), in the form of either urea (Engel *et al.* 2010) or AA (Venterea and Rolston 2000b), NO<sub>2</sub><sup>-</sup> can accumulate to higher levels, with a concomitant increase in N<sub>2</sub>O fluxes. Earlier studies suggested that these dynamics were due to toxicity effects of free NH<sub>3</sub> on NOB populations, but more recent work has raised questions about this hypothesis (Hawkins *et al.* 2010). In any case, some of the highest N<sub>2</sub>O fluxes ever reported occurred following AA application, when NO<sub>2</sub><sup>-</sup> levels exceeded 100 μg N per gram of soil (Venterea and Rolston 2000b). We do not know if NO<sub>2</sub><sup>-</sup> accumulation is more important in controlling N<sub>2</sub>O pulses, or how fertilizer banding intensity, fertilizer formulations, or soil organic C, pH, or texture affect NO<sub>2</sub><sup>-</sup> accumulation. Once present in soil, NO<sub>2</sub><sup>-</sup> reacts rapidly to form N<sub>2</sub>O due to both biological processes and chemical reactions (Venterea 2007). A wide range of non-biological reactions involving NO<sub>2</sub><sup>-</sup> reacting with organic compounds or metallic cations have been shown or hypothesized to produce N<sub>2</sub>O (see

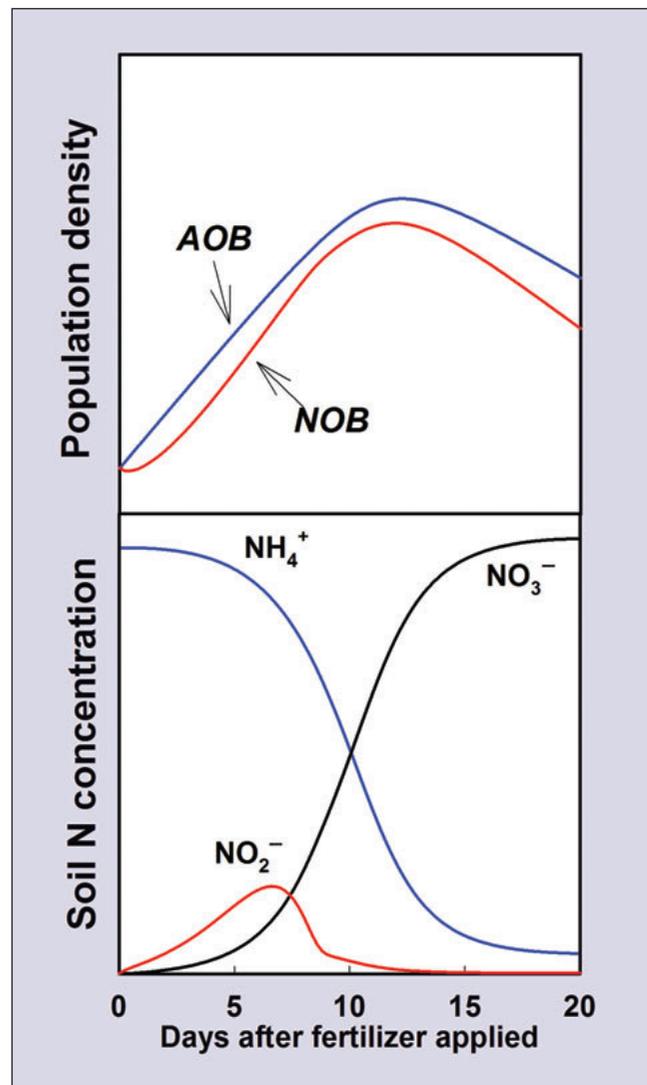
**Figure 4.** Model simulations that assume a condition where NH<sub>4</sub><sup>+</sup>-oxidizing bacteria (AOB) and NO<sub>2</sub><sup>-</sup>-oxidizing bacteria (NOB) population densities in soil are initially equal, followed by a discrete input of NH<sub>4</sub><sup>+</sup>, resulting in a pulse of NO<sub>2</sub><sup>-</sup> accumulation as NOB growth lags behind AOB. (Reprinted with permission from *J Environ Qual* 2000; 29: 1741–51.)

WebReferences). While these reactions are commonly lumped under the category “chemo-denitrification”, we do not know the relative importance of the different pathways, how they could be managed, or how to incorporate them into predictive models. Such knowledge gaps limit the ability of N<sub>2</sub>O emissions models to account for the wide suite of biological and abiotic factors that may limit mitigation practices for particular regions or cropping systems. While process-based models have the potential to represent the fundamental production pathways, more experimental data and modeling efforts are needed for model calibration, refinement, and testing (Del Grosso *et al.* 2012).

#### ■ Conclusions and directions

It is worth envisioning ideal management strategies that could reliably reduce N<sub>2</sub>O emissions. In a perfect world, managers could avoid N<sub>2</sub>O emissions pulses by frequent additions of N fertilizer, applied to coincide with crop demand and avoid wet conditions; using N rates that are adjusted spatially to match in-field variations in crop-N need and soil-N supply; and delivering N close to the root system using a chemical form that is stabilized to minimize losses of all other reactive N species. While this picture is far removed from current practices, several potentially effective technologies do exist, although many are in need of further development and require cost–benefit analyses.

An emerging approach for improved N management is variable-rate N application (VRNA), which adjusts N rate to meet real-time crop demand or prior-season yield variations within a given field. This practice can reduce N rates in some areas and increase it in others, while maintaining or even enhancing yield and net profit (Scharf *et al.* 2011). Sensors that measure light reflectance from crops can diagnose plant N needs in real time. Such crop reflectance sensors have been linked to automated fertilizer application systems to regulate application rates at fine spatial scales (Kitchen *et al.* 2010; Scharf *et al.* 2011). Only one study (Sehy *et al.* 2003) has measured the effects of VRNA on direct N<sub>2</sub>O emissions, but this study did not use the more recently developed crop-sensing technologies. In principle, VRNA could be used to address temporal as well as spatial variations in crop N demand. In rain-fed areas this would require multiple tractor passes, although fuel-derived GHG emissions would likely be small as compared with potential decreases in N<sub>2</sub>O emissions (Lal 2004). However, even if the number of applications was increased from one to four per season, each application would still require a greater amount of N than



the crop needed over the following few days to weeks. Also, applying N later in the season may be problematic in rain-fed areas because high crop canopies may require specialized application equipment. Moreover, fertilizer that is applied during prolonged dry periods may not be adequately solubilized or mobilized in the soil for efficient root uptake. In irrigated areas, the use of fertilizers dissolved in irrigation water (“fertigation”) may be more feasible, but little work has been published regarding fertigation and N<sub>2</sub>O emissions (Kallenbach *et al.* 2010).

Alternative (eg controlled-release) fertilizers have shown some promise in reducing N<sub>2</sub>O emissions. Yet, these products respond primarily to environmental factors, releasing N more rapidly as soil water content and temperature increase and therefore may not necessarily be synchronized with root N uptake. New formulations that respond more directly to crop root activity and/or soil-solution N levels may be more effective. Also, microbial (eg nitrification) inhibitors that have a longer duration of activity in soil and/or that can inhibit N<sub>2</sub>O-producing enzyme systems such as NO reductase (Hino *et al.* 2010) might be more successful.



**Figure 5.** Establishing N fertilizer treatments for a N<sub>2</sub>O field experiment in research plots at the University of Minnesota, in St Paul. Urea containing nitrification and urease inhibitors (blue granules) is being applied in concentrated bands between rows of corn seedlings, for comparison with conventional urea.

A variety of other mitigation practices are also being evaluated. There is some evidence that the use of pyrolysis products (eg biochar) as a soil amendment can reduce soil N losses through various possible mechanisms (Singh *et al.* 2010; Taghizadeh-Toosi *et al.* 2012; Spokas *et al.* 2012). Although N is generally the nutrient that limits crop yields, inadequate supplies of other nutrients (eg phosphorus, potassium, sulfur) can also limit crop NUE (Snyder *et al.* 2009); however, insufficient research has been completed for non-N nutrient management in relation to N<sub>2</sub>O emissions. Managing drainage systems to reduce NO<sub>3</sub><sup>-</sup> export to streams (Feser *et al.* 2010) and edge-of-field treatments to remove NO<sub>3</sub><sup>-</sup> from drainage waters (Elgood *et al.* 2010) have shown potential for reducing indirect N<sub>2</sub>O emissions. Another line of research involves the development of genetic strategies to enhance the ability of crops to release nitrification-inhibiting substances into the soil (Subbarao *et al.* 2012). Use of crop genomics to develop varieties and hybrids with higher physiological NUE, thereby improving overall NUE, is underway at several large corn seed companies, but they have yet to undergo field evaluation. More generally, there is a need for studies that combine improved timing, placement, source, or more effective soil amendments or new crop varieties with reduced N rate. For example, nearly all comparisons of alternative versus conventional fertilizers, or early versus late applications, have used the same N rates. Increased NUE achieved through alternative practices might allow for reduced N rate while maintaining yields and reducing N<sub>2</sub>O, but to date few experimental studies have examined this strategy for effectively reducing N rate.

Reducing N losses from fertilized cropping systems will not solve the entire N<sub>2</sub>O problem because it represents

only a part of the broader agricultural N cycle, which also includes animal production, manure processing, food consumption and conservation, and sewage treatment. On the other hand, with the range of technologies currently available (eg crop sensors, improved fertilizer products and delivery technologies, global positioning systems, and increasingly powerful data-processing and field-mapping capabilities), common methods of N-fertilizer management tend to appear crude in comparison and are poised for considerable improvement. While the costs of such improved practices will limit their adoption, their economic feasibility depends on factors that are likely to change in the future, such as fertilizer costs, crop prices, and policies aimed at internalizing environmental costs, including CO<sub>2</sub>e trading programs.

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#### ■ References

- Archer DW and Halvorson AD. 2010. Greenhouse gas mitigation economics for irrigated cropping systems in northeastern Colorado. *Soil Sci Soc Am J* **74**: 446–52.
- Babock BA. 1992. The effects of uncertainty on optimal nitrogen applications. *Rev Agr Econ* **14**: 271–80.
- Baggs EM, Stevenson M, Pihlatie M, *et al.* 2003. Nitrous oxide emissions following application of residues and fertilizer under zero and conventional tillage. *Plant Soil* **254**: 361–70.
- Baggs EM, Rees RM, Smith KA, and Vinten AJA. 2000. Nitrous oxide emissions from soils after incorporating crop residues. *Soil Use Manage* **16**: 82–87.
- Bierman P, Rosen CJ, Venterea RT, and Lamb J. 2012. Survey of nitrogen fertilizer use on corn in Minnesota. *Agric Syst* **109**: 43–52.
- Breitenbeck GA and Bremner JM. 1986. Effects of rate and depth of fertilizer application on emission of nitrous oxide from soil fertilized with anhydrous ammonia. *Biol Fert Soils* **2**: 201–04.
- CAR (Climate Action Reserve). 2012. Nitrogen management project protocol. Los Angeles, CA: CAR. [www.climateactionreserve.org/how/protocols/agriculture/nitrogen-management/](http://www.climateactionreserve.org/how/protocols/agriculture/nitrogen-management/). Viewed 25 Sep 2012.
- Cavigelli MA, Del Grosso SJ, Liebig MA, *et al.* 2012. US agricultural nitrous oxide emissions: context, status, and trends. *Front Ecol Environ* **10**: 537–46.
- Clough TJ, Bertram JE, Sherlock RR, *et al.* 2006. Comparison of measured and EF5-r-derived N<sub>2</sub>O fluxes from a spring-fed river. *Glob Change Biol* **12**: 352–63.
- Crutzen PJ, Mosier AR, Smith KA, and Winiwarer W. 2008. N<sub>2</sub>O release from agro-biofuel production negates global warming

- reduction by replacing fossil fuels. *Atmos Chem Phys* **8**: 389–95.
- Davidson EA. 2009. The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860. *Nat Geosci* **2**: 659–62.
- De Klein CR, Novoa SA, Ogle S, et al. 2006. N<sub>2</sub>O emissions from managed soils, and CO<sub>2</sub> emissions from lime and urea application. In: Eggleston S, Buendia L, Miwa K, et al. (Eds). 2006 IPCC guidelines for national greenhouse gas inventories. Vol 4: agriculture, forestry and other land use. Hayama, Japan: Institute for Global Environmental Strategies.
- Del Grosso SJ and Cavigelli MA. 2012. Climate stabilization wedges revisited: can agricultural production and greenhouse-gas reduction goals be accomplished? *Front Ecol Environ* **10**: 571–78.
- Del Grosso SJ, Parton WJ, Adler PR, et al. 2012. DayCent model simulations for estimating soil carbon dynamics and greenhouse gas fluxes from agricultural production systems. In: Liebig MA, Franzluebbers AJ, and Follet RF (Eds). Managing agricultural greenhouse gases: coordinated agricultural research through GRACEnet to address our changing climate. London, UK: Academic Press.
- Elgood Z, Robertson WD, Schiff SL, and Elgood R. 2010. Nitrate removal and greenhouse gas production in a streambed denitrifying bioreactor. *Ecol Eng* **36**: 1575–80.
- Engel R, Liang DL, Wallander R, and Bembek A. 2010. Influence of urea fertilizer placement on nitrous oxide production from a silt loam soil. *J Environ Qual* **39**: 115–25.
- FAO (Food and Agriculture Organization). 2011. Current world fertilizer trends and outlook to 2015. Rome, Italy: FAO. <ftp://ftp.fao.org/ag/agg/docs/cwfto15.pdf>. Viewed 3 Oct 2012.
- Feser SE, Strock JS, Sands GR, and Birr AS. 2010. Controlled drainage to improve edge-of-field water quality in southwest Minnesota, USA. In: Drainage IX: Proceedings of the Ninth International Drainage Symposium; 13–17 Jun 2010; Quebec City, Canada. St Joseph, MI: ASABE.
- Forster P, Ramaswamy V, Artaxo P, et al. 2007. Changes in atmospheric constituents and in radiative forcing. In: Solomon S, Qin D, Manning M, et al. (Eds). Climate change 2007: the physical science basis. New York, NY: Cambridge University Press.
- Fujinuma R, Venterea RT, and Rosen C. 2011. Broadcast urea reduces N<sub>2</sub>O emissions but increases NO emissions compared with conventional and shallow-applied anhydrous ammonia in a coarse-textured soil. *J Environ Qual* **40**: 1806–15.
- Gagnon B, Ziadi N, Rochette P, et al. 2011. Fertilizer source influenced nitrous oxide emissions from a clay soil under corn. *Soil Sci Soc Am J* **75**: 595–604.
- Galloway JN, Aber JD, Erisman JW, et al. 2003. The nitrogen cascade. *BioScience* **53**: 341–56.
- Glauber J. 2011. Development of technical guidelines and scientific methods for quantifying GHG emissions and carbon sequestration for agricultural and forestry activities. *Federal Register* **76**: 9534–37. <http://federalregister.gov/a/2011-3731>. Viewed 3 Oct 2012.
- Halvorson AD, Del Grosso SJ, and Pozzi Jantalia C. 2011. Nitrogen source effects on nitrous oxide emissions from strip-till corn. *J Environ Qual* **40**: 1775–86.
- Hawkins S, Robinson K, Layton A, and Saylor G. 2010. Limited impact of free ammonia on *Nitrobacter* spp inhibition assessed by chemical and molecular techniques. *Bioresour Technol* **101**: 4513–19.
- Hernandez-Ramirez G, Brouder SM, Smith DR, and Van Scoyoc GE. 2009. Greenhouse gas fluxes in an eastern corn belt soil: weather, nitrogen source, and rotation. *Environ Qual* **38**: 841–54.
- Hino T, Matsumoto Y, Nagano S, et al. 2010. Structural basis of biological N<sub>2</sub>O generation by bacterial nitric oxide reductase. *Science* **330**: 1666–70.
- Hoben JP, Gehl RJ, Millar N, et al. 2011. Non-linear nitrous oxide (N<sub>2</sub>O) response to nitrogen fertilizer in on-farm corn crops of the US Midwest. *Glob Change Biol* **17**: 1140–52.
- Johnson JMF, Archer DW, and Barbour NW. 2010. Greenhouse gas emission from contrasting management scenarios in the Northern Corn Belt. *Soil Sci Soc Am J* **74**: 396–406.
- Kallenbach CM, Rolston DE, and Horwath WR. 2010. Cover cropping affects soil N<sub>2</sub>O and CO<sub>2</sub> emissions differently depending on type of irrigation. *Agr Ecosyst Environ* **137**: 251–60.
- Kariyapperuma KA, Wagner-Riddle C, Furon AC, and Li C. 2011. Assessing spring thaw nitrous oxide fluxes simulated by the DNDC model for agricultural soils. *Soil Sci Soc Am J* **75**: 678–90.
- Kitchen NR, Sudduth KA, Drummond ST, et al. 2010. Ground-based canopy reflectance sensing for variable-rate nitrogen corn fertilization. *Agron J* **102**: 71–84.
- Lal R. 2004. Carbon emission from farm operations. *Environ Int* **30**: 981–90.
- Malhi S, Grant C, Johnston A, and Gill K. 2001. Nitrogen fertilization management for no-till cereal production in the Canadian Great Plains: a review. *Soil Till Res* **60**: 101–22.
- Millar N, Robertson GP, Grace PR, et al. 2010. Nitrogen fertilizer management for nitrous oxide (N<sub>2</sub>O) mitigation in intensive corn (maize) production: an emissions reduction protocol for US Midwest agriculture. *Mitig Adapt Strateg Glob Change* **15**: 185–204.
- Mosier A, Kroeze C, Nevison C, et al. 1998. Closing the global N<sub>2</sub>O budget: nitrous oxide emissions through the agricultural nitrogen cycle. *Nutr Cycl Agroecosys* **52**: 225–48.
- Omonide R, Smith D, Gál A, and Vyn T. 2011. Soil nitrous oxide emissions in corn following three decades of tillage and rotation treatments. *Soil Sci Soc Am J* **75**: 152–63.
- Phillips R, Tanaka D, Archer D, and Hanson J. 2009. Fertilizer application timing influences greenhouse gas fluxes over a growing season. *J Environ Qual* **38**: 1569–79.
- Post WM, Izaurralde RC, West TO, et al. 2012. Management opportunities for enhancing terrestrial carbon dioxide sinks. *Front Ecol Environ* **10**: 554–61.
- Ravishankara AR, Daniel JS, and Portmann RW. 2009. Nitrous oxide (N<sub>2</sub>O): the dominant ozone-depleting substance emitted in the 21st century. *Science* **326**: 123–25.
- Reay DS, Davidson EA, Smith KA, et al. 2012. Global agriculture and nitrous oxide emissions. *Nat Climate Change*; doi:10.1038/nclimate1458.
- Ribaudo M, Delgado J, Hansen L, et al. 2011. Nitrogen in agricultural systems: implications for conservation policy. Washington, DC: USDA. [www.ers.usda.gov/Publications/ERR127/](http://www.ers.usda.gov/Publications/ERR127/). Viewed 25 Sep 2012.
- Scharf PC, Kitchen NR, Sudduth KA, et al. 2005. Field-scale variability in economically-optimal N fertilizer rate for corn. *Agron J* **97**: 452–61.
- Scharf PC, Shannon DK, Palm HL, et al. 2011. Sensor-based nitrogen application out-performed producer-chosen rates for corn in on-farm demonstrations. *Agron J* **103**: 1683–91.
- Sehy U, Ruser R, and Munch JC. 2003. Nitrous oxide fluxes from maize fields: relationship to yield, site-specific fertilization, and soil conditions. *Agric Ecosyst Environ* **99**: 97–111.
- Shoji S, Delgado J, Mosier A, and Miura Y. 2001. Use of control release fertilizers and nitrification inhibitors to increase nitrogen use efficiency and to conserve air and water quality. *Commun Soil Sci Plant Anal* **32**: 1051–70.
- Singh BP, Hatton BJ, Singh B, et al. 2010. Influence of biochars on nitrous oxide emission and nitrogen leaching from two contrasting soils. *J Environ Qual* **39**: 1224–35.
- Sistani KR, Jn-Baptiste M, Lovanh N, and Cook KL. 2011. Atmospheric emissions of nitrous oxide, methane, and carbon dioxide from different nitrogen fertilizers. *J Environ Qual* **40**: 1797–1805.

- Snyder CS, Bruulsema TW, Jensen TL, and Fixen PE. 2009. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. *Agric Ecosyst Environ* **133**: 247–66.
- Spokas KA, Cantrell KB, Novak JM, *et al.* 2012. Biochar: a synthesis of its agronomic impact beyond carbon sequestration. *J Environ Qual* **41**: 973–89.
- Subbarao GV, Sahrawat KL, Nakahara K, *et al.* 2012. Biological nitrification inhibition – a novel strategy to regulate nitrification in agricultural systems. *Adv Agron* **114**: 249–302.
- Taghizadeh-Toosi A, Clough TJ, Sherlock RR, and Condon LM. 2012. Biochar adsorbed ammonia is bioavailable. *Plant Soil* **350**: 57–69.
- Van Groenigen JW, Velthof GL, Oenema O, *et al.* 2010. Towards an agronomic assessment of N<sub>2</sub>O emissions: a case study of arable crops. *Europ J Soil Sci* **61**: 903–13.
- Van Kessel C, Venterea R, Six J, *et al.* 2012. Climate, duration, and N placement determine N<sub>2</sub>O emissions in reduced tillage systems: a meta-analysis. *Glob Change Biol*; doi:10.1111/j.1365-2486.2012.02779.x
- Venterea RT. 2007. Nitrite-driven nitrous oxide production under aerobic soil conditions: kinetics and biochemical controls. *Glob Change Biol* **13**: 1798–1809.
- Venterea RT and Rolston DE. 2000a. Mechanistic modeling of nitrite accumulation and nitrogen oxide gas emissions during nitrification. *J Environ Qual* **29**: 1741–51.
- Venterea RT and Rolston DE. 2000b. Nitric and nitrous oxide emissions following fertilizer application to agricultural soil: biotic and abiotic mechanisms and kinetics. *J Geophys Res-Atmos* **105**: 15117–29.
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