Nitrification Inhibitors for Corn Production

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Nitrogen (N) is an essential element for plant growth and reproduction. The amounts of N taken up by corn exceed those of any other soil-derived element. Today an average 25% of plant-available N in soils (ammonium and nitrate) originates from the decomposition (mineralization) of organic N compounds in humus, plant and animal residues, and organic fertilizers, 5% from N in rainfall, and 70% from applied inorganic N fertilizers (Figure 1). In soils, organic N is converted to ammonium through microbial decomposition. Ammonium formed in soil, added as fertilizer, or in precipitation is rapidly oxidized to nitrate in the nitrification process carried out by specific bacteria. Nitrification results in the production of nitrate, a form of plant-available N which is readily lost from soils. Nitrification inhibitors are chemicals that slow down or delay the nitrification process, thereby decreasing the possibility that large losses of nitrate will occur before the fertilizer nitrogen is taken up by plants. This publication discusses N losses from soils, characteristics of nitrification inhibitors, and how nitrification inhibitors can be used to improve efficiency of corn production.

THE NITRIFICATION PROCESS

Ammonium (NH +) added to soils or formed by decomposition of organic N compounds is oxidized to nitrite (NO_2) by *Nitrosomonas* bacteria, and nitrite is further oxidized to nitrate (NO_3) by *Nitrobacter* bacteria in a process termed nitrification (Figure 1). Nitrate is normally the form of N taken up by plants; however, most plants can also assimilate ammonium. In most soils, nitrification of applied ammonium is rapid (2-3 weeks), but nitrification rates are greatly reduced by cool soil temperature (50°F), low pH (5.5), and waterlogged conditions. Nitrification converts ammonium, a positively charged ion that is bound to clay and organic matter, to nitrite and nitrate, negatively charged ions that are free in the soil solution and are readily lost from the plant rooting zone of soils.

N LOSS FROM SOILS

Only about 50% of the applied N is taken up by corn during the year following fertilizer addition. About 25% is immobilized during residue decomposition or remains in the soil as nitrate. The remaining 25% is lost from the plant rooting zone by leaching and/or denitrification. (See Table 1 for a generalized estimate of the fate of fertilizer N added to soils.) Some of the immobilized N will be mineralized (5% per year) and will be available to subsequent crops. Nitrate remaining in the profile at the end of the cropping season will be available to the succeeding crop unless lost over the winter and spring by leaching or denitrification.

Leaching is important in coarse-textured soils. Nitrate may be leached from naturally well-drained or tile-drained soils by percolating water. One inch of infiltrating water will move nitrate 1 to 2.5 inches downward in clay loam and sandy soils, respectively. Thus, during periods of excess rainfall, leaching may move nitrate out of the effective rooting zone of plants.

Denitrification (the microbiological conversion of nitrate and nitrite to gaseous forms of N) is the major pathway of N loss from most fine-textured soils. It normally occurs in soils that become waterlogged by excessive

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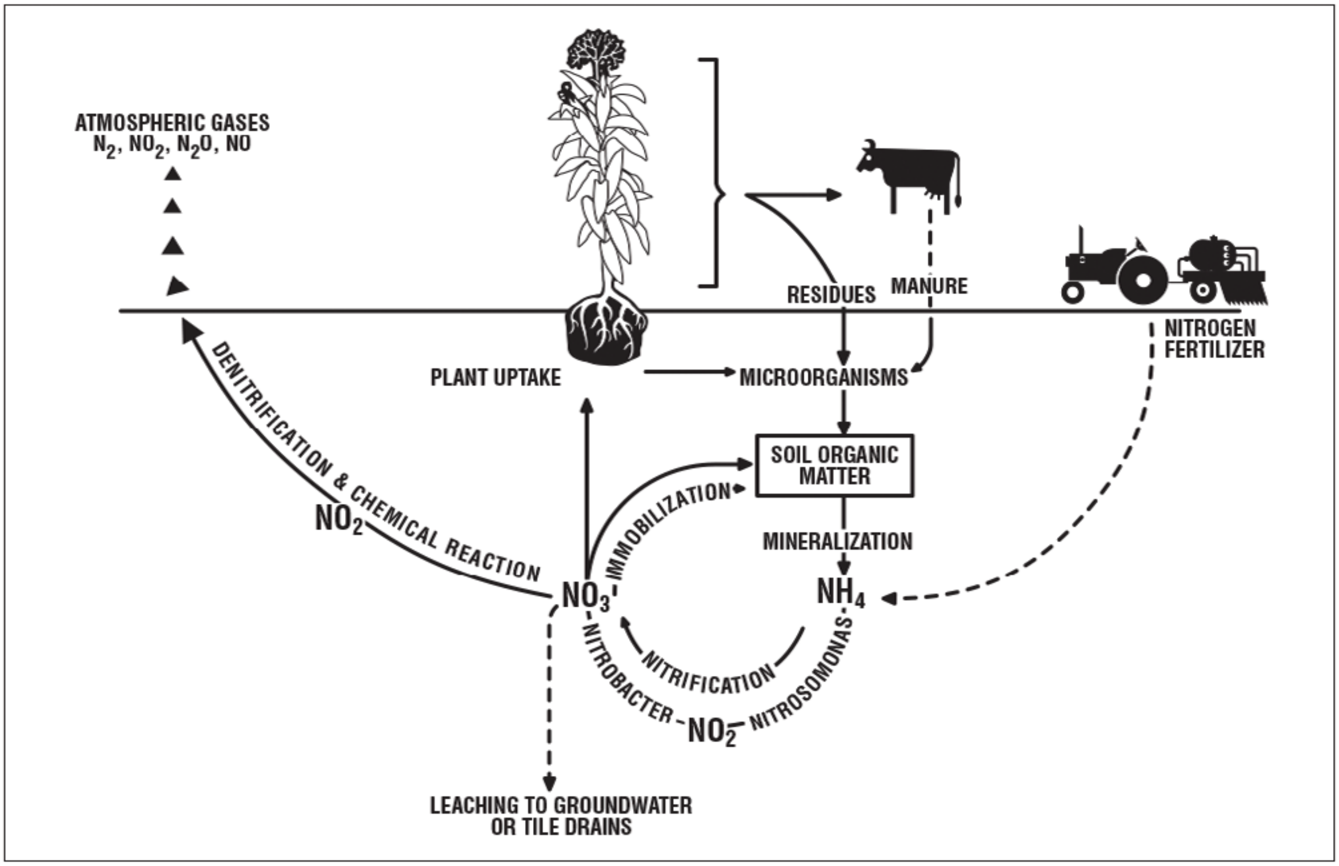

Figure 1. The nitrogen cycle in soils (adapted from Nitrogen in Agricultural Soils).

rainfall or irrigation. Denitrification occurs at maximum rates when soils are warm (60°F), pH values are high (7), nitrate is plentiful, and an energy source (carbon) is available. In waterlogged soils, more than 100 pounds of nitrate N per acre can be denitrified within a 5-day period. However, in cold soils (40°F) or soils with low pH values (5), denitrification rates are slow.

TYPES AND USES OF NITRIFICATION INHIBITORS

Nitrification inhibitors (NI) are chemicals that reduce the rate at which ammonium is converted to nitrate by killing or interfering with the metabolism of Nitrosomonas bacteria (Figure 1). The loss of N from the rooting zone can be minimized by maintaining applied N in the ammonium form during periods of excess rainfall prior to rapid N uptake by crops. A number of compounds have been shown to inhibit nitrification in laboratory and field studies (Table 2); however, only N-Serve® and Dwell® have U.S. Environmental Protection Agency approval for use on cropland in the United States. Additional compounds are used in Japan and other countries; and registration is expected for additional compounds in the U.S.

N-Serve is currently labeled for corn, sorghum, wheat, cotton, rice, and other crops and is sold in emulsifiable and nonemulsifiable formulations. Dwell was registered as a nitrification inhibitor in 1982, but it is uncertain if the product will be marketed. Both chemicals are effective nitrification inhibitors when 0.5 pounds of active ingredient (a.i.) per acre is used in a band application with anhydrous ammonia or N solution fertilizers.

Table 1. Generalized Fate of Fertilizer Nitrogen Applied to Corn.[1]

Fate of applied N	Soil texture: coarse	Soil texture: medium and fine
	-----% of applied N-----	
Plant uptake (first year)	40-60	50-60
Remains in soil as organic and inorganic N	20-25	25-30
Lost from root zone:		
Denitrification	5-10	15-25
Leaching	15-20	0-10

[1] Average values over years for soils in the Cornbelt and southeastern U.S. and irrigated soils of the Great Plains and western valleys.

N-Serve and Dwell may also be impregnated on solid fertilizers or mixed with N solution fertilizers prior to broadcast applications. However, incorporation of the nitrification inhibitor-treated fertilizer must occur shortly after application because both compounds are volatile. Higher rates (2 to 4 times band applications) of N-Serve and Dwell are often required to control nitrification of broadcast ammoniacal fertilizers.

Recent studies have shown that NI can also be effectively used with liquid animal manures and sewage sludges that are injected into the soil.

Table 2. Compounds Marketed or Proposed as Nitrification Inhibitors

Chemical name	Common or trade name	Manufacturer	Registered in the U.S.A.
Produced commercially:			
2-chloro-6-(trichloromethyl)-pyridine	N-Serve	Dow Chemical Co.	Yes
5-ethoxy-3-trichloromethyl-1, 2, 4-thiadiazol	Dwell, Terrazole (etradiazol)	Uniroyal Chemical	Yes
Dicyandiamide	DCD	SKW Trostberg AG	No
2-amino-4-chloro-6-methyl-pyrimidine	AM	Mitsui Toatsu Co.	No
2-mercapto-benzothiazole	MBT	Onodo Chemical Industries	No
2-sulfanilamidothiazole	ST	Mitsui Toatsu Co.	No
Thiourea	TU	Nitto Ryuso	No
Proposed as nitrification inhibitors:			
2,4-diamino-6-trichloromethyl-5-triazine	--	Amer. Cyanamid Co.	No
Polyetherionophores	--	Amer. Cyanamid Co.	No
4-amino-1, 2, 4-triazole	--	Ishihara Industries	No
3-mercapto-1, 2, 4-triazole	--	Nippon Gas Indus.	No
Potassium azide	--	Pittsb. Plate Glass Co.	No
Carbon bisulfide	--	Imperial Chem. Indus.	No
Sodium trithiocarbonate	--	Imperial Chem. Indus.	No
Ammonium dithiocarbamate	--	FMC	No
2, 3, dihydro-2, 2-dimethyl-7-benzofuranol methyl-carbamate	Furadan (carbofuran)	FMC	No
N-(2, 6-dimethylphenyl)-N-(Methoxyacetyl)-alanine methyl ester	--	Olin Corp.	No
Ammonium thiosulfate	--	--	No
1-hydroxypyrazole	--	BASF	No
2-methylpyrazole-1-carboxamide	CMP	GDR	No

EFFECTS OF NITRIFICATION INHIBITORS

A number of studies throughout the United States have demonstrated that NI effectively retards the conversion of ammonium to nitrate in a variety of soils. Results indicate that application of NI delays the conversion of ammonium to nitrate for 4 to 10 weeks, depending upon soil pH and temperature. With fall applications of N fertilizers, NI minimize nitrification until low soil temperatures (40°F) stop the process.

With spring applications, NI prevent the formation of nitrate during the late spring when rainfall is high and uptake of N by crops is low.

Corn yields are often increased as N losses from soils are reduced by the application of NI with both conventional tillage and reduced tillage systems (Table 3). The potential benefit from NI application depends on a number of site-specific factors, such as soil type, climate, cultural practices, and N management program. Highest probability of yield response from NI occurs with excessively drained or poorly drained soils because of N losses from leaching and denitrification, respectively. For example, a study in Indiana with fall-applied anhydrous ammonia showed that N-Serve application increased corn yields by 300% with a very poorly drained silty clay soil and 1% with a well-drained sandy loam soil. Significant corn yield responses from NI addition have also been observed with irrigated sandy soils (Table 4). Yield responses from NI are more frequent with fall N applications than with spring applications because of lower N losses from denitrification normally experienced when fertilizers are applied nearer to the time of crop need. There have been consistent yield responses from NI added to ammoniacal fertilizers for corn produced with a no-till system, presumably because of larger N losses from denitrification normally experienced with this production method.

The increased availability of inorganic N and the presence of ammonium in the soil resulting from NI addition also have been shown to increase the protein concentration of corn grain (Table 5). The feeding value of corn increases as the protein level increases. The application of NI to inorganic and organic N fertilizers also has reduced the severity of *Diplodia* and *Gibberella* stalk rots of corn, likely because of altered N metabolism in plants assimilating the ammonium form of N (Table 6). Corn stalks in areas receiving NI-treated fertilizers tend to remain green later in the growing season and have thicker rinds, both of which reduce pathogen effects and lodging. Grain moisture content at harvest is unaffected by NI addition to fertilizers.

The amounts of nitrate leached into groundwater and ozone-destroying nitrous oxide (N2O) emitted into the atmosphere through denitrification are reduced by NI application. The use of NI also gives great flexibility in timing the application of N fertilizers. For example, with most Cornbelt soils all of the N needed for a corn crop can be applied as anhydrous ammonia during

Table 3. Effects on Grain Yields of Corn Grown with Conventional and No-Till Systems from Addition of Nitrification Inhibitors to Fall- and Spring-Applied Ammoniacal Fertilizers.[1]

Location	Time of application	Number of experiments	Number of yield increases from NI[2]	% Yield increase from NI[3]
Indiana	Fall	24	17	12.5
	Spring	51	29	5.8
	Spring (no-till)	12	9	10.0
No. Illinois	Fall	12	5	5.0
	Spring	14	2	-1.0
So. Illinois	Fall (NH_3)	7	7	4.6
	Spring (NH_3)	9	7	4.6
	Spring (no-till)	2	2	8.5
	Fall (N solution)	5	4	3.3
	Spring (N solution)	5	2	-1.2
Kentucky	Spring (no-till)	8	7	14.3
Wisconsin	Fall	2	1	4.7
	Spring	2	0	1.5

[1] Adapted from R. G. Hoeft 1984. Current status of nitrification inhibitors. In R. O. Hauck (ed.) Nitrogen in Crop Production. Am. Soc. of Agronomy, Madison, Wi.
[2] Significant at 95% probability level.
[3] Average percent yield increase across all N rates and locations.

the previous fall if a NI is used, thereby reducing the workload in the critical spring planting season. The use of NI permits early spring application of N in many areas of the United States where N losses are a consistent problem.

Data in Table 3 show that NI addition does not result in yield increases in all soils and climatic conditions. In fact, in some situations there is a low probability of a corn yield increase from NI. Since the purpose of NI application is to increase the efficiency and amount of N available to plants by reducing N losses, no response to NI will be obtained during seasons or with soil types having little or no N loss. Little or no N loss occurs during seasons with below average rainfall following N application because N loss through leaching and denitrification is directly related to the amount and distribution of rainfall and the drainage characteristics of the soil.

No yield response will be obtained from NI addition when N rates used are far in excess of those required for maximum yield. For example, if maximum corn yields could be obtained with 150 pounds of N per acre but 300 pounds per acre are applied, as much as one-half of the applied N could be lost before a decrease in yield occurs. Late side-dress injections of N may reduce yield through mechanical damage to the root system and increased root rot. Immobilization of late-season applied N with a NI may further exacerbate this condition.

In sandy soils with very low cation exchange capacities, the addition of NI to ammoniacal fertilizers may not reduce N loss or increase crop yield because of differential movement of ammonia and NI from the zone of placement. Some studies have shown that ammonium ions were leached below the NI treated zone by rainfall and irrigation water. In this situation, nitrification deeper in the profile produced nitrate that was subsequently removed from the rooting zone by leaching.

Table 4. Effects of Nitrification Inhibitors on the Yield of Irrigated Corn Fertilized with Urea. (Hubbard Loamy Sand).[1]

	Nitrification Inhibitor		
N rate	None	N-Serve	Dwell
Pounds/acre	------corn yield, bushels/acre------		
0	59	--	--
60	89	119	98
120	105	151	145
180	136	170	171
240	171	182	186

[1] Taken from G. L. Malzer, T. J. Graff, and J. Lensing. 1979. Influence of nitrogen rate, timing of nitrogen application and use of nitrification inhibitors for irrigated spring wheat and corn. In Univ. Minn. Soil Series 105 Report on Field Research in Soils.

Table 5. Effect of a Nitrification Inhibitor on Corn Grain Protein Concentration[1]

	Treatment	
N applied	NH_3	NH_3 + N Serve
Pounds/acre	------grain protein, %------	
0	6.76	--
60	7.76	9.24
120	9.38	10.60
160	10.80	11.71

[1] Study conducted in Indiana using B73 x Mo17 corn hybrid.

Table 6. Effects of a Nitrification Inhibitor on Stalk Rot of Corn.[1]

Number of studies	N Source	Treatment	
		N	N + N Serve
		% of plants with stalk rot[1]	
3	NH_3	38	16
4	Swine manure	54	23

[1] Average values for all locations, years, and N rates from studies in Indiana.

WHERE SHOULD NITRIFICATION INHIBITORS BE USED?

The response of corn to applications of NI with ammoniacal fertilizers varies greatly throughout the United States because of major differences in N loss potential from differing climate, soils, and production systems. A summary of research results on corn yield responses from NI addition for various corn production regions is presented in Table 7, and the probabilities for obtaining a yield response from NI for several combinations of region, soil texture, and time of fertilizer application are given in Table 8. The addition of NI to fertilizer should be looked upon as insurance against N loss, and, thus, a decision to use NI should be based on the probability of obtaining yield increases over a period of time, e.g., 5 years. The usefulness of NI for corn production in three general regions of the United States is discussed below.

Southeast

The response of corn to NI applications in the southeastern United States has been mixed. The relatively high soil temperatures during the winter result in nitrification of fall-applied N and subsequent leaching or denitrification of the nitrate that is formed. The addition of NI does not alleviate this problem because of the limited longevity of the currently registered inhibitor compounds in soil and the long period of time between N application and crop uptake of the nutrient. Thus, yield responses to NI added to fall-applied fertilizers have not been consistently observed. A number of studies have shown modest corn yield increases from the addition of NI to spring- applied N even though inhibitor persistence is limited by high soil temperatures. Overall, the probability of corn yield response from currently available NI in the southeastern U.S. is poor for fall-applied N and fair to poor for spring-applied N.

Eastern Cornbelt

The response of corn to NI application has been more consistent over years in the eastern Cornbelt than other portions of the United States because of high rainfall, finer textured soils, and cold soil temperatures during the winter. However, overall only about 50 and 70% of the trials with spring- and fall- applied N have shown yield response from NI. Yield responses have been obtained with both spring- and fall-applied N in Indiana, Kentucky, Ohio, and southern Illinois. The consistency of yield responses to NI has been less in Michigan, Wisconsin, Missouri, central and northern Illinois, and Iowa than in other eastern Cornbelt states. However, all states in the eastern Cornbelt have studies showing corn yield increases from NI addition, and the largest and most consistent increases are normally observed with fall- applied N or with non-tillage programs.

There is a good probability of obtaining a yield increase from application of NI to fall-applied ammoniacal fertilizers in the eastern Cornbelt because of the large N loss normally associated with fall applications. The use of NI will allow producers to apply N fertilizers somewhat earlier than generally considered feasible (50°F is traditionally considered the maximum soil temperature for application of ammoniacal fertilizers in the fall without a NI). Fall application of N is not recommended for low CEC coarse-textured soils because of the possibility of ammonium leaching.

The probability is good that NI added to spring-preplant N will increase yields of corn growth on fine- textured soils of the eastern Cornbelt because of the likelihood of N losses by denitrification after fertilization. Only a fair probability exists for a yield response to NI added with spring-preplant N applied to silt loams and coarser textured soils. The probability of loss in such soils depends upon the nitrification rate following fertilization, the internal drainage of the soil, and the distribution and intensity of rainfall. Heavy rains

Table 7. Regional Summary of Corn Yield Responses from Nitrification Inhibitors Added to Ammoniacal Fertilizers Appled at Varying Times.[1]

Region	Time of application	% of studies with yield increase	% yield increase[2]
Southeast (GA, MD, NC, SC, TN)	Fall Spring	17 43	14 15
Eastern Cornbelt (IL, IN, OH, KY)	Fall Spring Spring (no-till)	69 51 82	9 3 13
Northern Cornbelt (MI, MN, WI) not irrigated	Fall Spring	25 17	5 12
Western Cornbelt (KS, MN, NE) irrigated coarse-textured soils	Spring	52	30
Western Cornbelt (KS, NE) irrigated medium- and fine-textured soils	Spring	10	5

[1] Data taken from a variety of research progress reports and published materials.
[2] Average increases obtained in experiments where NI addition gave significant yield increases.

occurring 2 to 8 weeks after fertilization may result in extensive N losses and yield responses to NI application. However, if a below average rainfall period follows fertilization, little N loss or response to NI will occur.

Western Cornbelt

Few yield responses to NI have been observed with dryland corn or irrigated corn produced on fine- textured soils in Minnesota, North Dakota, South Dakota, and other states west of the Missouri river. However, the use of NI has resulted in increased yields in areas where preplant N is applied to irrigated corn grown on sandy soils. Data from Minnesota (Table 4) illustrate the type of responses that are sometimes obtained when a NI is used to reduce nitrate leaching in irrigated sandy soils.

There is poor probability of yield response with spring-applied fertilizer for dryland corn production in the western Cornbelt; however, with irrigated coarse- textured soils the probability of a yield increase improves. There is a fair probability of a response to NI with fall applied fertilizer on finer textured soils. Fall application of ammoniacal fertilizers is not recommended for sandy soils.

ADDITIONAL CONSIDERATIONS WHEN USING NITRIFICATION INHIBITORS

More consistent yield responses have been obtained with no-till grown corn than with conventional tillage systems fertilized in the spring (Tables 3 and 8). This finding results from greater infiltration rates, higher water contents, a higher population of denitrifying bacteria in no-till soils and, thus, increased N losses from leaching and/or denitrification.

The probability of yield responses to NI added to spring-sidedress-applied N is considered low for all soils because the fertilizer is added close to the time of plant uptake. However, a few investigators in the eastern Cornbelt have observed significant yield increases from NI added to early sidedressed N fertilizers. Additional studies are needed at several locations in all corn-growing regions to determine the long-term probability of a response to NI application with sidedress N should exist on coarse-textured soils receiving excess rainfall or irrigation water.

The commercially available NI have properties that affect how they can be added to various types of fertilizers. N-Serve and Dwell can be impregnated on solid fertilizers, or an emulsifiable formulation may be mixed with N solution fertilizers. N-Serve can be added directly to bulk anhydrous ammonia because of its high solubility in liquid ammonia. However, Dwell is not soluble in ammonia, but can be added to anhydrous ammonia with a small electric pump that meters the compound into the ammonia stream between the nitrolator and the manifold system on the applicator.

Table 8. Probability of Corn Yield Increase from the Addition of NI to Ammoniacal Fertilizers Applied at Varying Times.

Soil texture	Application time	Region of the U.S. Southeast	Eastern Cornbelt	Western Cornbelt
		---Probability of corn yield increase[1]---		
Sands	Fall	Poor	Poor	Poor
	Spring	Fair	Fair	Fair[2]
Loamy sands, sandy loams and loams	Fall	Poor	Fair	Poor
	Spring	Fair	Fair[3]	Fair[2]
Silt loams	Fall	Poor	Good	Fair
	Spring	Fair	Fair[3]	Poor
Clay loams and clays	Fall	Poor	Good	Fair
	Spring	Fair	Good	Poor

[1] Poor = less than 20% chance of yield increase at any location any year; fair = 20-60% chance of increase; good = greater than 60% chance of increase.
[2] Fair for irrigated soils, poor for dryland corn.
[3] Good for no-till production systems.

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