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A meta-evaluation of nitrapyrin agronomic and environmental effectiveness with emphasis on corn production in the Midwestern USA

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Abstract

The effectiveness of nitrification inhibitors for abatement of N loss from the agroecosystem is difficult to measure at typical agronomic scales, since performance varies at the research-field scale due to complex interactions among crop management, soil properties, length of the trial, and environmental factors. The environmental impact of the nitrification inhibitor nitrapyrin on N losses from agronomic ecosystems was considered with emphasis on the Midwestern USA. A meta-evaluation approach considered the integrated responses to nitrification inhibition found across research trials conducted in diverse environments over many years as measured in side-by-side comparisons of fertilizer N or manure applied with and without nitrapyrin. The resulting distributions of response indices were evaluated with respect to the magnitude and variance of the agronomic and environmental effects that may be achieved when nitrification inhibitors are used regionally over time. The indices considered (1) crop yield, (2) annual or season-long maintenance of inorganic N within the crop root zone, (3) NO_3-N leached past the crop root zone, and (4) greenhouse gas emission from soil. Results showed that on average, the crop yield increased (relative to N fertilization without nitrapyrin) 7% and soil N retention increased by 28%, while N leaching decreased by 16% and greenhouse gas emissions decreased by 51%. In more than 75% of individual comparisons, use of a nitrification inhibitor increased soil N retention and crop yield, and decreased N leaching and volatilization. The potential of nitrification inhibitors for reducing N loss needs to be considered at the scale of a sensitive region, such as a watershed, over a prolonged period of use as well as within the context of overall goals for abatement of N losses from the agroecosystem to the environment.

Introduction

The use of nitrification inhibitors is an established agronomic practice for conservation of fertilizer nitrogen in the root zone where it may be utilized by a crop. A side effect of this practice is environmental protection afforded by the reduction of N loss from the agroecosystem. A substantial amount of literature details the environmental and agronomic performance of nitrification inhibitors when used in combination with N fertilizer or manure (see Meisinger et al. 1980; Wolt 2000). Even though most published data focuses on nitrification inhibition as a crop production tool (see, for instance, Meisinger et al. 1980), this same body of information provides considerable insight as to N stabilization through application of nitrification inhibitors, with the consequences of altered movement of N from the root zone by either leaching or volatilization.

Nitrification inhibitor performance and variability in response

As with any technology aimed at nutrient management, nitrification inhibitor performance in reducing N losses through leaching or volatilization will be variable at the field level due to complex interactions among crop management, soil, and environmental factors. The microbial ecology of bacterial nitrifiers is considerably influenced by multiple factors that confound interpretations of nitrification inhibitor performance (Keeney 1980). The persistence and activity of nitrification inhibitors in the soil will also be affected by many of these same factors (Touchton et al. 1978b; Wolt 2000). Thus, the year-to-year performance of a nitrification inhibitor in a given field or research plot may vary, even though the performance attributes of the nitrification inhibitor may be evident when considered across a larger region, such as a watershed or ecoregion, over time.

Nitrification inhibitors have been shown under a variety of field and laboratory conditions to reduce nitrate-N leaching as compared to fertilizer-only treatments (Wolt 2000). Reduced leaching is achieved when nitrification inhibition in the crop root zone allows for N to be retained in the upper soil profile and utilized by the crop. This effect is best documented in long-term lysimeter studies where annual reduction in N loss is observed. For instance, Owens (1987) showed that with 6 years continuous use of the nitrification inhibitor nitrapyrin for corn production in Ohio, USA, cumulative N leaching was reduced an average of 20% in comparison to fertilizer application without a nitrification inhibitor. Similar effects have been shown in other environments (Yadav 1997; Randall 2000), but in contrast there are instances where a variable benefit of nitrification inhibition is observed (see, for example, Timmons 1984).

The greenhouse gas nitrous oxide is produced in soils during both nitrification of ammonium-N and denitrification of nitrate-N, with the greater level being produced by denitrification. Accelerated nitrous oxide fluxes from annual cropping systems are likely a consequence of high N availability (Robertson et al. 2000). There appears to be a direct effect of nitrification inhibitors on reducing nitrous oxide produced during nitrification, while the effect on denitrification appears to be indirect from lower soil nitrate levels. Bronson and Mosier (1993) reported that nitrification inhibitors applied with N fertilizer decreased nitrous oxide emissions by 43 to 71% when periodic measurements were taken from time of fertilization to harvest in a field trial of irrigated corn. In addition to the effect on nitrous oxide loss from soil, there is some evidence to indicate that nitrification inhibitors also reduce the efflux of methane from soil, perhaps through an indirect effect on methanotroph ecology (Arif et al. 1996). The environmental benefit of reduced greenhouse gas emissions may be offset by efflux of acid-forming NH_3 in situations where nitrification inhibitor use occurs in conjunction with surface-applied urea or ammonium fertilizers in warm, moist soils (Harrison and Webb 2001).

Nitrification inhibitor performance in soils is most effective and consistent when conditions favor slower biological degradation of the inhibitor and reduced Nitroso-group bacterial activity. Thus, optimal performance is more common with late fall or early spring application when soil temperatures are low. These periods are associated with increased groundwater recharge and runoff in continental temperate climates due to lower evapotranspiration and seasonal precipitation patterns. As a consequence of the temperature effect, historical nitrification inhibitor performance has generally been best in the upper Midwestern USA as compared to more southerly climates. Nitrification inhibitor performance is best established for corn, since this crop has an especially high N requirement and is frequently grown on soils with high N-loss potential, namely, poorly drained soils, tile-drained soils, and irrigated sandy soils. The efficacy and environmental effects of nitrification inhibition are best documented for the intense corn production region of the upper Midwest. The greatest environmental benefits of nitrification inhibitors normally occur when used with rates of N fertilization that are well matched to crop N demand (Wolt 2000); therefore, nitrification inhibitor use is compatible with other nutrient management technologies that improve N-use efficiency.

Meta-effects evaluation of nitrification inhibitor performance

The published literature regarding nitrification inhibitor performance in the field focuses nearly exclusively on the effects achieved at the research scale; that is, individually, the data reflect performance at the field or research-plot scale and over typical time spans of one to three years. In contrast, any environmental effect of nitrification inhibition on N loss will be of consequence at the scale of a vulnerable watershed or larger over a period of many years. Crop × environment × management factors contribute to variability at the field scale that lends uncertainty to the annual realization of microeconomic benefits from nitrification inhibitors when used for yield enhancement (Nelson and Huber 1980), even though there may be societal benefits of nitrification inhibitor use over broader scales of space and time for reduction of N loss from agroecosystems to the environment. The research reported herein considers comprehensively the environmental effect of nitrification inhibition using a meta-evaluation approach that probabilistically treats the distribution in outcomes found across studies conducted in diverse environments over many years. The meta-evalution approach entails integrated description of heterogeneous data. In the present case, data from short-duration agronomic trails conducted under diverse conditions were integrated to allow for a generalized assessment of agronomic and environmental effectiveness. Such an approach provides insight in to the environmental benefit that may be achieved when nitrification inhibition is used regionally over time. Data detailing the effectiveness of the product nitrapyrin [2-chloro-6-(trichloro-methyl)pyridine] are considered here, since this product has been used for nitrification inhibition in the intense corn production regions of the Midwestern USA for over 25 years and its efficacy in controlling N loss is well documented in the published literature.

Methods

A detailed review of published literature was conducted to identify research trials where indices of effectiveness of nitrification inhibition were measured in side-by-side comparisons of N fertilizer or manure with and without added nitrapyrin. The indices selected for consideration were (1) grain yield (indicative of N availability and retention in the crop root zone), (2) annual or season-long maintenance of inorganic N (typically, NH_4-N plus NO_3-N) within the crop root zone, (3) N leached past the crop root zone, and (4) gaseous flux (typically N_2O volatilization) from soil.

For those trials where relevant data were identified, the relative effect of nitrapyrin was calculated as the difference in effect observed for the comparable treatment without nitrapyrin, expressed as a percentage of the effect without nitrapyrin [(effect with nitrapyrin – effect without nitrapyrin) × 100/effect without nitrapyrin], for a given location and year. When the study design involved multiple comparisons, such as the effect of nitrapyrin over a range of N levels or N sources, the average effect across these treatments was determined. The intention of this analysis is to consider the effects of nitrification inhibition that may be expected with typical grower practice; therefore, control treatments receiving no N or treatments using N fertilization rates well in excess of crop N demand were typically not considered. Treatments using nitrapyrin well in excess of the maximum recommended use rate (1.12 kg ai ha^{-1}; Dow AgroSciences 1999) were also excluded from consideration.

For many of the studies reported, the original results were summarized in figures. In these instances, the relevant information for comparisons of nitrapyrin effect were translated from graphical to tabular form by scanning the figures and extracting the data using UnGraph version 4.0 (BIOSOFT, Cambridge, UK).

The data from the literature were used to develop a statistical distribution of relative effect of nitrapyrin on the indices of interest, from which the grand mean and standard error in response across studies were developed and probabilities of nitrification inhibitor effectiveness were determined.

Results

Grain yield

The database developed describing the effect of nitrapyrin on grain yield consists of 189 observations comprising 437 mean comparisons across 158 location–years of experiments (Table 1). The preponderance of data are for field corn yield, but yields of wheat, grain sorghum, and sweet corn are also included. These data reflect studies conducted principally in the Midwestern USA, but also include results from transitional climate zones in the Southeastern USA and from Europe. The distribution in mean response for a given yield comparison ranges from −20.1 to 60.9%, with 141 of 189 observations showing a positive effect of nitrapyrin on yield (Figure 1). The grand mean (± standard error of the mean) effect represents a relative yield increase from nitrapyrin of 7.0% (± 0.8%). Although the data describing the effect of nitrapyrin on yield do not de-

Table 1. Relative crop yield from nitrapyrin when applied with sources of fertilizer or manurial N.

Relative effect (%)[a]	Identity	Nitrogen fertilization practice					Soil (subgroup)	Reference
		Crop	Time	Method	Rate (kg ha^{-1})	Form[b]		
3.0	Ames IA 1982	Corn	Spring	Inject	112, 224	AA	Nicollet (Aquic Hapludolls) and Webster (Typic Hapludolls)	Blackmer and Sanchez 1988
0.0	Ames IA 1983							
5.1	Ames IA 1984							
1.9	Nashua IA 1982						Readlyn (fAquic Hapludolls)	
− 20.1	Nashua IA 1983							
0.3	Nashua IA 1984							
1.9	Ames #1 IA 1985	Corn	Spring	Incorp	56, 112, 168	AS	Nicollett (Aquic Hapludolls)	Cerrato and Blackmer 1990
1.7	Ames #1 IA 1986							
− 5.1	Ames #1 IA 1987							
5.2	Ames #2 IA 1985						Canisteo (Typic Haplaquolls)	
5.5	Ames #2 IA 1986							
4.9	Ames #2 IA 1987							
− 7.9	Holestein IA 1986						Galva (Typic Hapludolls)	
− 0.5	Holestein IA 1987							
− 2.0	Ida Grove IA 1986						Marshall (Typic Hapludols)	
− 7.7	Ida Grove IA 1987							
0.3	Iowa City IA 1985						Mahaska (Aquic Agriudolls)	
5.0	Kalona IA 1985						Bremer (Typic Agriaquolls)	
− 1.4	Kalona IA 1986							
8.2	Kalona IA 1987							
0.7	Marengo IA 1985						Nevin (Aquic Agriudolls)	
− 3.9	Marengo IA 1986							
− 4.8	Marengo IA 1997							
− 1.2	Williamsburg IA 1985						Mahaska (Aquic Agriudolls)	
11.3	Bath Co. KY 1976	Corn	Spring	Surface	85, 170	AN	Lowell silt loam (Typic Hapludafls)	Frye et al. 1981
19.6	Lee Co. KY 1978				85, 170		Monongahela silt loam (Typic Paleudalfs)	
11.8	Lewis Co. KY 1977				85		Cavode silt loam (Aeric Ochraquults)	
17.4	Princeton KY 1974				140		Tilsit silt loam – Johnsburg silt loam intergrade (Typic Fragiudults)	
21.8	Princeton KY 1975				140			
42.4	Princeton KY 1976				110			
7.9	Princeton KY 1977				90, 135, 180			
− 4.6	Princeton KY 1978				90, 135, 180			
22.8	Buffalo ND 1997	Wheat	Fall	Inject	84	AA	Gardena loam (Pachic Hapludolls)	Goos and Johnson 1999
5.3	Knox Co. IN 1974	Wheat	Fall	Surface	44, 88	Urea	Patton silty clay loam (Typic Haplaquolls)	Huber et al. 1980
4.7	Knox Co. IN 1975		Fall	Surface		Urea	Alford silty loam (Typic Hapluafs)	
0.0	Knox Co. IN 1977		Fall	Inject		AA		

Table 1. (Continued).

Relative effect (%)[a]	Identity	Nitrogen fertilization practice					Soil (subgroup)	Reference
		Crop	Time	Method	Rate (kg ha^{-1})	Form[b]		
8.2	LaGrange Co. IN 1973		Fall	Inject, surface		AA, Urea		
17.6	LaGrange Co. IN 1973		Fall, spring	Surface		Urea	Elston sandy loam (Typic Agriudolls)	
16.1	LaGrange Co. IN 1977		Fall	Inject, surface		AA, Urea	Ockley silty loam (Typic Haplualfs)	
17.5	Sullivan Co. IN 1973		Fall	Surface		Urea, AS, CN	Elston sandy loam (Typic Agriudolls)	
1.5	Sullivan Co. IN 1973		Fall, spring	Surface		Urea, AS, CN		
20.0	Sullivan Co. IN 1974		Fall	Surface		AS, CN	Patton silty clay loam (Typic Haplaquolls)	
21.5	Sullivan Co. IN 1975		Fall	Surface		AS, CN		
8.4	Sullivan Co. #2 IN 1975		Fall	Surface		AS, CN	Elston sandy loam (Typic Agriudolls)	
44.4	Sullivan Co. IN 1976		Fall	Surface		AS	Patton silty clay loam (Typic Haplaquolls)	
11.2	Sullivan Co. IN 1976		Fall, spring	Surface		AS		
7.2	Buttlerville IN 1992	Corn	Spring	Inject	67, 174, 280	AA	Silty clay loam	Huber et al. 1993
6.6	Buttlerville IN 1992				67, 174, 280	SM		
2.8	Lafayette IN 1992				84, 168	AA	Silt loam	
6.0	Lafayette IN 1992				84, 168	SM		
1.8	Pinney #3 IN 1992				112, 224	AA	Tracy sandy loam (Ultic Hapludalfs)	
4.1	Pinney #3 IN 1992				112, 224	SM		
7.3	Vincennes IN 1992				67, 123	SM	Fine sandy loam	
3.0	Brookston OH	Corn	Fall	Inject	90, 112	AA, UAN	Brookston silty clay loam (Typic Agriaquolls)	Johnson 1995
7.5	Brookston OH		Spring		90, 112			
10.7	Crosby OH		Fall		112, 180		Crosby silt loam (Aeric Epiaqualfs)	
7.2	Crosby OH		Spring		112, 180			
3.1	Hoytville OH		Fall		180		Hoytville silty clay loam (Mollic Epiaqualfs)	
3.8	Hoytville OH		Spring		180			
− 2.2	Scioto OH 1994	Corn	Spring	Inject	134	AA, UAN	Kokomo silty clay loam (Typic Argiaquolls)	Johnson 1997
8.7	Scioto OH 1995							
8.4	Scioto OH 1996							
17.6	Germany 1977-81	Various	Fall	NR	65 − 338	Urea	Sand-Rosterden	Katzur et al. 1984
5.6	Germany 1977-81		Fall, spring		65 − 338			
12.9	Germany 1977-81		Spring		65 − 338			
15.3	Germany 1982-87		Fall		108 − 280			
21.6	Germany 1982-87		Fall, spring		108 − 280			
− 0.2	Belleville IL 1977	Wheat	Fall	Incorporate	45, 90, 135	Urea	Weir silt loam (Typic Orchaqualfs)	Liu et al. 1984

Table 1. (Continued).

Relative effect (%)[a]	Identity	Nitrogen fertilization practice					Soil (subgroup)	Reference
		Crop	Time	Method	Rate (kg ha^{-1})	Form[b]		
3.3	Belleville IL 1977			Incorporate	45, 90, 135	UAN		
7.0	Belleville IL 1977			Inject	45, 90, 135	AA		
12.5	Belleville IL 1979			Incorporate	45, 90, 135	Urea		
3.4	Belleville IL 1979			Incorporate	45, 90, 135	UAN		
23.0	Belleville IL 1979			Inject	45, 90, 135	AA		
5.4	Carbondale IL 1977			Incorporate	45, 90, 135	Urea	Stoy silt loam (Aquic Hapludalfs)	
1.7	Carbondale IL 1977			Incorporate	45, 90, 135	UAN		
0.5	Carbondale IL 1977			Inject	45, 90, 135	AA		
18.1	Carbondale IL 1979			Incorporate	45, 90, 135	Urea		
23.5	Carbondale IL 1979			Incorporate	45, 90, 135	UAN		
23.0	Carbondale IL 1979			Inject	45, 90, 135	AA		
4.0	Carbondale IL 1980			Incorporate	50, 100, 150	Urea		
− 1.6	Rossville KS 1978	Corn	Spring	Inject	84, 168, 252	AA	Eudora fine sandy loam (Fleuventic Hapluquolls)	Maddux et al. 1985
0.1	Rossville KS 1979		Fall, spring		84, 168			
− 1.6	Rossville KS 1979 #III		Spring		84, 168			
− 3.4	Scandia KS 1979		Fall, spring		84, 168		Crete silty loam (Pachic Argiustolls)	
10.1	St John KS 1979		Fall, spring		84, 168		Pratt loamy fine sand (Psammentic Haplustalfs)	
9.1	Becker MN	Corn	Spring	Incorporate	134	Urea, UAN	Hubbard lomy coarse sand (Udorthentic Haploborolls)	Malzer 1989
− 4.5	IA 1987		Spring	Inject	157	AA, Urea	Webster clay loam (Typic Hapudolls)	
− 3.9	MN 1982		Fall, Spring	Inject	134	AA		
− 0.5	MN #2 1982		Spring	Inject, Incorp	157 − 168	AA, UAN, Urea	Coarse-textured soil	
26.7	MN 1982,83		Spring	Inject, Incorp	157 − 168	AA, UAN, Urea		
0.0	MN 1983		Spring	Inject	134	AA	Webster clay loam (Typic Hapudolls)	
1.3	MN 1985, 86, 87		Spring	Inject, Incorp	157 − 168	AA, UAN, Urea	Coarse-textured soil	
20.0	Northern IL 1983		Spring	Inject, Incorp	NR	SM	Derinda silt loam (Oxyaquic Hapludalfs)	
10.5	Northern IL 1984		Spring	Inject, Incorp	NR	SM		
− 0.1	Northern IL 1985		Spring	Inject, Incorp	NR	SM		

Table 1. (Continued).

Relative effect (%)[a]	Identity	Nitrogen fertilization practice					Soil (subgroup)	Reference
		Crop	Time	Method	Rate (kg ha^{-1})	Form[b]		
7.5	Northern IL 1986		Spring	Inject, Incorp	NR	SM		
1.4	WI 1984, 85, 86		Spring	Inject, Incorp	157 − 168	AA, UAN, Urea	Coarse-textured soil	
− 0.3	WI 1987		Spring	Inject, Incorp	134	AA, UAN, Urea		
23.5	Becker MN		Spring	Incorp	134	Urea	Hubbard loamy coarse sand (Udorthentic Haploborolls)	
15.2	Becker MN		Spring	Incorp	134	UAN		
3.7	West Lafayette IN 1978	Corn	Spring	Inject	154, 345	SM	Chalmers silty clay loam (Typic Haplaquolls)	McCormick et al. 1984
60.0	West Lafayette IN 1979		Fall		75, 144	SM		
1.7	West Lafayette IN 1979		Fall		168	AA		
− 4.3	West Lafayette IN 1979		Spring		161	SM		
− 0.9	West Lafayette IN 1979		Spring		168	AA		
27.9	West Lafayette IN 1980		Fall		104, 166	SM		
1.4	West Lafayette IN 1980		Fall		168	AA		
12.7	West Lafayette IN 1980		Spring		159, 286	SM		
11.5	West Lafayette IN 1980		Spring		168	AA		
15.6	GA 1978	Sweet corn	Spring	Surface	40	AS + CN	Cecil clay loam	McElhannon and Mills 1981
19.9	GA 1979							
3.2	Marna G MN	Corn	Fall, spring	Inject	170, 340	SM	Marna silty clay loam (Typic Hapludolls)	Randall et al. 1999
7.9	Nicollet A MN				64, 127	DM	Nicollet clay loam (Aquic Halludolls)	
0.9	Nicollet C MN				59, 118	DM		
7.3	Nicollet E MN				113, 226	SM		
− 2.6	Nicollet F MN				215, 431	SM		
3.4	Port Bryan B MN				59, 118	DM	Port Bryan silt loam (Typic Hapludolls)	
0.5	Webster D MN				66, 133	DM	Webster clay loam (Typic Endoaquolls)	
23.9	El Reno OK 1991-94	Wheat	Fall	Surface	60	Urea	Renfrow silt loam, pH 4.8, 1% OC	Rao 1996
1.6	El Reno OK 1991-94			Incorporate				

Table 1. (Continued).

Relative effect (%)[a]	Identity	Nitrogen fertilization practice					Soil (subgroup)	Reference
		Crop	Time	Method	Rate (kg ha^{-1})	Form[b]		
6.8	Hamerly A MN 1992	Corn	Spring	Inject	93	DM	Hamerly clay loam (Aeric Calciaquolls)	Schmitt et al. 1995
19.4	Maxcreek C MN 1992				69	DM	Maxcreek silty clay loam (Typic Endoaquolls)	
− 3.5	Maxfield D MN 1992				119	DM	Maxfield silty clay loam (Typic Endoaquolls)	
− 2.7	Maxfield F MN 1993				129	SM		
− 5.8	Racine B MN 1992				106	SM	Racine silt loam (Mollic Hapludalfs)	
6.5	Schley G MN 1993				80	SM	Schley silt loam (Udollic Ochraqualfs)	
4.1	Webster E MN 1993				63	SM	Webster clay loam (Typic Haplaquolls)	
2.0	Springfield OH 1978	Corn	Fall	Inject	90, 180	AA	Crosby silt loam(Aeric Epiaqualfs)	Stehouwer and Johnson 1990
3.5	Springfield OH 1978		Spring					
16.1	Springfield OH 1979		Fall					
− 2.4	Springfield OH 1979		Spring					
22.2	Springfield OH 1980		Fall					
0.6	Springfield OH 1980		Spring					
5.4	Springfield OH 1981		Fall					
14.1	Springfield OH 1981		Spring					
− 0.8	Springfield OH 1982		Fall					
12.5	Springfield OH 1982		Spring					
3.9	Springfield OH 1983		Spring					
2.2	Springfield OH 1983		Spring					
0.0	Springfield OH 1984		Fall					
− 0.7	Springfield OH 1984		Spring					
8.2	Springfield OH 1985		Fall					
− 5.6	Springfield OH 1985		Spring					
6.5	Crawfordsville IN 1982	Corn	Spring	Inject	238	AA + SM	Odell silt loam (Aquic Agridolls)	Sutton et al. 1985, 1986
5.9	Crawfordsville IN 1982		Winter		211			
5.1	Crawfordsville IN 1983		Late fall		193			
11.7	Crawfordsville IN 1983		Spring		122			
5.4	Crawfordsville IN 1984		Late fall		214			
− 0.6	Crawfordsville IN 1984		Spring		271			
0.0	Brownstown IL 1976	Corn	Fall	Inject	67, 134	AA	Cisne silt loam (Mollic Albaqualfs)	Touchton et al. 1979a
− 0.1	Brownstown IL 1976		Spring					
14.6	Urbana IL #2 1976	Corn	Fall	Incorp	67, 134	Urea	Flanagan silt loam (Typic Hapludolls)	Touchton et al. 1979b

Table 1. (Continued).

Relative effect (%)^{a}	Identity	Nitrogen fertilization practice					Soil (subgroup)	Reference
		Crop	Time	Method	Rate (kg ha^{-1})	Form^{b}		
− 2.0	Urbana IL 1975		Spring	Inject	67, 134, 268	AA	Drummer clay loam (Typic Haplaquolls)	
− 12.1	Urbana IL 1976		Fall	Inject	67, 134, 268	AA		
3.6	Urbana IL 1976		Spring	Inject	67, 134, 268	AA		
− 0.1	Bonanza Farm MN 1980	Corn	Spring	Incorp	90, 180	Urea	Estherville sandy loam (Typic Hapludolls)	Walters and Malzer 1990a
1.5	Bonanza Farm MN 1981							
2.2	Bonanza Farm MN 1982							
206.9	Sullivan Co. #1 IN 1973	Corn	Late fall	Inject	134	AA	Kings silty clay (Vertic Endoaquolls)	Warren et al. 1975
1.3	Sullivan Co. #2 IN 1973				200		Elston fine sandy loam (Typic Agriudolls)	
30.7	Sullivan Co. #2 IN 1974				134, 224			
8.7	Pinney #1 IN	Corn	Fall	Inject	83, 166	AA	Runnymede loam (Typic Argiaguolls)	Warren et al. 1980
0.6	Pinney #1 IN		Spring		83, 166			
18.8	Pinney #2 IN		Fall		83, 166		Tracy sandy loam (Ultic Hapludalfs)	
1.7	Pinney #2 IN		Spring		83, 166			
9.8	West Lafayette IN		Fall		66, 132		Chalmers silty clay loam (Typic Haplaquolls)	
− 1.0	West Lafayette IN		Spring		66. 132			
13.1	Hix IN 1982	Corn	Spring	Inject	175	DM	Blount clay (Aeric Ochraqualfs)	Welty et al. 1986
2.1	Hix IN 1983				143			
21.5	Hix IN 1984				349			
− 16.8	Jackson IN 1982				349			
60.9	Jackson IN 1983				349			
25.4	Jackson IN 1984				349			
− 0.3	Altus OK 1976	Grain sorghum	Late spring	Inject, Incorp	45, 90, 180	AA, Urea	Holister clay loam (Pachic Paleustolls)	Westerman et al. 1981
− 0.8	Altus OK 1978				67, 134, 201	UAN		
8.4	Altus OK 1979							
− 1.6	Haskell OK 1979						Taloka silt loam (Mollic Albaqualfs)	
− 7.4	Tipton OK 1977					Urea, UAN	Tipton fine sandy loam (Pachic Agriustolls)	
3.5	Lewisburg TN 1982	Corn	Fall	Surface	376	DM	Huntington silt loam (Fluvaquentic Eutrochrepts)	Wolt 1985
4.1	Lewisburg TN 1982		Spring	Inject	376	DM		
− 3.9	Lewisburg TN 1982		Spring	Incorp	140	AN		
14.5	Lewisburg TN 1983		Fall	Surface	341	DM		
17.4	Lewisburg TN 1983		Spring	Inject	341	DM		
7.4	Lewisburg TN 1983		Spring	Incorp	140	AN		
9.1	Blackville SC 1981	Corn	Spring	Incorp	168	UAN	Varina loamy sand (Plinthic Paleudults)	Zublena 1984

Table 1. (Continued).

Relative effect (%)[a]	Identity	Nitrogen fertilization practice					Soil (subgroup)	Reference
		Crop	Time	Method	Rate (kg ha^{-1})	Form[b]		
6.7	Blackville SC 1982							
4.5	Florence SC 1981						Bonneau sand (Arenic Paleudults)	
− 3.4	Florence SC 1982						Goldsboro loamy sand (Aquic Paleudult)	
3.1	Sumter SC 1981						Dothan sandy loam (Plinthic Paleudults)	
23.0	Sumter SC 1982							

[a] [(effect with nitrapyrin – effect without nitrapyrin) × 100/effect without nitrapyrin]; [b] AA, anhydrous ammonia; AN, ammonium nitrate; AS, ammonium sulfate; CN, calcium nitrate; DM, dairy manure, SM, swine manure; UAN, uryl ammonium nitrate.

scribe an effect on reduced environmental loss of fertilizer N *per se*, they are an integrated measure of N availability during the crop cycle and, therefore, are directionally indicative of N lost from the agroecosystem (increased N availability to the crop represents N which was not lost from the root zone).

Inorganic N in the root zone

In comparison to the database for yield response, that for inorganic N in the root zone is somewhat more limited (50 observations comprising 43 location–years of experimental results reflecting varied annual or season-long sampling strategies; Table 2). Results are also more variable, ranging from − 39.8 to 135.3%. The grand mean (± standard error) effect for nitrapyrin to increase inorganic N retained in the root zone is 28.2% (± 5.4%) relative to N retention in the absence of a nitrification inhibitor (Figure 2). Thirty-nine of 50 observations show a benefit from nitrapyrin in terms of increased year-long or seasonal inorganic N retention in the root zone and, consequently, reduced N loss from agroecosystems. These data largely represent soil N retention during the crop cycle in which nitrapyrin is applied; therefore, they do not indicate the long-term fate of seasonally retained N within the agroecosystem.

N leached from the root zone

The database for N leached from the root zone confirms the trend for nitrapyrin application with fertilizer or manurial N to increase yield and root zone N retention (Table 3). Twenty-four observations comprising 26 location–years of experimental results describe N occurrence in percolates or in soil sampled from below the root zone. As with measurements of inorganic N within the root zone, these data largely reflect the leaching of N that occurs within the crop cycle when a nitrification inhibitor is used. The relative percent N leached when nitrapyrin was used ranges from − 42.6 to 31.7. The grand mean (± standard error) effect is − 15.8% (± 3.8%), indicative of reduced N transport in soil percolates. Nineteen of 24 observations show a benefit from nitrapyrin in terms of decreased year-long or seasonal inorganic N loss out of the root zone (Figure 3).

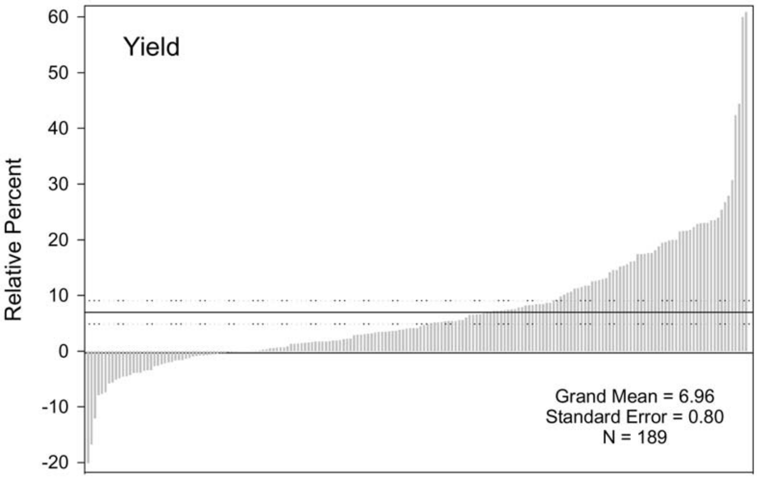

Figure 1. Frequency distributions describing the relative change in crop yield attributable to nitrification inhibition for comparisons of N fertilization with and without nitrapyrin (mean ————; standard error ···············).

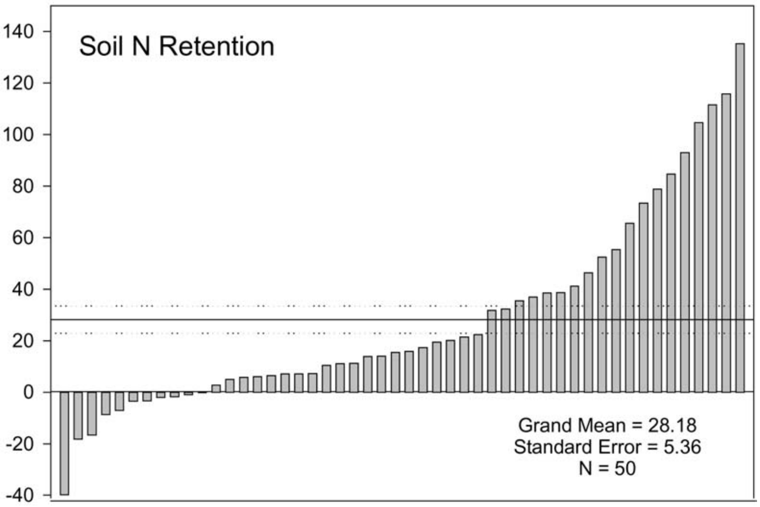

Figure 2. Frequency distributions describing the relative change in root zone N retention attributable to nitrapyrin for comparisons of N fertilization with and without nitrapyrin (mean ————; standard error ···············).

Volatilization of greenhouse gases

A somewhat more limited set of data describes the relative impact of nitrapyrin use on N loss to the atmosphere (Table 4). Nitrapyrin may contribute to reduced emission of gases from agricultural soils through a variety of direct and indirect mechanisms and, therefore, the nature and the particular volatile compound that is considered governs the magnitude of the effect attributed to nitrapyrin. Denitrification losses of N in the form of N_2O are the most directly attributable to inhibition of nitrification, whereas effects on CH_4 emission will be more indirect through shifts in microbial processes in the agroecosystems (13 of the comparisons summarized in Table 4 describe NO_2 efflux and 1 describes CH_4 efflux). In any event, overall these data demonstrate an effect of nitrapyrin to reduce atmospheric emission of greenhouse gases with an overall mean (± standard error) effect of −51.2% (± 4.0%) (Figure 4).

Discussion

A large body of literature describes the performance of nitrification inhibitors in terms of crop response

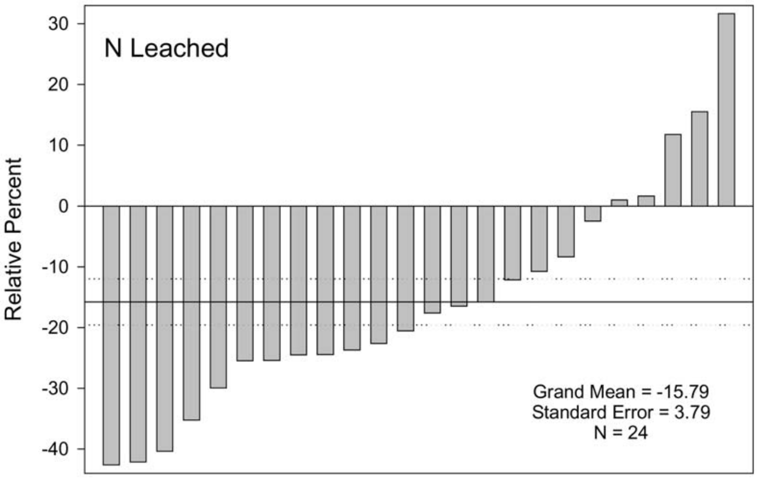

Figure 3. Frequency distributions describing the relative change in N leached from the root zone attributable to nitrapyrin for comparisons of N fertilization with and without nitrapyrin (mean ————; standard error ··············).

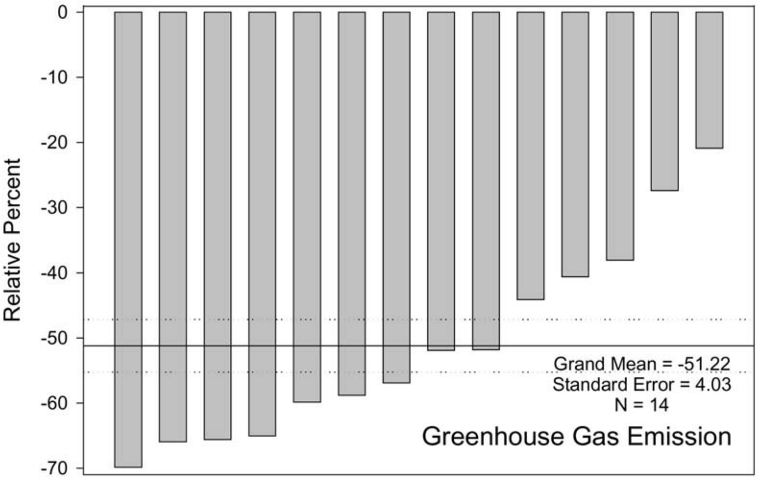

Figure 4. Frequency distributions describing the relative change in greenhouse gas emissions attributable to nitrapyrin for comparisons of N fertilization with and without nitrapyrin (mean ————; standard error ··············).

and N fate within agronomic ecosystems. Considerable variability in response is reported from individual research findings and is anticipated based on the numerous crop, environment, and management factors that in combination contribute variability to the processes whereby N is cycled and utilized within crop production systems. When described in terms of relative responses among diverse experiments, indices of N loss indicate a consistent effect of nitrification inhibitor use in conjunction with N fertilization. The distributions of effects when compared across various indices of N loss (Figure 5) show that for ≥ 75% of the comparisons considered, nitrapyrin increased annual or season-long N retention in the crop root zone, increased crop yield, decreased N leaching from the root zone, and decreased volatilization of greenhouse gases.

On a regional basis over time, factors such as nitrogen fertilization practice (rate, timing, source, placement), soil factors (texture, organic matter content, pH), and environmental conditions (soil cover, temperature, moisture) combine to influence the overall performance of a nitrification inhibitor. The integrated effect of these factors on nitrapyrin performance is represented by the meta-evaluation of diverse studies that in combination describe the anticipated effect of sustained use of nitrification inhibitors in a region over time. The observed variance in

Table 2. Relative amount of inorganic N retained within the crop root zone as affected by nitrapyrin applied with sources of fertilizer or manurial N.

		Nitrogen fertilization practice						
Relative effect (%)[a]	Identity	Crop	Time	Method	Rate (kg ha^{-1})	Form[b]	Soil (subgroup)	Reference
15.8	Marengo IA 1986	Corn	Spring	Incorporate	56, 112, 178	AS	Nevin (Aquic Agriudolls)	Cerrato and Blackmer 1990
− 0.9	Kalona IA 1986						Bremer (Typic Agriaquolls)	
4.9	Ames #1 IA 1986						Nicollett (Aquic Hapludolls)	
5.7	Ames #2 IA 1986						Canisteo (Typic Haplaquolls)	
6.0	Ida Grove IA 1986						Marshall (Typic Hapludols)	
− 1.7	Holestein IA 1986						Galva (Typic Hapludolls)	
21.5	Narrabri #1 NSW	Uncropped	Fall	Incorporate	120	Urea	Fine-textured grey clay (Typic Pellusterts)	Chen et al. 1994
31.8	Narrabri #2 NSW							
84.7	Buffalo ND 1997	Wheat	Fall	Inject	84	AA	Gardena loam (Pachic Hapludolls)	Goos and Johnson 1999
38.7	Fargo ND 1997						Fargo silty clay (Typic Epiaquerts)	
− 2.0	Benerembah NSW	Rice		Incorporate	80	Urea	Grey clay (Typic Pelloxererts)	Keerthisinghe et al. 1993
35.4	Columbia, MO 91	Wheat	Fall	Inject	56, 112	AA	Mexico silt loam (Udollic Ochraqualf)	Kidwaro and Kephart 1998
19.5	Columbia, MO 92							
− 8.7	Bellville IL 1977	Wheat	Fall	Incorporate	152	Urea	Weir silt loam (Typic Orchaqualfs)	Liu et al. 1984
− 18.2						UAN		
115.7	Bellville IL 1979				100, 151	Urea		
78.9						UAN		
17.3	Carbondale IL 1980				112	Urea	Stoy silt loam (Aquic Hapludalfs)	
46.3	Rossville KS 1979 #III	Corn	Spring	Inject	84, 168, 260	AA	Eudora fine sandy loam (Fleuventic Haplu-quolls)	Maddux et al. 1985
111.5	West Lafayette IN 1979	Fallow	Spring	Inject	157	SM	Chalmers silty clay loam (Typic Haplaquolls)	McCormick et al. 1983
− 3.5	Edinburgh UK	Grassland	Spring	Surface	120	AS, Urea	Winton clay loam	McTaggart et al. 1997
38.5	Nicollet A MN	Corn	Fall, spring	Inject	116, 234	DM	Nicollet clay loam (Aquic Hapludolls)	Randall et al. 1999
41.2	Port Bryan B MN				108, 215		Port Bryan silt loam (Typic Hapludolls)	
11.1	Nicollet C MN						Nicollet clay loam (Aquic Halludolls)	
13.8	Webster D MN				121, 241		Webster clay loam (Typic Endoaquolls)	
− 3.5	Nicollet E MN				175, 350	SM	Nicollet clay loam (Aquic Hapludolls)	
15.5	Nicollet F MN				331, 662			
7.2	Marna G MN				262, 524		Marna silty clay loam (Typic Hapludolls)	
135.3	El Reno OK 1991	Wheat	Fall	Surface, incorp.	60	Urea	Renfrow silt loam (Udertic Paleustolls)	Rao 1996
32.3	El Reno OK 1992							
36.9	El Reno OK 1993							
6.5	El Reno OK 1994							
7.1	Northwest IL 1986 #1	Corn	Spring	Inject	302	BM	Derinda silt loam Oxyaquic Hapluafs)	Sawyer et al. 1990
65.6	Northwest IL 1986 #2							
20.1	Crawfordsville IN 1982	Corn	Fall	Inject	235	AA + SM	Odell silt loam (Aquic Agridolls)	Sutton et al. 1986

Table 2. (Continued).

		Nitrogen fertilization practice						
Relative effect (%)[a]	Identity	Crop	Time	Method	Rate (kg ha^{-1})	Form[b]	Soil (subgroup)	Reference
10.4	Crawfordsville IN 1983				228			
22.3	Crawfordsville IN 1983				183			
− 0.2	Crawfordsville IN 1982		Spring		295			
− 16.7	Crawfordsville IN 1983				133			
− 39.8	Crawfordsville IN 1983				239			
55.3	Urbana IL 1975	Corn	Fall	Inject	67, 134	AA	Drummer silty clay loam (Typic Haplaquolls)	Touchton et al. 1978a
93.0	Urbana IL 1976		Spring					
14.0	Urbana IL 1975		Spring					
− 7.1	Brownstown IL 1976		Spring					
73.4			Fall					
11.2	Bonanza Farm MN 1980	Corn	Spring	Incorporate	90, 180	Urea	Estherville sandy loam (Typic Hapludolls)	Walters and Malzer 1990b
104.6	Bonanza Farm MN 1981							
52.4	Altus OK 1976	Grain sorghum	Spring	Incorporate, inject	45, 90, 180	AA	Holister clay loam (Pachic Paleustolls)	Westerman et al. 1981
7.1	Tipton OK 1977				67, 134, 202	Urea, UAN	Tipton fine sandy loam (Pachic Agriustolls)	
2.7	Altus OK 1978					UAN	Holister clay loam (Pachic Paleustolls)	

[a] [(effect with nitrapyrin – effect without nitrapyrin) × 100/effect without nitrapyrin]; [b] AA, anhydrous ammonia; AS, ammonium sulfate; BM, beef manure; DM, dairy manure, SM, swine manure; UAN, uryl ammonium nitrate.

Table 3. Relative quantity of N leached from the crop root zone as affected by nitrapyrin applied with sources of fertilizer or manurial N.

			Nitrogen fertilization practice					
Relative effect (%)[a]	Identity	Crop	Time	Method	Rate (kg ha^{-1})	Form[b]	Soil (subgroup)	Reference
− 20.6	Germany 1977-81	Various	Spring	NR	Various	Urea	Sand-Rosterden	Katzur and Zietz 1984
− 29.9			Fall					
− 17.6			Fall, Spring					
− 22.6	Germany 1982-87	Various	Spring	NR	Various	Urea	Sand-Rosterden	Katzur et al. 1984
− 15.8			Fall					
− 12.1			Fall, Spring					
15.5	Coshocton OH 1977-78	Corn	Spring	Incorporate	300	Urea	Rayne silt loam (Typic Hapludults)	Owens 1987
− 8.4	Coshocton OH 1978-79							
− 16.5	Coshocton OH 1979-80							
− 42.1	Coshocton OH 1980-81							
− 35.3	Coshocton OH 1981-82							
− 24.5	Coshocton OH 1982-83							
− 25.4	Coshocton OH 1983-84	Wheat, rye						
− 40.4	Hurley UK	Perennial ryegrass	Winter	Inject	221	DM	Frilsam loam	Thompson et al. 1987
− 42.6	Huley UK		Spring		234			
− 10.7	Lab column #1	None	N/A	Surface	200	AA	Estherville sandy loam (Typic Hapludolls)	Timmons 1984
31.7	Lab column #2					Urea		
− 23.7	Westport MN 1977	Corn	Spring	Incorporate		Urea		
− 2.5	Westport MN 1978							
11.8	Wesport MN 1979							
1.6	Bonanza Farm MN 1980	Corn	Spring	Incorporate	80 & 160	Urea	Estherville sandy loam (Typic Hapludolls)	Walters and Malzer 1990b
1.0	Bonanza Farm MN 1981							
− 24.5	Olmsted Co. MN	Corn	Various	NR	Various	Various	NR	Yadav 1997
− 25.4	Goodhue Co. MN							

[a] [(effect with nitrapyrin – effect without nitrapyrin) × 100/effect without nitrapyrin]; [b] AA, anhydrous ammonia; DM, dairy manure.

Table 4. Relative amount of greenhouse gas forced from agricultural soils as affected by nitrapyrin applied with sources of fertilizer or manurial N.

Relative effect (%)[a]	Identity	Crop	Nitrogen fertilization practice				Soil (subgroup)	Reference
			Time	Method	Rate (kg ha^{-1})	Form[b]		
− 51.9	Ames IA 1979	Fallow	Fall	Injection	180	AA	Webster clay loam (Typic Haplaquolls)	Bremner et al. 1981
− 59.9	Ames IA 1980		Spring					
− 65.1	Ft Collins CO 1989 #1	Corn	Early summer	Incorporated	195	Urea	Nunn clay loam (Aridic Argiustolls)	Bronson et al. 1992
− 65.6	Ft Collins CO 1989 #2							
− 40.6	Ft Collins CO 1990							
− 27.4	Benerembah NSW	Dry-seeded flooded rice		Incorporated	0 & 71	Urea	Grey clay (Typic Pelloxererts)	Keerthisinghe et al. 1993
− 69.8								
− 56.9	Hurley UK	Perennial ryegrass	Winter	Inject	221	DM	Frilsam loam	Thompson et al. 1987
− 20.9			Spring		234			
− 58.8	Darling Downs QLD 1982 #1	Fallow	Spring	Injection	80	AA	Mywybilla clay (Typic Pellusterts)	Magalhaes et al. 1984
− 66.0	Darling Downs QLD 1982 #2				60		Anchorfield clay (Typic Chromusterts)	
− 51.8	Darling Downs QLD 1982 #3						Norilee clay (Typic Chromusterts)	
− 38.1	Edinburgh UK	Grassland	Spring	Surface	120	AS, Urea	Winton clay loam	McTaggart et al. 1997
− 44.2	GA 1979	Sweet corn	Spring	Surface	40	AS + CN	Cecil clay loam (Typic Kanhapludults)	McElhannon and Mills 1981

[a] [(effect with nitrapyrin – effect without nitrapyrin) × 100/effect without nitrapyrin]; [b] AA, anhydrous ammonia; AS, ammonium sulfate; CN, calcium nitrate; DM, dairy manure; [c] N_2O. [d]CH_4.

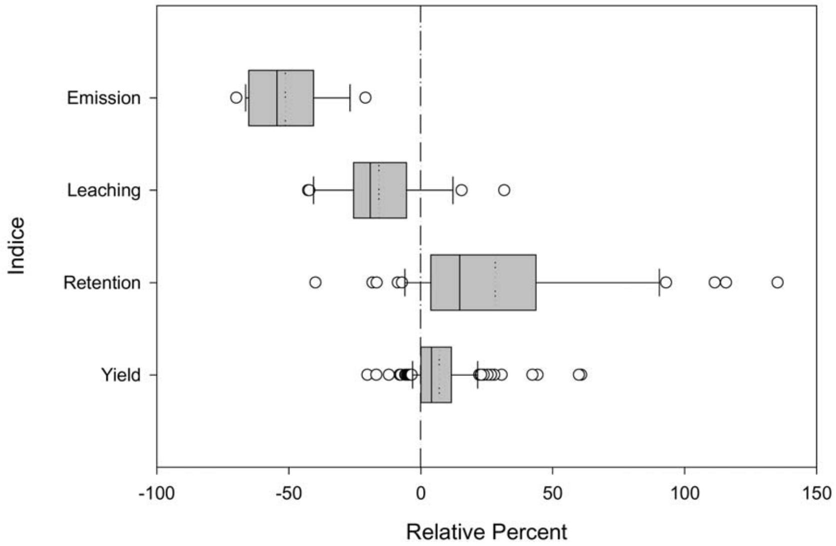

Figure 5. Comparative distribution of nitrapyrin effect, expressed as relative percent of the change attributable to nitrapyrin, for four indices of N mobility. Box plots represent the 10, 25, 50, 75, and 90th percentile effect with mean (dotted line) and outliers (upper and lower 10 percentile of distribution).

the response elements considered reflects the varied source data representing a wide range of environments and management scenarios where a nitrification inhibitor may be used. Conditions of use including fertilizer timing, source, and placement as well as environmental properties such as soil cover, temperature, and moisture content affect the physicochemical and biological performance of the nitrification inhibitor (Wolt 1999) as well as the overall nitrogen cycle.

In approximately 25% of the instances considered, use of a nitrification inhibitor did not positively affect agronomic or environmental performance. These instances may represent situations where environmental conditions were not conducive to N losses from the agroecosystem (Blackmer and Sanchez 1988), or they may represent situations where nitrification inhibitor use in conjuction with fertilization practice results in N loss through ammonia volatilization (Thompson et al. 1987). Examples of the latter would be fertilization strategies involving N forms (urea or ammonium fertilizers), placements (surface application), and timings (fall applications) as well as prolonged periods where soils are warm and moist, allowing for ammonia volatilization (Brink et al. 2000; Harrison and Webb 2001). As a consequence, the positive aspects of nitrification inhibition in reducing N leaching and reduced greenhouse gas evolution must be balanced against the potential negative effects of environmental acidification through soil ammonia efflux.

This analysis has considered the agronomic and environmental effectiveness of nitrapyrin, a widely studied product with a long history of use for nitrogen inhibition in the intense corn production regions of the Midwestern USA. Nitrapyrin is representative of a broad class of compounds that act as nitrification inhibitors and that appear to affect the initial rate limiting step of nitrification involving NH_4^+ oxidation:

$$2NH_4^+ + 3\,O_2 \xrightarrow{Nitrosomonas} 2\,NO_2^- + 4\,H^+ + 2\,H_2O.$$

Alternative forms of nitrification inhibitors (for example, dicyandiamide, ammonium thiosulfate, and etridiazol) can be expected to have similar relative responses as has been considered here for nitrapyrin. The performance of any of these, as compared to nitrapyrin, will vary dependent on considerations of physico-chemical properties, efficacy, and persistence in various environments and management regimes. For instance, comparative differences in field performance of different nitrification inhibitors have been attributed to physical (volatility) and biological (efficacy and persistence) properties as affected by factors such as surface cover, timing of application, and method of placement (Malzer 1989; McTaggart et al. 1997; Goos and Johnston 1999).

Conclusions

A comprehensive assessment of nitrapyrin effect on indices of N loss from agricultural ecosystems shows that despite the anticipated variability in response there is a positive impact on N use efficiency and consequently N loss when viewed from the perspective of impact within a region over time. These findings are of special consequence to the potential for nitrification inhibitors to be effectively employed for mitigating the adverse consequences of N loss from soils receiving inputs of N fertilizer or manure. Field research to date has focused primarily on the impact of nitrification inhibition at the agronomic scale over rather short timeframes, whereas the potential benefits of nitrification inhibitor use in relation to N loss to ground and surface water or to the atmosphere need to be considered at the scale of a sensitive region, such as a watershed, over a prolonged period of use. The results reported here suggest that nitrification inhibition when considered within this context can positively contribute to reduced NO_3 and greenhouse gas losses from agricultural lands. These benefits must be considered within the context of overall goals for abatement of N losses through agricultural best management practices.

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