Short-Term Excess Water Impact on Corn Yield and Nitrogen Recovery

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Optimum N management for soils which can have short-term, early-season periods of excessive soil water requires farmers to balance economic and environmental concerns. The objectives of this study were to evaluate corn (*Zea mays* L.) yield and N fertilizer recovery following 0, 4, or 6 in. of excess soil water. Field studies were conducted from 1985 to 1988 on Cisne silt loam (fine, montmorillonitic, mesic Mollic Albaqualf), Drummer silty clay loam (fine-silty, mixed, mesic Typic Haplaquoll), and Plainfield sand (mixed, mesic Typic Udipsamment) at three Illinois locations. Water stress was imposed by applying 0, 4, or 6 in. of water to soils at field capacity (0.33 bar). Fertilizer rates ranged from 0 to 200 lb N/acre with an additional 50 lb N/acre being applied to half the plot following the water stress treatments. Isotopic ^{15}N was used for the 150 lb N/acre treatment. Relative yield on Drummer decreased approximately 1% for each day soil water tension was below 0.33 bar. On Cisne, three stress days decreased yields less than 1%, but 7 d increased the loss to about 5%. Regression equations showed that even with 200 lb N/acre, 17 in. of water during May and June resulted in yields that were only 18% of those produced with 5 in. on a Plainfield sand. Fertilizer recovery averaged 88, 61, and 61% for Cisne; 83, 50, and 44% for Drummer; and 25, 8, and 13% for Plainfield soils with 0, 4, and 6 in. of excess water. Denitrification was the primary loss mechanism for the Cisne and Drummer soils, while for the Plainfield sand, it was leaching. Equations developed from this study will result in more economical and environmentally sustainable N management decisions.

The two primary N loss mechanisms, denitrification and leaching, have been well documented in the literature (Allison, 1966; Hauck, 1984). Unfortunately, little work has been done to develop a practical technique that farmers or their advisers could use to predict the magnitude of N loss associated with excess precipitation received in late spring or early summer after preplant N applications have been made. Much effort has been made to develop conceptual models of N cycling in the plant-soil system, but these models simulate processes for which little or no quantitative field data are available, or they include parameters that are impractical to measure in farmer fields (Tanji, 1982). Lacking this practical system, farmers adverse to economic risk over apply N to compensate and those willing to accept risk under apply for those years in which the loss occurs. Over application creates a potential environmental risk, whereas both under and over application result in economic loss.

The magnitude of N loss associated with denitrification and leaching is directly related to soil type and moisture condition. Leaching increases as infiltration and percolation increase and water holding capacity decreases (Allison, 1973). As a result, leaching losses have been reported to be much higher on sandy soils (where rapid water movement is likely) than on heavier textured soils (Legg and Meisinger, 1982). If rainfall in early spring exceeds evapotranspiration, significant amounts of nitrate can be leached below the rooting zone before vigorous plant growth begins (Allison, 1973).

Denitrification occurs more frequently on finer textured, than on sandy soils, as the finer textured soils tend to be more poorly drained and, as such, retain excess water longer than do sandier soils. Pilot and Patrick (1972) and Ryden and Lund (1980) found denitrification occurred only at soil moisture conditions near saturation. Mulvaney and Kurtz (1984) found that denitrification occurred only if soil moisture tension fell below 0.33 bar.

Denitrification increases rapidly with increasing temperature (Keeney et al., 1979; Bremner and Shaw, 1958). Craswell (1978) found that the minimum water content necessary for denitrification increased as temperature decreased, becoming undetectable in flooded soils at soil temperatures of 50 °F or less. In Illinois, soil temperatures during the winter are usually low enough to prevent significant denitrification losses, but in late spring and early summer, temperature and moisture levels are frequently adequate for rapid denitrification.

Studies have shown a rapid change in N evolution rate during wetting and drying cycles in the soil (Ryden et al., 1979; Ryden and Dawson, 1982; Rolston et al., 1982; Mulvaney and Kurtz, 1984). Smith and Tiedje (1979) found rapid increases in denitrification occurred within 6 h of water application. Sexstone et al. (1985) found denitrification occurred in bursts in response to rainfall and both the time of initiation and the duration of denitrification varied depending on soil type. They found that

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Table 1. Physical and chemical characteristics of soils examined in this study.

Location	Soil Series	Soil Subgroup	Surface texture†	pH	Organic C	Total N	Available P	Available K	Permeability‡
					%	%	lb/acre	lb/acre	in./h
DeKalb	Drummer	Typic Haplaquoll	sicl	6.7	2.3	0.25	103	208	0.52–2.00
Brownstown	Cisne	Mollic Albqualf	sil	6.5	0.7	0.08	82	398	0.14–0.57
Havana	Plainfield	Typic Udipsamment	s	6.4	0.2	0.02	50	290	6.00–20.00

† sicl = silty clay loam; sil = silt loam; s = sand.
‡ From Hinckley (1978), Downey and Odell (1969), and Calsyn (1989), respectively.

38 to 55% of the total N loss occurred within 48 h of rainfall events greater than 0.4 in. during late spring.

Corn yield response to N fertilizer is dependent on weather factors, especially rainfall (Asghari and Hanson, 1984; Bondavalli et al., 1970; Voss et al., 1970). Precipitation in excess of that needed for plant growth enhances the potential for N loss, whereas inadequate rainfall inhibits growth and N use. Improved N management could be achieved if the interaction between soil moisture regimes and yield response to N were better understood.

The objectives of this study were to: (i) determine the effects of soil moisture regimes during the early growing season at various N rates on N uptake and corn yield; and (ii) determine the effect of supplemental N after periods of excessive soil moisture on plant N uptake and corn yield.

MATERIALS AND METHODS

Field experiments were established at Brownstown, DeKalb, and Havana, IL, on a Cisne silt loam, Drummer silty clay, and Plainfield sand, respectively. The experiments were conducted from 1985 to 1988.

Nitrogen loss problems have been identified on each of these three major Illinois soil types. A relatively impermeable claypan in the Cisne frequently results in the persistence of excess soil moisture for extended periods in the spring and early summer; thus this soil has a high potential for denitrification. Even though the Drummer is tile drained, internal permeability of this soil is low enough that it frequently remains saturated in the early spring. Leaching of nitrate has been identified as a major problem on the excessively well drained Plainfield. Chemical and physical characteristics of the soils (Table 1) were determined from surface (0- to 6-in.) samples at each site. In the analyses reported in Table 1, pH was determined with a glass electrode (soil-to-water ratio, 1:1), organic C by the Walkley-Black procedure (Nelson and Sommers, 1982), total N by a permanganate-reduced iron modification of a semimicro-Kjeldahl procedure (Bremner and Mulvaney, 1982), available P by the Bray-1 method (Knudsen, 1980), and available K by flame photometry following NH_4OAc extraction (Carson, 1980).

Nitrogen was applied at 0, 100, 150, and 200 lb N/acre in factorial combination with moisture levels of ambient; ambient plus 4 in. of water evenly distributed over a 3-d period; and ambient plus 6 in. of water evenly distributed over an 8-d period. These treatments simulate rainfall that occasionally occurs in Illinois. A split plot design with three replications was used with moisture treatment as the main plots. Corn was planted in early to mid-May

Table 2. Total rainfall and irrigation from 1 April through 30 September.

	1985 Rain	1985 Irrig†	1987 Rain	1987 Irrig†	1988 Rain	1988 Irrig†
	in.					
			Cisne			
Total	14.6	1.2	7.6	1.1	9.5	9.1
Excess‡						
4 in.		2.1		4.0		2.9
6 in.		4.0		6.2		5.2
			Drummer			
Total	25.1	0	30.1	0	14.3	0
Excess‡						
4 in.		4.0		4.3		3.9
6 in.		5.4		6.1		5.9
			Plainfield			
Total	15.1	12.0	9.6	13.0	8.8	20.7
Excess‡						
4 in.		2.1		3.2		3.9
6 in.		5.9		5.8		6.9

† Values reported represent water applied to all plots for corn production for adjustment of soil moisture tension (0.33 bar) prior to establishment of water regimes. No application (other than excess moisture treatments) were made to Drummer soil, as irrigation facilities were limited, and rainfall was adequate to reduce soil moisture tension to <0.33 bar before moisture treatment application.
‡ Excess water application initiated at the V6–V8 leaf corn growth stage. Values represent actual application achieved for the 4- to 6-in. excess water treatment.

and N application was made at the V1 to V3 growth stage. To insure that a substantial portion of the N was present as nitrate, N was broadcast as ammonium nitrate in 1985, and as potassium nitrate in 1987 and 1988 on plots measuring 15 by 50 ft on the Cisne and Drummer and 15 by 35 ft on the Plainfield. In 1987 and 1988, N was broadcast over all but a 7.5 by 12 ft microplot in the center of the 150 lb N/acre plot area. To this area, arranged to include four rows of corn, ^{15}N-enriched potassium nitrate was applied as uniformly as possible, using a compressed air sprayer. A ^{15}N content of 2.79 atom % ^{15}N was used on the Drummer and Cisne soils and 2.29 atoms % ^{15}N was used on the Plainfield soil in 1987 and 1988. The location of the micro plot within the macro plot was moved each year to prevent contamination by the previous year's application.

Following N application, sufficient water was applied to the entire plot area to bring soil moisture tension to approximately 0.33 bar at a depth of 6 in. Once that moisture level was obtained, the moisture regimes were established using a solid set sprinkler system on the Drummer and Cisne and a traveling gun on the Plainfield. Border rows were placed between the moisture treatments. The 4- and 6-in. applications were target values for the excess water treatments; actual application rates are given in Table 2.

Table 3. Effects of rate of N application and soil moisture level on total plant N uptake and fertilizer N recovered at harvest (lb/acre), Cisne sil in 1985, 1987, and 1988.†

	Soil moisture level								
	Ambient			Ambient + 4 in.			Ambient + 6 in.		
Fertilizer N (lb/acre)	1985	1987	1988	1985	1987	1988	1985	1987	1988
	Plant N uptake (lb/acre)								
0	97.5	78.4	63.9	124.0	53.2	70.6	102.2	57.5	66.6
100	156.8	150.7	168.2	163.8	129.2	168.5	170.1	121.0	130.8
150	174.0	162.7	198.6	201.6	167.0	149.3	195.1	159.8	179.3
0 + 50 suppl.	168.2	100.3	120.0	129.0	85.5	110.8	134.5	86.4	92.9
100 + 50 suppl.	204.4	151.0	183.8	177.5	128.2	221.6	201.9	150.6	197.2
150 + 50 suppl.	205.2	174.1	189.8	227.0	164.3	224.3	202.4	166.5	196.0
200 + 50 suppl.	222.1	151.9	219.1	219.5	167.3	228.5	190.2	143.5	198.8
Fertilizer N recovered (150 lb/acre rate), derived from ^{15}N analysis.									
Remaining in soil		17.8	44.6		15.8	34.0		12.8	26.5
Plant uptake		80.4	97.6		80.0	73.6		62.3	74.0
Total recovered		98.2	142.2		95.9	108.0		84.3	100.5

† Values are means of three replicates. Suppl. = supplemental N application after water treatment.

Tensiometers were installed on the Drummer and Cisne soils in 1987 and 1988 to monitor the soil moisture conditions at the 6-in. depth. Water-retention curves were determined for each soil with intact soil samples and a pressure-plate apparatus (Klute, 1965). Percentage moisture was determined for 18 subsamples brought from saturation to a soil moisture tension of 0.1, 0.2, 0.33, 0.5, and 1 bar. The tensiometer data and moisture retention curves were used to calculate the number of days that soil moisture tension remained below 0.33 bar during the experimental period. Total rainfall + irrigation during the growing season for each soil are given in Table 2. Bulk density was determined from intact soil samples taken from each depth on each soil for calculation of fertilizer N recovery.

After water treatments were imposed and soil moisture content was no longer at saturation (approximately 7 d after completion of the excess water treatment), supplemental N was applied to one-half of each plot at a rate of 50 lb N/acre as ammonium nitrate. Additional water was applied as needed to the Cisne and Plainfield soils to prevent water stress due to drought during the growing season.

Plant samples were collected from a 5- by 5-ft area in the center of the plots at harvest. Plant samples from the 150 lb N/acre plots were collected from a 5-ft section from the inside two rows in the microplot area at harvest. Plant samples were dried, weighed, ground, and analyzed for N content using a salicylic acid-thiosulfate modification of the semimicro Kjeldahl method described by Bremner and Mulvaney (1982). Grain, cob, and remaining plant parts were analyzed for N concentration and N uptake in the above-ground portion of the plant was calculated.

Grain yield was collected from the center of each plot. The harvested area measured 7.5 by 50 ft on the Cisne, 10 by 50 ft on the Drummer, and 10 by 15 ft on the Plainfield. Plots were hand harvested on the Plainfield, while mechanical harvesters were used at the two other locations. Production problems at the Plainfield location prevented accurate measurement of plant response in 1988 and was therefore eliminated. Grain yield was corrected to 15.5% moisture and relative yield was calculated from the relation, relative yield (%) = (treatment yield/maximum yield) × 100, where maximum yield is the mean yield for the highest yielding treatment for each year for each soil type.

Soil samples were collected at 12-in. increments down to 48 in. depth at harvest. Immediately after collection, the samples were frozen until analyzed for nitrate-N and total N. Soil samples were wet-sieved and inorganic N

Table 4. Effects of rate of N application and soil moisture level on corn yield (bu/acre). Cisne sil—1985, 1987, and 1988.†

	Soil moisture level				
Fertilizer N (lb/acre)	Ambient	Ambient + 4 in.	Ambient + 6 in.	Mean	Suppl. N mean
	Yield (bu/acre)				
		1985			
0	77.4	106.2	89.5	91.0a*	
100	126.6	122.7	124.6	124.7b	
150	144.3	145.2	149.7	146.4c	129.3a
200	156.0	157.9	151.3	156.0c	
0 + 50 suppl.	140.6	131.2	114.9	129.4a	
100 + 50 suppl.	148.8	131.9	151.1	143.9b	
150 + 50 suppl.	153.6	155.3	135.9	148.3c	154.5b
200 + 50 suppl.	152.7	158.6	154.2	155.2c	
Mean	137.5a	138.6a	134.1a		
		1987			
0	55.1	53.0	62.7	57.2a	
100	140.9	130.9	143.0	137.9b	
150	149.0	131.3	154.4	144.4c	125.8a
200	160.9	156.8	172.1	163.5c	
0 + 50 suppl.	116.8	104.2	101.1	106.2a	
100 + 50 suppl.	175.0	128.8	158.9	151.6b	
150 + 50 suppl.	172.8	159.7	173.6	168.2c	146.3b
200 + 50 suppl.	164.2	166.5	148.4	159.1c	
Mean	141.9a	128.9b	139.3a		
		1988			
0	48.7	47.7	48.9	48.4a	
100	140.7	140.5	122.7	134.6b	
150	151.1	150.8	140.7	147.5c	121.0a
200	152.3	162.9	145.3	153.5c	
0 + 50 suppl.	116.0	110.4	98.2	108.2a	
100 + 50 suppl.	152.1	154.6	144.1	150.3b	
150 + 50 suppl.	150.0	160.9	167.2	159.3c	142.6b
200 + 50 suppl.	148.8	162.7	146.8	152.8c	
Mean	132.5a	136.3a	126.7b		

* Values within a column or row within year followed by the same letter do not differ significantly (0.05).

† Values represent means of three replicates. Suppl. = supplemental N application after excess water treatment.

concentration was determined using the magnesium oxide-Devarda's alloy method on potassium chloride soil extracts as described by Keeney and Nelson (1982). Total N concentration of soil samples was determined using permanganate-reduced iron modification of a semimicro Kjeldahl method described by Bremner and Mulvaney (1982).

Distillates from total and inorganic N analysis were retained for ^{15}N analysis with an automated mass spectrometer (Mulvaney et al., 1990). Total recovered fertilizer N was calculated by summing the soil and plant fertilizer N contents. Fertilizer N in the organic form was calculated from the difference between total N and inorganic N content. Significance of treatment effects was determined by least significant differences (SAS Institute, 1982).

The effect of N rate, supplemental N, and moisture level on total recovered N were evaluated using regression analysis. Calculation of total N recovery for the regression analysis was made by the difference method, using the following equation: Total recovered N = $(NP_t + NS_t) - (NP_c + NS_c)$; where NP_t is treatment plant N, NS_t is treatment inorganic soil N (nitrate + ammonium in 4-ft depth), NP_c is control plant N, and NS_c is control inorganic soil N.

Relative yield and N uptake data were pooled across years (1988 data for Plainfield were not included) to develop a regression equation for each soil relating relative yield to N application rate, supplemental N application, and moisture regime. Three different measures of soil moisture status, including total rainfall plus irrigation in May and June, number of days in May and June with soil moisture tension below 0.33 bar, and number of days in May and June with soil moisture tension below 90% of 0.33 bar were evaluated as independent variables in the regression analysis. Each of these is a readily available measure of soil moisture that could be used by farmers or their advisors.

Quadratic and interaction terms of the independent variables were considered in the model. Multiple regression equations were developed using stepwise and backward elimination procedures (SAS Institute, 1982). The R^2 statistic and C_p criteria were used to select the best fit regression equation as described by Neter and Wasserman (1974). The best fit equations were used to develop response curves for each soil, relating N rate and moisture to relative yield. The curves were developed by

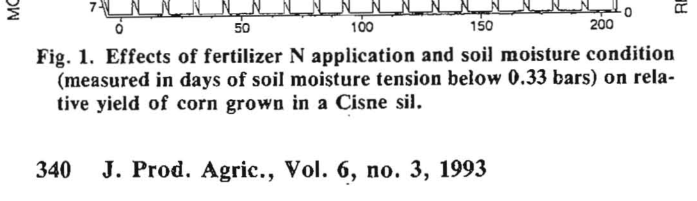

Fig. 1. Effects of fertilizer N application and soil moisture condition (measured in days of soil moisture tension below 0.33 bars) on relative yield of corn grown in a Cisne sil.

solving the equations for arbitrary values of the independent variables within the range measured in the study. Because only two rates of supplemental N were used in this study, separate response curves for 0 and 50 lb N/acre supplemental N were developed. Data presented in figures is for 0 lb N/acre only.

RESULTS AND DISCUSSION

Cisne

Averaged across water treatments, N uptake and yield increased with increasing N rate up to 150 lb N/acre on the Cisne (Tables 3 and 4). Application of supplemental N increased yields, but at a decreasing rate as the initial N application was increased.

Because of differences in water application and weather conditions during the study, moisture treatments did not significantly influence N uptake and their effect on yield was not consistent across years. In 1985, late application of the moisture treatments, along with inadequate amounts of water applied during the treatments, reduced the potential for N loss. Consequently, the excess moisture treatments did not adversely affect N uptake or yield. In 1987, plants were under prolonged water stress because the irrigation system was not adequate to alleviate the drought conditions. In that year, the 4-in. water treatment resulted in a reduction in yield, but there was no significant reduction associated with the 6-in. water treatment. This may have been due to the fact that the 6-in. water treatment maintained soil moisture tension below 0.33 bar for only 1 d more than the 4-in. treatment, but it maintained soil moisture at 90% of 0.33 bar tension for 4 d longer than the 4-in. water treatment. The additional water associated with the 6-in. treatment sustained better plant growth during the dry period and increased yield (Table 4), even though it had caused a reduction in N uptake (Table 3). This agrees with previous work showing that the efficiency of N use increases as water stress decreases (Eck, 1988).

Soil moisture tension in 1988 was below 0.33 bar for 2 and 7 d for the 4- and 6-in. treatments, respectively. With the 4-in. moisture treatment, no significant yield decrease was found when averaged across N treatment. However, a significant yield reduction was detected with the 6-in. excess moisture treatment.

Using the pooled data, the best regression equation for relative grain yield (Y) was: $Y = 32.1978 + 0.5762\ N + 0.5889\ N_s - 0.0014\ N^2 - 0.0031\ N \times N_s - 0.1004\ M^2$ ($R^2 = 0.8436$). In this equation, N represents applied N (lb/acre), N_s is supplemental N (lb/acre), and M represents the number of days of soil moisture tension below 0.33 bar (Fig. 1).

While relative yield losses of less than 1% were predicted for soil moisture conditions wetter than 0.33 bar for up to 3 d, the loss of relative yield increased rapidly for each additional day of 0.33 bar soil moisture tension (Fig. 1). When soil moisture was wetter than 0.33 bar for 7 d, relative yield was reduced about 5%.

Gallium et al. (1978) suggested that any factor that decreased water flow in a soil probably will increase

Table 5. Effects of rate of N application and soil moisture level on total plant N uptake and fertilizer N recovered at harvest (lb/acre), Drummer sicl in 1985, 1987, and 1988.†

	Soil moisture level								
	Ambient			Ambient + 4 in.			Ambient + 6 in.		
Fertilizer N (lb/acre)	1985	1987	1988	1985	1987	1988	1985	1987	1988
	Plant N uptake (lb/acre)								
0	85.8	67.4	82.6	67.8	70.4	76.4	55.8	61.8	58.6
100	132.3	140.7	145.0	132.7	121.0	123.6	118.8	109.8	133.0
150	159.8	166.8	141.4	159.8	116.7	132.7	153.0	118.1	135.9
200	172.6	191.2	162.4	159.9	146.8	161.4	157.7	145.2	202.1
0 + 50 suppl.	93.8	100.7	108.7	96.0	110.0	101.7	89.2	105.9	90.5
100 + 50 suppl.	140.7	166.5	140.5	154.3	150.1	134.8	150.5	141.4	140.7
150 + 50 suppl.	176.8	176.8	167.4	163.1	141.0	148.3	153.5	157.2	182.9
200 + 50 suppl.	179.0	174.7	186.8	176.8	152.2	181.3	169.0	151.6	184.6
Fertilizer N recovered (150 lb/acre rate), derived from ^{15}N analysis.									
Remaining in soil		56.0	71.6		37.0	36.3		19.5	28.5
Plant uptake		62.5	59.9		35.4	54.2		45.0	51.0
Total recovered		118.5	131.5		72.3	90.5		64.6	79.5

† Values are means of three replicates. Suppl. = supplemental N application after water treatment.

Table 6. Effects of rate of N application and soil moisture level on corn yield (bu/acre). Drummer sicl—1985, 1987, and 1988.†

	Soil moisture level				
Fertilizer N (lb/acre)	Ambient	Ambient + 4 in.	Ambient + 6 in.	Mean	Suppl. N mean
	Yield (bu/acre)				
		1985			
0	94.3	85.0	75.5	84.6a*	
100	157.0	155.8	143.4	152.1b	
150	167.1	164.3	160.1	163.8c	140.9a
200	171.9	165.7	151.9	163.2c	
0 + 50 suppl.	110.3	120.3	112.0	114.2a	
100 + 50 suppl.	153.3	167.3	150.5	157.0b	
150 + 50 suppl.	155.3	155.3	167.4	153.3c	148.2b
200 + 50 suppl.	168.1	169.0	152.0	163.0c	
Mean	147.2a	147.8a	138.7b		
		1987			
0	77.9	82.6	70.9	77.2a	
100	138.6	123.8	125.7	129.4b	
150	138.8	119.1	126.9	128.3bc	119.2a
200	152.5	132.3	139.4	141.4c	
0 + 50 suppl.	102.7	97.8	95.8	98.8a	
100 + 50 suppl.	140.2	141.1	125.8	135.7b	
150 + 50 suppl.	144.0	142.4	143.9	143.6bc	129.5b
200 + 50 suppl.	142.2	140.1	138.2	140.3c	
Mean	129.6a	122.8b	120.8b		
		1988			
0	45.3	47.9	42.5	45.3a	
100	95.3	79.9	83.7	86.3b	
150	91.6	86.0	81.7	86.5b	78.4a
200	90.0	94.4	102.9	95.8c	
0 + 50 suppl.	62.7	65.0	63.3	63.7a	
100 + 50 suppl.	89.8	88.2	74.3	84.1b	
150 + 50 suppl.	101.2	90.1	85.0	92.1b	84.4b
200 + 50 suppl.	99.4	99.5	94.4	97.7c	
Mean	84.4a	81.4a	78.5a		

* Values within a column or row within year followed by the same letter do not differ significantly (0.05).

† Values represent means of three replicates. Suppl. = supplemental N application after excess water treatment.

denitrification. Analysis of soil samples revealed that most of the fertilizer N recovered in soil was found in the top foot of soil (Torbert et al., 1992), with fertilizer N concentration below the 12- to 24-in. zone being within the range of background variability. This would indicate that leaching was not responsible for the N loss at this location. Since leaching is closely related to water movement (Allison, 1973), the impermeable hardpan on this soil, which restricts water movement and creates saturated conditions, would restrict the leaching of nitrate below the rooting zone.

Because soil analysis indicated only small losses of N due to leaching, the yield loss was most probably the result of denitrification. Even with 7 d of soil moisture tension below 0.33 bar, addition of 50 lb supplemental N/acre was sufficient to maintain yield equivalent to that observed at the ambient level with an initial application of 150 lb N/acre.

Drummer

When averaged across water treatments, N uptake and yield increased with increasing N application up to 150 lb N/acre in 1985 and 1988 and 200 lb N/acre in 1987 (Tables 5 and 6). Averaged over the 3 yr of the study, maximum yield was achieved with application of about 200 lb N/acre (Fig. 2). The addition of supplemental N increased yield in 1985 and 1987, but the magnitude of increase decreased with increasing initial N rate.

The 6-in. water treatment in 1985 and the 4- and 6-in. water treatments in 1987 decreased yields. Tensiometers were not installed in 1985, but it is assumed that soil moisture tension was maintained below 0.33 bar for extended periods at the 6-in. excess moisture treatment only. In 1987, tensiometers indicated that soil moisture tension

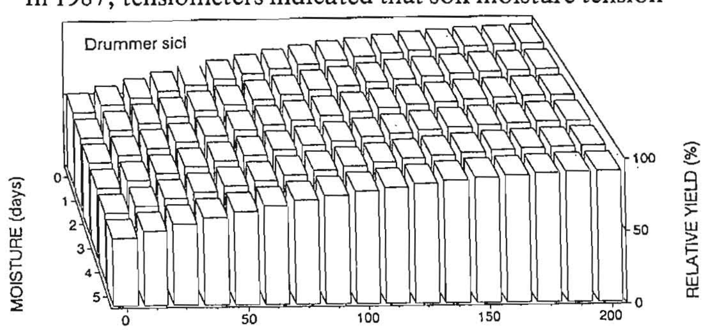

Fig. 2. Effects of fertilizer N application and soil moisture condition (measured in days of soil moisture tension below 0.33 bars) on relative yield of corn grown on a Drummer sicl.

Table 7. Effects of rate of N application and soil moisture level on total plant N uptake and fertilizer N recovered at harvest (lb/acre), Plainfield s in 1985, 1987, and 1988.†

	Soil moisture level					
	Ambient		Ambient + 4 in.		Ambient + 6 in.	
Fertilizer N (lb/acre)	1985	1987	1985	1987	1985	1987
	— Plant N uptake (lb/acre) —					
0	16.5	10.0	10.4	11.4	15.2	14.5
100	73.0	24.5	61.2	13.1	35.5	14.4
150	101.9	36.5	87.1	31.2	50.3	24.8
200	126.8	40.9	90.8	12.7	59.1	14.4
0 + 50 suppl.	60.4	39.7	45.9	38.4	38.8	24.3
100 + 50 suppl.	96.8	55.9	72.6	43.4	66.6	27.7
150 + 50 suppl.	126.3	65.5	107.7	46.2	76.7	39.3
200 + 50 suppl.	141.1	70.5	98.4	53.9	89.7	41.8
Fertilizer N recovered (150 lb/acre rate), derived from ^{15}N analysis.						
Remaining in soil		2.9		4.1		2.5
Plant uptake		23.4		8.5		9.8
Total recovered		26.3		12.6		12.3

† Values are means of three replicates. Suppl. = supplemental N application after water treatment.

for the 4-in. moisture treatment remained below the 0.33 bar level for 4 d, with the 6-in. excess moisture treatment extending this period only one additional day. The 6-in. water treatment significantly reduced the amount of fertilizer N recovered in the plant-soil system as compared with the ambient treatment (Table 5).

Drought conditions occurred on the Drummer in 1988 (Table 2). Limited irrigation facilities at this site resulted in severe water stress and consequently low yield. Thus, the application of excess water did not adversely affect yield.

The best fit regression equation for relative yield was: $Y = 51.9975 + 0.4062\ N + 0.2813\ N_s - 0.0009\ N^2 - 0.0014\ N \times N_s - 1.0579\ M$ ($R_2 = 0.6504$). The pooled results from the 3 yr indicated a decrease in relative yield of about 1% for each day of soil moisture tension below 0.33 bar. Addition of 50 lb N/acre supplemental N to plots that were saturated for 4 d after receiving 150 lb N/acre initially was sufficient to obtain a yield comparable to that achieved with the same initial N rate at ambient moisture.

As in the Cisne soil, most of the N remaining in the soil was found in the surface 1 ft of the soil profile (Torbert et al., 1992). The consistently low levels of fertilizer N observed at greater depths in the soil profile indicate very little loss of N by leaching. Where excess water resulted in significant N loss, a high percentage of the supplemental N applied after the excess moisture treatments had been applied was recovered (Table 5). This suggests that in years of excess rainfall early in the growing season, split application of N could be advantageous. No advantage would be expected in years when soil moisture conditions are not conducive to N loss.

Plainfield

Very low recovery of fertilizer N was observed in the plant-soil system at all moisture levels (Table 7). Less than 5% of the fertilizer N was recovered by plants under the excess water treatments, indicating that the N had been

Table 8. Effects of rate of N application and soil moisture level on corn yield (bu/acre). Plainfield s 1985 and 1987.

	Soil moisture level				
Fertilizer N (lb/acre)	Ambient	Ambient + 4 in.	Ambient + 6 in.	Mean	Suppl. N mean
	Yield (bu/acre)				
		1985			
0	15.5	12.6	18.0	15.4a*	
100	116.2	101.4	54.9	90.9b	
150	148.3	141.2	93.9	127.8c	91.3a
200	151.1	135.7	106.2	131.0c	
0 + 50 suppl.	95.9	78.7	46.6	73.7a	
100 + 50 suppl.	136.3	115.9	87.6	113.3b	
150 + 50 suppl.	138.2	147.9	119.0	134.7c	115.3b
200 + 50 suppl.	162.1	133.7	121.7	139.4c	
Mean	120.8a	108.3b	81.0b		
		1987			
0	2.0	0.9	4.5	2.5a	
100	17.5	6.9	1.1	8.5ab	
150	24.8	11.9	4.8	17.2b	12.3a
200	37.5	6.8	2.3	15.5b	
0 + 50 suppl.	47.5	41.3	22.0	37.0a	
100 + 50 suppl.	74.1	55.5	24.3	51.3ab	
150 + 50 suppl.	80.2	55.8	33.7	56.6b	51.9b
200 + 50 suppl.	89.5	63.0	36.1	62.9b	
Mean	47.9a	30.3b	16.1c		

* Values within a column or row within year followed by the same letter do not differ significantly (0.05).

† Values represent means of three replicates. Suppl. = supplemental N application after excess water treatment.

leached below the rooting zone early in the season. Both N uptake and yield increased with increasing N and supplemental N application and decreased with excess water (Tables 7 and 8). In 1987, mechanical failure of the irrigation pump during pollination and grain fill along with excess water applied as irrigation to the entire plot area early in the growing season, resulted in abnormally low yields (Table 8). The addition of supplemental N dramatically increased yields in this year, indicating that N deficiency was largely responsible for the low yields.

In 1987, fertilizer N accounted for 67 to 89% of the total N uptake in the plant over the three moisture regimes (calculated by the ^{15}N method). Only 15% of the fertilizer N applied was recovered in the above-ground plant with the ambient water treatment. Fertilizer N recovery in the above-ground plant was only 15% with the ambient water treatment and decreased to 6% with both 4- and 6-in. water treatments.

Small amounts of fertilizer N were found at all depths throughout the 4 ft profile at both sampling periods and both years, indicating that leaching was the cause of N loss on this soil (Torbert et al., 1992). This agrees with the findings by Hensler and Attoe (1970), who reported little retention of fall applied fertilizer N in the upper 9 ft of a Plainfield soil sampled the following spring.

The best fit regression equation for relative yield on the Plainfield was: $Y = 23.896 + 0.5751\ N + 0.3969\ N_s - 0.004\ N \times N_s - 1.683\ M - 0.0284\ N \times M + 0.000332\ N \times N_s \times M$ ($R^2 = 0.6709$) where N represents applied N (lb/acre), N_s is supplemental N (lb/acre), and M represents total rainfall + irrigation in May and June (in.).

Relative yield response to both initial and supplemental N application was highly correlated to moisture treatment. Yield losses were proportionally larger with

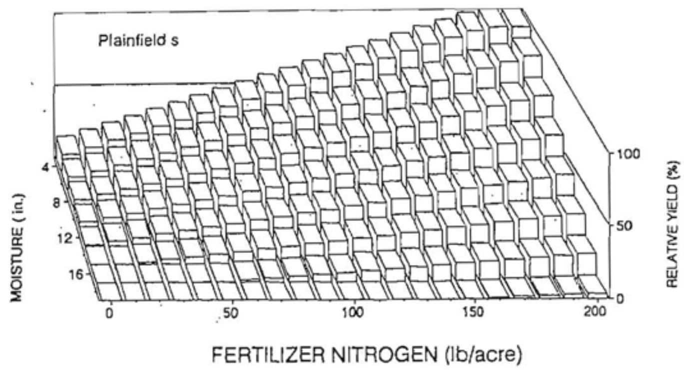

Fig. 3. Effects of fertilizer N application and soil moisture condition (measured in total rainfall + irrigation in May and June) on relative yield of corn grown on a Plainfield s.

increasing N rates and increasing moisture levels (Fig. 3). Similar to the other soils, the effect of supplemental N on relative yield was decreased as the initial rate of N increased. Even with the application of 200 lb N/acre, 17 in. of rainfall plus irrigation in May and June resulted in relative yields as low as 18%. Application of 50 lb N/acre after water treatment increased the relative yield at the 200 lb N/acre rate by 12%.

As expected, excess moisture had a negative effect on corn yield on all three soils, but the response was different among soil types. Yield loss associated with excess water was greatest on the Plainfield sand, where, based on the data obtained, yield would be reduced by 20% with 8 in. of precipitation plus irrigation in May and June without the addition of supplemental N. Each additional inch of excess water would reduce yield about 9.6%. This compares to an N loss of 33% under the same moisture conditions, with a reduction of about 6% with each additional inch. Precipitation in May and June provided the best indication of the amount of yield loss that occurred on the sandy soil.

Number of days in which soil moisture content was wetter than 0.33 bar provided the best correlation to yield loss on the silty clay loam and silt loam soils. On the Drummer silty clay loam, yield decreased at a linear rate of about 1% for each day the soil remained wetter than 0.33 bar. On the Cisne silt loam, yield decreased at an increasing rate as the duration of soil moisture tension wetter than 0.33 bar persisted. Decreases of less than 1% were associated with saturation for up to 3 d, but increased to 5% when soils were saturated for 7 d.

In those instances where yields were reduced by excess water on the finer textured soils, application of supplemental N at a rate of 50 lb/acre resulted in yields comparable with those obtained with the ambient water treatment. The response to supplemental N was dependent on the initial N application rate. On the Plainfield sand, supplemental addition of 50 lb N/acre was not adequate to restore yield of the water treated plots to the level attained with the ambient moisture without the additional N in 2 of the 3 yr.

Application of supplemental N can be difficult, damaging to the crop, expensive, and is usually limited to early in the growing season (Olson and Kurtz, 1982). The equations developed in this study could be used to predict yield losses experienced with large rainfall events to assist in management decisions of whether supplemental N application is advisable and economically warranted.

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REFERENCES

Allison, F.E. 1966. The fate of nitrogen applied to soils. Adv. Agron. 18:219–258.

Allison, F.E. 1973. Soil organic matter and its role in crop production. Elsevier Scientific Publishing, New York.

Asghari, M., and R.G. Hanson. 1984. Nitrogen, climate, and previous crop effect on yield and grain N. Agron. J .76:536–542.

Bondavalli, F., D. Coyler, and E. Kroth. 1970. Effects of weather, nitrogen, and population on corn yield response. Agron. J. 62:669–672.

Bremner, J.M., and C.S. Mulvaney. 1982. Nitrogen—Total. p. 595–625. *In* A.L. Page et al. (ed.) Methods of soil analysis: Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Bremner, J.M., and K. Shaw. 1958. Denitrification in soil. II. Factors affecting denitrification. J. Agric. Sci. 51:39–52.

Calsyn, D.E. 1989. Soil survey of Cass County, Illinois. USDA-SCS, Washignton, DC.

Carson, P.L. 1980. Recommended potassium test. p. 17–18. *In* Recommended soil test procedures for the North Central Region. North Dakota Agric. Exp. Stn. Bull. no. 499 (rev.).

Craswell, E.T. 1978. Some factors influencing denitrification and nitrogen immobilization in a clay soil. Soil Biol. Biochem. 10:241–245.

Downey, C.E., and R.T. Odell. 1969. Soil survey of Montgomery County, Illinois. USDA-SCS, Washington, DC.

Eck, H.V. 1988. Winter wheat response to nitrogen and irrigation. Agron. J. 80:902–908.

Gallium, J.W., S. Dasberg, L.J. Lund, and D.D. Focht. 1978. Denitrification in four California soils: Effects of soil profile characteristics. Soil Sci. Soc. Am. J. 42:61–66.

Hauck, R.D. 1984. Technological approaches to improving the efficiency of nitrogen fertilizer use by crop plants. p. 551–560. *In* R.D. Hauck (ed.) Nitrogen in crop production. ASA, CSSA, and SSSA, Madison, WI.

Hensler, R.F., and O.J. Attoe. 1970. Rural source of nitrates in water. *In* V.L. Snoeyink (ed.) Nitrate and water supply: Source and control. Proc. 12th Sanitary Engr. Conf., Urbana, IL. 11–12 Feb. Univ. of Illinois, Urbana.

Hinckley, K.C. 1978. Soil survey of DeKalb County, Illinois. USDA-SCS, Washington, DC.

Keeney, D.R., I.R. Fillery, and G.P. Marx. 1979. Effect of temperature on the gaseous nitrogen products of denitrification in a silt loam soil. Soil Sci. Soc. Am. J. 43:1124–1128.

Keeney, D.R., and D.W. Nelson. 1982. Nitrogen—Inorganic forms. p. 643–693. *In* A.L. Page et al. (ed.) Methods of soil analysis: Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Klute, A. 1965. Water capacity. p. 273–278. *In* C.A. Black et al. (ed.) Methods of soil analysis: Part 1. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Knudsen, D. 1980. Recommended phosphorus tests. p. 14–16. *In* Recommended soil test procedures for the North Central Region. North Dakota Agric. Exp. Stn. Bull. no. 499 (rev.).

Legg, J.O., and J.J. Meisinger. 1982. Soil nitrogen budget. p. 203–557. *In* F.J. Stevenson et al. (ed.) Nitrogen in agricultural soils. Agron. Monogr. 22. ASA and SSSA, Madison, WI.

Mulvaney, R.L., C.L. Fohringer, V.J. Bojan, M.M. Michilk, and L.F. Herzog. 1990. A commercial system for automated nitrogen isotope-ratio analysis by the Rittenberg technique. Rev. Sci. Instrum. 61:897–903.

Mulvaney, R.L., and L.T. Kurtz. 1984. Evolution of dinitrogen and nitrous oxide from nitrogen-15 fertilized soil cores subjected to wetting and drying cycles. Soil Sci. Soc. Am. J. 48:596–602.

Nelson, D.W., and L.E. Sommers. 1982. Total carbon, organic carbon, and organic matter. p. 565–571. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Neter, J., and W. Wasserman. 1974. Applied linear statistical models. Richard D. Irwin, Inc., Homewood, IL.

Olson, R.A., and L.T. Kurtz. 1982. Crop nitrogen requirements, utilization, and fertilization. p. 567–599. *In* F.J. Stevenson et al. (ed.) Nitrogen in agricultural soils. Agron. Monogr. 22. ASA and SSSA, Madison, WI.

Pilot, L., and W.H. Patrick. 1972. Nitrate reduction in soils: Effect of soil moisture tension. Soil Sci. 114:312–316.

Rolston, D.E., A.N. Sharpley, D.W. Toy, and F.E. Broadbent. 1982. Field measurement of denitrification: III. Rates during irrigation cycles. Soil Sci. Soc. Am. J. 46:289–296.

Ryden, J.C., and K.P. Dawson. 1982. Evaluation of the acetylene inhibition technique for field measurement of denitrification in grassland soils. J. Sci. Food Agric. 33:1197–1206.

Ryden, J.C., and L.J. Lund. 1980. Nature and extent of directly measured denitrification losses from some irrigated vegetable crop production units. Soil Sci. Soc. Am. J. 44:505–511.

Ryden, J.C., L.J. Lund, J. Letey, and D.D. Focht. 1979. Direct measurement of denitrification loss from soils: II. Development and application of field methods. Soil Sci. Soc. Am. J. 43:110–118.

SAS Institute. 1982. SAS users guide: Statistics. SAS Inst., Cary, NC.

Sexstone, A.J., T.B. Parkin, and J.M. Tiedje. 1985. Temporal response of soil denitrification rates to rainfall and irrigation. Soil Sci. Soc. Am. J. 49:99–103.

Smith, M.S., and J.S. Tiedje. 1979. The effect of roots on soil denitrification. Soil Sci. Soc. Am. J. 43:951–955.

Tanji, K.K. 1982. Modeling of the soil nitrogen cycle. p. 721–773. *In* F.J. Stevenson et al. (ed.) Nitrogen in agricultural soils. Agron. Monogr. 22. ASA and SSSA, Madison, WI.

Torbert, H.A., R.G. Hoeft, R.M. Vanden Heuvel, and R.L. Mulvaney. 1992. Effect of moisture regime on recovery and utilization of fertilizer N applied to corn. Commun. Soil Sci. Plant Anal. 23:1409–1426.

Voss, R.E., J.J. Hanway, and W.A. Fuller. 1970. Influence of soil management and climate factors on the yield response by corn (*Zea Mays* L.) to N, P, and K fertilizer. Agron. J. 62:736–740.