The Identification of Management Strategies that Target Multiple Nitrogen Loss Pathways (Part 3 of 3)

By Tai McClellan Maaz and Cliff Snyder

In the previous two articles, we presented recent research that highlighted the limitations of using N rate as the sole means to calculate N_2O fluxes, and provided source, timing, and placement recommendations to further reduce emissions. Both Omonode et al. (2017) and Eagle et al. (2017) provided evidence that stabilized N sources reduced N_2O emissions in corn production in the North American Midwest. Stabilized N refers to N fertilizers that have been treated with urease and/or nitrification inhibitors. Urease and nitrification inhibitors target different processes in the N cycle (**Figure 1; Table 1**) and therefore temporarily regulate different forms of plant available N and downstream loss pathways. Fertilizers (other than those supplying N in the form of nitrate only) can be treated with urease plus nitrification inhibitors to target multiple loss pathways.

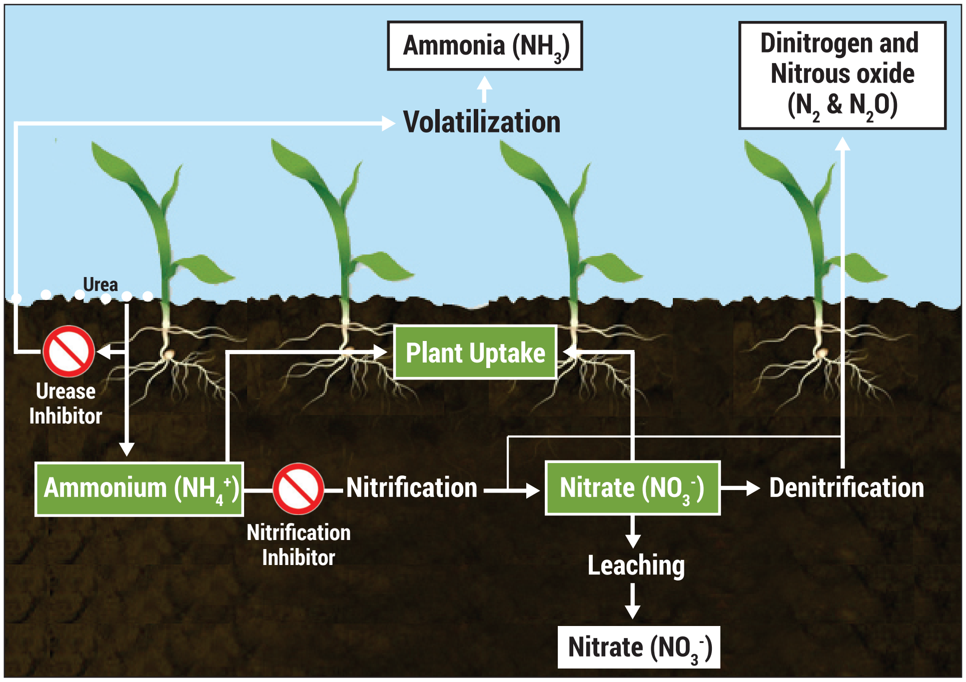

Figure 1. Stabilized urea can contain a urease inhibitor to temporarily prevent ammonia loss via volatilization. Nitrification inhibitors can temporarily prevent rapid conversion of ammonium to nitrate, which in turn is susceptible to loss through leaching and its conversion to gaseous forms of N via denitrification.

In both articles, stabilized N sources reduced N_2O emissions. Omonode et al. (2017) assessed the effect of urease inhibitors with and without nitrification inhibitors, and found 19 to 48% less emission of N_2O. The second paper, by Eagle et al. (2017), examined effects of nitrification in-

Table 1. Modes of action for stabilized N sources.

Stabilized N	Mode of action
Urease inhibitor	Urease inhibitors temporarily block the urease enzyme that is responsible for splitting the urea into NH_3 and CO_2. Therefore, urease inhibitors regulate the pool of plant-available NH_4^+ and can also reduce NH_3 volatilization, which is more likely in soils with high pH, high temperature, and low moisture, particularly for surface-applied urea.
Nitrification inhibitor	Nitrification inhibitors temporarily block the activity of nitrifying bacteria, which are responsible for transforming NH_4^+ to NO_3^-, thereby regulating the pool of plant-available NO_3^-. Studies have determined these inhibitors can reduce losses of NO_3^- leaching in coarser soils and N_2O emissions in poorly-aerated, wet, warm soils.
Urease plus nitrification inhibitor	Some products combine nitrification inhibitors with urease inhibitors for multiple modes of action.

SUMMARY
Stabilized N sources are N fertilizers treated with urease inhibitors, nitrification inhibitors, or a combination of both. They can comprise "right source" in many situations in which 4R Nutrient Stewardship is implemented. Several meta-analyses demonstrate that nitrification inhibitors with and without urease inhibitors consistently reduce N_2O emissions. Nitrification inhibitors are effective at decreasing NO_3^- leaching but can increase ammonia volatilization, while urease inhibitors are effective at preventing volatilization losses.

KEYWORDS:
stabilized N; N emission; N volatilization; N leaching

ABBREVIATIONS AND NOTES:
N = nitrogen; N_2O = nitrous oxide; NH_3 = ammonia; NH_4^+ = ammonium; NO_3^- = nitrate

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hibitors, which these authors reported reduced N_2O emissions by 31%. However, stabilized N sources had unexpected relationships with crop N recovery or with NO_3^- leaching. Omonode et al. (2017) reported that reductions in N_2O emissions did not correspond with increases in crop N recovery. Eagle et al. (2017) reported that NO_3^- leaching did not respond to applications of nitrification inhibitors. Both of these findings are a concern since reductions in N_2O emission may come at the expense of other loss pathways that can limit yields. Since these papers did not assess effects of stabilized N sources on yield or NH_3 volatilization, these findings led to the following research questions:

1. In other recent reviews, do stabilized N sources consistently reduce direct N_2O emissions?
2. What are the effects of stabilized sources of N on yield, NO_3^- leaching, and NH_3 volatilization?

Do stabilized N sources consistently reduce N_2O emissions?

In 2017, Snyder published a paper reviewing recent meta-analyses examining the impact of stabilized N sources on crop yield, NO_3^- leaching, NH_3 volatilization, and/or N_2O emissions (**Table 2**). Nitrification inhibitors alone or combined with urease inhibitors consistently reduced N_2O emissions, with the average effects ranging from 8 to 100% (Snyder et al., 2009; Thapa et al., 2016; Lam et al., 2017; Qiao et al., 2015; Li et al., 2018). One of these studies reported that nitrification inhibitors reduced N_2O emissions across different land uses, climatic conditions, and for a range of soil texture and pH (Li et al., 2018). These findings were supported by a second meta-analysis, which reported that these effects were consistent for nitrification inhibitors combined with urease inhibitors for corn and wheat; across a range of soil pH and texture; under rain-fed or irrigated conditions; when broadcasted or banded; and under tilled and no-tilled conditions (Thapa et al., 2016). However, when applied alone, urease inhibitors were not always effective at reducing N_2O emissions (Akiyama et al., 2010; Thapa et al., 2016; Li et al., 2018). Urea treated with urease inhibitors was more effective at reducing N_2O emissions re-

Table 2. Recently reported effects of urease and nitrification inhibitors on crop yield, NO_3^- leaching, NH_3 volatilization, and N_2O emissions (Snyder, 2017). Negative values indicate a reduction in yield or increase in N loss relative to conventional N source.

		Range or average effect of stabilized N versus reference conventional N source			
Stabilizer or mode of action	Review or meta-analysis	Crop yield increase	Reduction in NO_3^- leaching	Reduction in NH_3 volatilization	Reduction in N_2O emission
Nitrification inhibitor	Quemada et al., 2013	3%	17%		
	Abalos et al., 2014	4.5%			
	Linquist et al., 2013	7%			
	Thapa et al., 2016	7%			38%
	Qiao et al., 2015	5 to 14%	48%	-20%	44%
	Snyder et al., 2009				19 to 100%
	Lam et al., 2017			-3 to -65%	8 to 57%
	Pan et al., 2016			-38%	
	Burzaco et al., 2014	2%			
	Li et al., 2018	5%	44%	-18%	57%
Urease inhibitor	Thapa et al., 2016	2%			
	Linquist et al., 2013	5%			
	Abalos et al., 2014	10%			
	Saggar et al., 2013			25 to 100%	
	Snyder et al., 2009				0 to 5%
	Pan et al., 2016			54%	
	Li et al., 2018	6%	39%	63%	21%
Urease plus nitrification inhibitors	Thapa et al., 2016	0%			30 to 34%
	Linquist et al., 2013	3%			
	Abalos et al., 2014	9%			
	Snyder et al., 2009				37 to 46%
	Li et al., 2018	5%	29%	53%	49%

Surface broadcast urea granule in No-till crop residue.

lated to untreated urea in coarse-textured soils, under split application of fertilizers, and irrigated conditions (Thapa et al., 2016), as well as neutral or alkaline soils, and subsurface placement (Li et al., 2018).

How do these inhibitors impact yield, NO_3^- leaching, or NH_3 volatilization?

Several meta-analyses agree that stabilized N sources contribute to modest increases in crop yield, as well as sizeable, but variable, reductions in specific environmental N loss pathways. However, it is increasingly apparent that yield increases and reductions in N losses are site-specific. Yield increases are also not expected if the N rate does not limit yields. For instance, Abalos et al. (2014) reported that yields and N use efficiencies increased when applying stabilized N. However, enhancements in productivity were greater at high N rates and for acidic soils, coarser soils, and irrigated conditions. In the following section, we summarize the findings of the impact of specific modes of actions on yield, NO_3^- leaching, and NH_3 volatilization.

Nitrification Inhibitors

The impact of nitrification inhibitors on yields were consistently positive but small (<10%) (Linquist et al., 2013; Thapa et al., 2016; Burzaco et al., 2014; Qiao et al., 2015). Burzaco et al. (2014) reported that nitrification inhibitors improved yields with a 56% probability, which was not necessarily due to increased uptake efficiencies. Fertilizer management, water management, and soil type can also influence their effectiveness. For instance, nitrification inhibitors were more beneficial for cereal production in neutral to alkaline soils, fine or coarse soil, broadcast or split applied, and under irrigated conditions (Thapa et al., 2016) and in alkaline soils or when applied in advance of permanent flooding for rice (Linquist et al., 2013). Nitrification inhibitors also reduced NO_3^- leaching by 48%, decreased total N losses by 16%, and increased plant N recovery by 58% (Qiao et al., 2015). In irrigated systems, nitrification inhibitors reduced leaching losses by 19% but did not consistently increase yields (Quemada et al., 2013). Nitrification inhibitors mitigated losses due to NO_3^- leaching in both grassland and dryland systems, across a precipitation gradient, and for a range of soil properties according to one meta-analysis (Li et al., 2018). However, Eagle et al. (2017) found no evidence that nitrification inhibitors reduced NO_3^- leaching based on

TAKE IT TO THE FIELD

Stabilized N sources reduce N_2O emissions across a range of soils and fertilizer management. These inhibitors result in modest yield gains, but effectiveness depends on soil and management factors. Urease and nitrification inhibitors have different modes of action, which make urease inhibitors effective at reducing ammonia volatilization and nitrification inhibitors effective at decreasing NO_3^- leaching.

data provided in four studies conducted in Midwestern corn systems.

There is also a potential tradeoff between N_2O emissions and NH_3 volatilization when applying nitrification inhibitors. In a review of six studies, Lam et al. (2017) reported that NH_3 volatilization often increased with the application of nitrification inhibitors, coinciding with consistent decreases in N_2O emissions (Qiao et al., 2015; Pan et al., 2016; Li et al., 2018). Therefore, unless ammonia volatilization is mitigated by deep subsurface placement, combining a urease inhibitor with a nitrification inhibitor may offset ammonia losses associated with the nitrification inhibitors.

Urease Inhibitors with or without Nitrification Inhibitors

Like nitrification inhibitors, urease inhibitors can be effective at increasing yields, but these effects are often also small and variable (Thapa et al., 2016; Linquist et al., 2013; Abalos et al., 2014). Unlike nitrification inhibitors, urease inhibitors are highly effective at reducing NH_3 volatilization (Saggar et al.,2013; Pan et al., 2016). Pan et al. (2016) reported that urease inhibitors decreased NH_3 emissions by 54%, whereas Saggar et al. (2013) reported decreases of 45%. Urease inhibitors mitigated NH_3 volatilization across a range of soil types and pH, land use, and annual precipitation gradient (Li et al., 2018). Urease inhibitors can also benefit rice systems particularly when N fertilizers are applied well in advance of permanent flooding (Linquist et al., 2013). However, high soil carbon content and temperatures can reduce the efficacy of urease inhibitors (Saggar et al., 2013).

Little is known about the effect of urease inhibitors on NO_3^- leaching, and therefore its effect is currently inconclusive. A recent study analyzed the results of three studies with only five observations (Li et al., 2018). Urease inhibitors reduced NO_3^- leaching by 39% on average, but its effect was highly variable and therefore not significant.

When combined, urease inhibitors plus nitrification inhibitors can increase yields but effects are also small and variable (Thapa et al., 2016; Abalos et al, 2014; and Linquist et al., 2013; Li et al., 2018). The combination of inhibitors can be more beneficial for neutral to alkaline soils, medium to coarse soil, and under irrigated conditions (Thapa et al., 2016). Li et al. (2018) reported that double inhibitors can reduce both N_2O and NH_3 emissions, but were ineffective at combatting NO_3^- leaching in a handful of observations for dryland systems. However, Snyder's (2017) review exposes the challenges of reporting data from studies measuring multiple N loss pathways, and there is no consensus due to lack of data whether combining urease and nitrification inhibitors can simultaneously decrease N_2O emission, NH_3 volatilization, and leaching losses (Snyder, 2017).

The lack of such critical data makes assessments of trade-offs among pathways difficult under site-specific conditions. If the quantities of N losses are not known, Snyder (2017) recommends the adoption of stabilized N sources should depend on:

- Current cropping system management abilities
- Agronomic and environmental knowledge of crop adviser or nutrient manager
- Crop and fertilizer economics
- Compatibility of current soil and water conservation practices
- Availability of nutrient management technology
- Risks and magnitude of dominant N loss pathway(s)
- Regulatory policies
- Trends in N use efficiency over time

These considerations recognize the agronomic, economic, social, and environmental goals must be simultaneously assessed for effective N_2O emission mitigation using stabilized N sources. **BC**

Part 1: *Can Lower Nitrogen Balances and Greater Recovery by Corn Reduce N_2O Emissions?* is available at https://doi.org/10.24047/BC102227

Part 2: *Effects of 4R Management, Climate, and Soil Variables on Nitrogen Losses* is available at https://doi.org/10.24047/BC102315

Dr. McCellan Maaz (e-mail: tmaaz@ipni.net) is director of the IPNI Nitrogen Program based in Peachtree Corners, GA, USA; Dr. Snyder is a former (retired) IPNI Director.

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