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Nitrogen Management Impacts on Yield and Nitrate Leaching in Inbred Maize Systems

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ABSTRACT

Little information is available regarding N management of inbred maize (*Zea mays* L.), which exports less N than hybrid maize. Nitrate contamination of the groundwater has been a concern in St Joseph County in southwest Michigan where >20 000 ha of seed maize are grown on sand and sandy loam soils. Over application of N fertilizer potentially reduces profits of the local growers and poses a threat to the environment. A field experiment was conducted from 1990 to 1994 to estimate N fertilizer requirements of three different inbred varieties for maximizing yields while minimizing ground water pollution. Yield and N content of grain and stover were analyzed at the end of each growing season. Nitrate leaching was monitored throughout the 5 yr of study by collecting and analyzing drainage flows out of five large field lysimeters. Grain yield was the least responsive to N fertilization, compared with stover biomass, and grain and stover N concentrations. Analyses of yield, NO_3–N leaching and soil N balance indicated that the appropriate fertilization of the P38 mid-season inbred approximated 108 kg N ha^{-1}. Nitrate leaching out of unfertilized plots reached a threshold of 12 to 15 kg N ha^{-1} yr^{-1}, during the last 2 yr of treatment. Application of 101 and 202 kg N ha^{-1} generated an average annual loss of 26 and 60 kg N ha^{-1}, respectively, during the last 2 yr of treatment.

INBRED MAIZE, planted for hybrid seed production, is a major crop and source of income for growers in St Joseph County, southwest Michigan. Inbred maize is produced in the county on approximately 20 000 ha. The region presents favorable climatic conditions and soil types, mostly sandy loams and sands, and has abundant irrigation water. In the last decade, NO_3–N concentrations above the U.S. Environmental Protection Agency's maximum contaminate level of 10 mg NO_3–N L^{-1} were found in the ground water used for public water supply of one community, which raised concerns about the impact of seed maize production on ground water quality. Nitrogen fertilization in excess of inbred maize requirements could be a major source of NO_3–N contamination. Ground water contamination by NO_3–N leached from over-fertilized hybrid maize fields has been reported in numerous studies (Ferguson et al., 1991; Jemison and Fox, 1994; Kladivko et al., 1991). Inbred maize plants produce less biomass and lower grain yield than hybrids (Wilhelm et al., 1995); however, N fertilization has been reported to increase seed yields of inbred lines (Peterson and Corak, 1993; Wilhelm et al., 1995).

The low cost of N fertilizers combined with a growers incentive policy for above-average yields has encouraged farmers to over-fertilize their inbred-maize fields. Nitrogen fertilizer application in excess of maize requirements is considered cheap insurance against excess rainfall, which may move N below the root zone (Martin, 1992). Several researchers have expressed the need for better tailoring N fertilization management to inbred maize requirements (Peterson and Corak, 1993; Martin, 1992; Wilhelm et al., 1995; Wych, 1988). Average N fertilization for inbred maize was 163 kg N ha^{-1} for St Joseph County in 1991 (Rod King, County Extension

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Abbreviations: VNR, variable nitrogen rate; PRF, plat response to fertilization.

Director, 1997, personal communication). However, the N requirements of inbred maize and associated NO_3–N leaching have not been clearly determined. This article reports a 5-yr research project conducted to investigate whether N application could be reduced, while sustaining seed maize yields.

MATERIAL AND METHODS

A field experiment was conducted from 1990 to 1994 on an Elston sandy loam (coarse-loamy, mixed mesic Typic Argiudolls) at Constantine (St Joseph County), in southwest Michigan. The soil at the experimental site averaged 1.41% C and 0.12% N in the surface 0 to 22.5 cm, and 0.74% C and 0.06% N at a depth of 22.5 to 50.0 cm. Three N treatments and a 0 N control were tested on three inbred lines consisting of an early season (P02), a mid-season (P38), and a late-season (T10) maturity types. The N treatments were: (i) 202 kg N ha^{-1} as preplant application, (ii) 101 kg N ha^{-1} applied as 34 kg N ha^{-1} preplant and 67 kg N ha^{-1} sidedress, (iii) variable N rate (VNR), and (iv) a zero N control. Locations of individual research plots and corresponding treatments were kept constant during the 5-yr period. Nitrogen was applied in the form of ammonium-nitrate (34–0–0) and sidedress applications were conducted between the sixth and eighth leaf stage. The plots were under seed maize production in 1989. Prior to that year, the site consisted of a mixed field of grasses and alfalfa (*Medicago sativa* L.). The experiment was established following a split-plot design with N fertilizer as main plot and variety as sub-plot. Every treatment was represented within each of the four complete blocks. Plots were 6 m long and contained 10 rows of inbred maize. For every growing season, inbred maize was planted and thinned to 61 730 plants ha^{-1} in 76-cm rows at a depth of 4.5 cm. Plots were chisel plowed in April, planted in May, and cultivated in June of each year. Two blocks of four inbred rows were designated as productive female plants, while the remaining two maize rows of each plot were assigned as male plants for pollination. Maize plants from female rows were detasselled, while male plants were cut at soil level after silking of the female plants was completed. Ears were removed at harvest, while plant stover remained on the plots. Irrigation of the research plots was scheduled according to the computer program SCS-Scheduler (Shayya and Bralts, 1993) that uses precipitation and temperature data from the research site to estimate the soil water balance.

The VNR treatment was used to test different rates of N fertilization for each individual growing season. For the first two growing seasons, VNR was based on plant response to fertilization (PRF). The basic concept for PRF is to provide N fertilizer when the plants display incipient signs of N deficiency. Plant height and chlorophyll meter measurements were used to decide upon N fertilization. The greenness of the canopy and the growth rate of the plants were compared with a well fertilized plot. Nitrogen fertilizer was added immediately after a significant difference was observed. No deficiencies were observed in 1990, therefore plots remained unfertilized. In 1991, VNR plots received 45 kg N ha^{-1} for PO2 and 0 kg N ha^{-1} for P38 and T10. The PRF technique, as used in the early stage of this study, did not properly detect N deficiencies and resulted in delayed or canceled N fertilization. For the following growing seasons, N was sidedressed at rate of 56 kg N ha^{-1} in 1993 and 1992, and 67 kg N ha^{-1} in 1994.

Yields and biomass measurements were conducted by harvesting all plants from two rows out of each plot. Samples were separated into stover, grain, and cob. The samples were oven dried at 65°C, finely ground and analyzed for total N using standard Kjeldahl procedure (Bremner and Mulvaney, 1982). Grain yield, reported at 15.5% moisture content, and dry stover biomass were computed on a per total field surface basis.

Five in situ field lysimeters, 92 cm by 381 cm by 183 cm deep, were installed in 1988, as described by Kalmbach (1995). The width of the lysimeters corresponds to five rows of maize. The 0, 101 N, and VNR treatments were each represented by one lysimeter, while two lysimeters were installed in plots receiving 202 N. Data from the two 202 N lysimeters were averaged. All lysimeters were established in plots planted with the P38 variety. Each lysimeter was equipped with an access chamber 122 cm by 122 cm by 183 cm deep. The access chambers were installed 56 cm deeper than the bottom of the lysimeter to allow a collection container to be placed under the drainage pipe. Lysimeters were installed 30 cm below the soil surface so that normal field operations could be conducted across the plots. Collection and sampling of the drainage water from each lysimeter was conducted from July 1989 to September1993 by an automated system consisting of a tipping bucket, a data logger, a water pump, and an autosampler. In September 1993, the automated sampling system failed. At that time, large sealed collection containers were installed. From then on, sampling was conducted manually with a water pump once every 2 wk. Water samples from the lysimeters were analyzed for NO_3–N by spectrophotometry (Environmental Monitoring and Support Laboratory, 1983) using a QuickChem automated flow injection ion analyzer (Lachat Instruments, Milwaukee, WI). Nitrate concentration of the lysimeter leachate was used with drainage volume to derive NO_3–N leaching loss over time.

Yield components and N contents were analyzed for each individual year by the contrast method using the mixed model procedure of the SAS system (Littel et al., 1996). On an individual year basis, no fertilizer by variety interactions were found significant for any of the yield components. Consequently, fertilizer treatments were pooled together in the analyses of the variety factor, and varieties were pooled together for analyzing N fertilization effects. In a second step, the five growing seasons were considered together and yield components were analyzed using univariate repeated measure techniques based on the mixed procedure of the SAS system (Gregoire et al., 1995; Littel et al., 1996). In this analysis, the 5 yr of data were combined together to test for significant treatment and interaction effects. The regrouping of the five growing seasons in one analysis enhanced the sensitivity of the statistical tests. Repeated measures analyses permit inference on main effects and interactions between treatments and treatments by time while accounting for the fact that repeated observations on the same experimental unit are not independent.

RESULTS

Biomass Components and Yields

Grain yields were significantly affected by the variety factor for four growing seasons out of five (Table 1). Inbreds PO2 and P38 produced similar grain yields in 3 out of 5 yr, while the T10 variety displayed significantly lower yields compared with the two other inbreds for the 1990 to 1993 growing seasons. Grain yields appeared little affected by N fertilizer treatments (Table 1). For 4 out of 5 yr, no overall response to fertilizer was observed. No significant fertilizer effect on grain yield was observed when the five growing seasons were grouped

Table 1. Grain yields (84.5% dry matter) and stover biomass (100% dry matter) responses to variety and N fertilizer for the 1990 to 1994 growing seasons.

	Grain yields					Stover biomass				
	1990	1991	1992	1993	1994	1990	1991	1992	1993	1994
	kg ha^{-1}					kg ha^{-1}				
Variety										
PO2	5270b†	6350a	6230a	6400a	4490a	4950c	8200b	7280b	6560b	3810b
P38	6350a	5780ab	5050b	6370a	4380a	7260a	9030a	8176a	8850a	4010ab
T10	4450c	5390b	3860c	4990b	4260a	6070b	9560a	7530b	8600a	4390a
SE‡	257	302	228	241	225	244	320	278	340	211
N										
202N	5410a	5820a	5140a	5850a	5100a	6160a	9090a	8090a	8670a	4930a
101N	5350a	6220a	5220a	5600a	4330ab	6290a	9610a	7910a	8130ab	4120b
VNR	5590a	5770a	5310a	5700a	4400ab	6270a	8740a	7710a	7880bc	4050b
0 N	5110a	5570a	4520a	5740a	3590b	5640a	8288a	6940a	7300c	3140c
SE	300	366	308	400	390	347	466	466	394	284

† Within years and factors, means followed by the same letter are not significantly different at $P \leq 0.05$.
‡ Standard errors for mean comparisons.

in a repeated measures analysis (Table 2). Nevertheless, the interaction between variety and N fertilizer across the 5-yr period was highly significant, which implies that varieties responded differently to N fertilization. Consequently, a separate analysis of the effect of N fertilization on grain yield was required for each individual variety. Grain yields for the varieties PO2 and P38 were significantly affected by N fertilization (Table 3), while T10 did not significantly respond to N fertilization. Varieties PO2 and P38 presented a different response to N fertilization. The PO2 variety produced maximum grain yield with a preplant application of 202 kg N ha^{-1} (Table 3). The P38 variety produced maximum grain yields with a split application of 101 kg N ha^{-1}, with significant yield increases compared with the VNR treatment and zero N control. On a 5-yr average, split application of 101 kg N ha^{-1} increased grain yields by 20% compared with the zero N control. No significant yield improvement was observed by an application of 202 kg N ha^{-1} compared with 101 kg N ha^{-1} for the P38 variety.

Total production of dry stover biomass was significantly affected by the variety factor 4 out of 5 yr, and by N fertilization 3 out of 5 yr (Table 1). Though T10 displayed lower grain yields, it produced equal or greater quantities of stover biomass than PO2 and P38. Differences in stover biomass between fertilizer treatments increased from 1990 to 1994. The zero N treatment consistently produced less stover biomass than the other treatments. During the 5-yr period, differences in stover biomass production were pronounced ($P \leq 0.001$) among varieties and significant ($P \leq 0.05$) among fertilizer treatments (Table 2).

Nitrogen concentration of the grain was significantly increased by N fertilization 3 out of 5 yr but only significantly altered by the variety factor in 1991 (Table 4). Grain N responses to N fertilization from 1991 to 1994 were consistently in the order 202 kg N ha^{-1} > 101 kg N ha^{-1} > VNR > zero N control. During the 5-yr period, grain N concentration was not significantly modified by the variety factor, but displayed a pronounced ($P \leq 0.001$) response to N fertilization (Table 2). The apparent absence of varietal effect on grain N concentration is partially hidden in the significant variety by year interaction. This indicates that the variety factor did not display a consistent effect on grain N throughout the five growing seasons. During the 5-yr period, N concentration of the stover was significantly modified by variety and N fertilization (Table 2). Variety P38 reached the greatest N concentration in the stover compared with PO2 and T10 for three growing seasons out of five (Table 4). No significant difference in stover N between varieties was observed for the two other growing seasons. Nitrogen fertilization significantly increased the N concentration of the stover, with 202 N having consistently greatest N concentrations.

In three growing seasons out of five, T10 exported the least amount of N through grain removal compared with PO2 and P38 (Table 5). Nitrogen fertilization significantly increased grain N exports compared with the unfertilized treatment only in 1992 and 1994. Nevertheless, across the 5-yr period, the effect of N fertilization

Table 2. Significance of the main effects, variety, N, and year and their interactions for a multiple year analysis from 1990 to 1994.

	Significance for multiple year analysis 1990–1994						
Source of variation	Grain biomass	Stover biomass	Grain N percent	Stover N percent	Total N grain	Total N stover	Total N plant
Variety	***	***	NS	**	***	***	***
N	NS	*	***	**	***	**	***
Variety × N	**	NS	NS	NS	*	NS	NS
Year	***	***	***	***	***	***	***
Variety × Year	***	***	***	NS	***	**	**
N × Year	NS	NS	NS	NS	NS	**	*
Variety × N × Year	NS	NS	NS	NS	NS	NS	NS

*, **, ***Significant at $P \leq 0.05$, 0.01, and 0.001, respectively.

Table 3. Nitrogen fertilization effect on grain yields (84.5% dry matter) analyzed by repeated measures analyses across the 1990 to 1994 period.

N Fertilization	Variety PO2	Variety P38	Variety T10
		kg ha^{-1}	
202N	6270a†	5740ab	4620a
101N	5710b	6060a	4490a
VNR	5690b	5500bc	4890a
0 N	5330b	5020c	4370a
SE‡	260	260	260

† Within varieties, means followed by the same letter are not significantly different at $P \leq 0.05$.
‡ Standard errors for mean comparisons.

on grain N exports was pronounced ($P \leq 0.001$) (Table 2). Total amount of N contained in the stover biomass was consistently higher for the P38 variety (Table 5). Higher rates of N fertilizer application induced greater amounts of N in the stover.

Nitrate Leaching and Soil Nitrogen Balance

Total amounts of NO_3–N leached out of the field lysimeters during the 1991 to 1994 period was greatest for the 202 N treatment and smallest for the 0 N control (Table 6). Though the 0 N control lost 34 kg N ha^{-1} on average each year, a decline in N leaching was observed from 1990 to 1993. Nitrate leaching losses averaged only 13 kg N ha^{-1} for the last 2 yr in the 0 N lysimeter. The 101 N and VNR treatments displayed similar quantities of NO_3–N leaching during the 5 yr of study. The 202 N consistently presented the highest NO_3–N leaching losses throughout the 5-yr period.

Peaks of NO_3–N leaching for each of the 5 yr were observed in November 1990, November 1991, September 1993, October 1994, and January 1995 (Fig. 1). Nitrate leaching during the spring and summer months was only a small fraction of the NO_3–N leached over an entire year. The repetitive pattern of NO_3–N leaching throughout the 5-yr period was only partially matched by the more evenly distributed pattern of precipitation.

The amount of N gained or lost by the soil from 1990 to 1994 is represented by the difference between the N inputs, in the form of fertilizers, and the N outputs from grain exports and leaching (Table 6). The assumption was made that minor N inputs from atmospheric deposition and outputs from denitrification canceled out their contributions to the soil N budget. Denitrification rates of well drained sandy loams were reported to range from 0.015 to 0.040 kg N ha^{-1} d^{-1} (Myrold and Tiedje, 1986). Atmospheric deposition of inorganic N averaged 7.0 kg N ha^{-1} yr^{-1} for the period from 1990 to 1994 (National Atmospheric Deposition Program [on line], 1998). All treatments displayed a negative soil N balance in 1990 (Table 6). Soil N balances of the 202 N and 101 N treatments became positive in 1991 and 1994, respectively. Soil N balances remained negative throughout the 5 yr of study for the VNR and unfertilized treatments. The soil profile of the 0 N treatment lost an estimated 486 kg N ha^{-1} during the 5-yr study to seed N exports and NO_3–N leaching.

DISCUSSION

Biomass Components and Yields

Grain yields displayed little response to N fertilization, while stover biomass, stover N, grain N and plant N were significantly modified by N fertilization treatment (Table 2). Similar results were obtained by Peterson and Corak (1993), who reported a response from inbred grain yields to N fertilization at only 15 out of 71 site-years. The low grain yield response to N fertilization strongly suggests that inbred maize has the capacity to compensate for low N availability by partitioning more N to the grain. Nevertheless, the apparent lack of response from inbred seed yields to N fertilization has to be tempered by two observations. First, on an individual year basis, 1994 displayed for the first time in the study a significant yield loss due to the lack of N fertilization. All plots were under a mixed stand of grass and alfalfa for many years prior to 1989, which suggests that the soil contained substantial quantities of easily mineralizable N at the beginning of the study. Several studies have reported the contribution of alfalfa stands to the N uptake of subsequent maize crops. Bruulsema and Christie (1987) estimated that the N replacement value of alfalfa to a succeeding maize crop ranged from 90 to 125 kg N ha^{-1}. Fox and Piekielek (1988) reported a total N replacement value for a 3-yr old alfalfa stand followed

Table 4. Nitrogen concentration of grain and stover in response to variety and N fertilizer for the 1990 to 1994 growing seasons.

	Grain N concentration 1990	1991	1992	1993	1994	Stover N concentration 1990	1991	1992	1993	1994
						%				
Variety										
PO2	1.62a†	1.43b	1.44a	1.50a	1.53a	1.22a	0.80b	0.72c	0.95b	0.91a
P38	1.61a	1.63a	1.46a	1.50a	1.48a	1.21a	0.96a	1.02a	1.11a	1.07a
T10	1.54a	1.57a	1.50a	1.58a	1.47a	1.08a	0.73c	0.91b	1.11a	0.97a
SE‡	0.06	0.03	0.05	0.04	0.05	0.14	0.03	0.04	0.07	0.09
N										
202N	1.65a	1.65a	1.55a	1.60a	1.67a	1.15a	1.05a	1.13a	1.20a	1.17a
101N	1.68a	1.62a	1.48a	1.58a	1.52b	1.18a	0.92b	0.87b	1.07a	0.97ab
VNR	1.51a	1.49b	1.46a	1.53a	1.48b	1.14a	0.70c	0.83bc	1.06a	0.97ab
0 N	1.52a	1.39c	1.37a	1.40b	1.31c	1.22a	0.66c	0.69c	0.89a	0.82b
SE	0.08	0.04	0.06	0.05	0.06	0.16	0.05	0.08	0.15	0.10

† Within years and factors, means followed by the same letter are not significantly different at $P \leq 0.05$.
‡ Standard errors for mean comparisons.

Table 5. Total N content of grain and stover in response to variety and N fertilizer for the 1990 to 1994 growing seasons.

	Total grain N					Total stover N				
	1990	1991	1992	1993	1994	1990	1991	1992	1993	1994
	kg N ha^{-1}									
Variety										
PO2	72.5†	71.2a	76.4a	81.5a	59.0a	60.5b	66.1b	52.6c	63.6b	36.3a
P38	87.2a	79.7a	62.8b	81.3a	54.8a	87.2a	88.3a	85.3a	98.1a	44.4a
T10	58.1c	71.5a	49.3c	66.6b	53.4a	65.3b	69.8b	68.4b	96.1a	42.8a
SE‡	4.6	5.8	4.0	3.5	3.4	8.6	4.4	5.1	7.9	4.2
N										
202N	76.6a	81.3a	66.9a	84.8a	72.0a	71.7a	95.2a	92.7a	104.3a	57.7a
101N	77.2a	77.4a	66.1a	80.0a	56.1b	75.0a	87.9a	69.8b	88.4ab	40.5b
VNR	71.6a	72.2a	65.9a	73.6a	55.2b	70.8a	60.8b	65.1b	85.2ab	40.2b
0 N	65.2a	65.6a	52.3b	67.8a	39.6c	66.6a	54.8b	48.2c	66.1b	26.1c
SE	6.8	6.7	4.6	6.7	4.9	9.9	5.9	7.1	12.0	5.6

† Within years and factors, means followed by the same letter are not significantly different at $P \leq 0.05$.
‡ Standard errors for mean comparisons.

by 3 yr of consecutive maize to be 167 kg N ha^{-1}. The soil in the zero N control probably became progressively depleted in easily mineralizable N in the course of the 5-yr experiment. Nevertheless, the decrease in grain yields over the successive growing seasons was not linear. Hence, grain yields in 1993 were not improved by N fertilization, which suggests that the weather conditions were favorable to soil organic matter mineralization at times corresponding to maximum plant uptake. This possible depletion of soil N pools during the 1993 growing season could be responsible for the significant yield loss in the control treatment in 1994. The second factor masking grain yield responses to N fertilization is the strong interaction between variety and fertility. As mentioned in the results section, the three varieties presented different responses to N fertilization. Variety PO2 produced maximum grain yields with a preplant application of 202 kg N ha^{-1}. Variety P38 produced similar grain yields with 202 or 101 kg N ha^{-1}, with significant yield depletion under VNR and unfertilized managements. Grain yields for the variety T10 were not significantly augmented by N fertilization during the 5 yr of study. These observations imply that each new variety should be tested separately for its response to N fertilization. Similar observations were reported for hybrid maize by Tsai et al. (1984) who observed greater N fertilizer requirements for high yielding varieties. When hybrid maize yields are contained within a fairly narrow range, the interaction between N fertilizer rate and variety ceases to exist (Bundy and Carter, 1988). Developing specific recommendation for each inbred might not be practically feasible. Nevertheless, the variety that did not respond to N fertilization is low yielding compared with the two varieties that responded to N fertilization. The T10 variety averaged 4570 kg ha^{-1} across years and N application rates, while PO2 and P38, respectively, averaged 5770 and 5580 kg ha^{-1}. Preplant application of 202 kg N ha^{-1} generated higher yields than a split application of 101 kg N ha^{-1} only for the PO2 variety. Not only is the PO2 variety high yielding,

Table 6. Nitrate leaching, ear (grain and cob) N exports, N applied and resulting soil N balance for variety P38 from May 1990 to May 1995.

Treatment	N Leaching	Ear N exports	N applied	Soil N balance
	kg N ha^{-1}			
May 1990–May 1991				
202N	139	94	202	−31
101 N	122	108	101	−129
VNR	75	96	0	−171
0 N	81	81	0	−162
May 1991–May 1992				
202N	68	93	202	41
101 N	45	99	101	−43
VNR	42	78	0	−120
0 N	34	71	0	−105
May 1992–May 1993				
202N	77	72	202	53
101 N	37	73	101	−9
VNR	37	67	56	−48
0 N	27	52	0	−79
May 1993–May 1994				
202N	52	89	202	61
101 N	22	100	101	−21
VNR	26	82	56	−52
0 N	12	70	0	−82
May 1994–May 1995				
202N	68	80	202	54
101 N	30	64	101	7
VNR	27	52	67	−12
0 N	15	42	0	−57
May 1990–May 1995				
202N	404	428	1010	178
101 N	256	443	505	−194
VNR	207	375	179	−403
0 N	170	316	0	−486

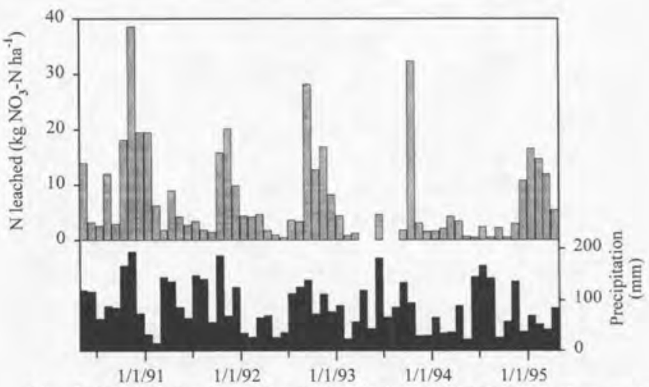

Fig. 1. Nitrate leaching (kg N ha^{-1}) from 202 N lysimeters and precipitation, as monthly totals, for the period from 1 May 1990 to 1 May 1995.

but it also reaches maturity earlier in the season than the P38 variety, which suggests that PO2 might have a greater need for soil N earlier in the season than P38. Therefore, the PO2 variety has the potential for a greater use efficiency of preplant N application than P38.

Nitrate Leaching and Soil Nitrogen Balance

Nitrate leaching from the 0 N lysimeter decreased annually from 1990 to 1993 to reach NO_3–N losses comprised between 12 and 15 kg N ha^{-1} yr^{-1} in 1993 and 1994. Consequently, minimum NO_3–N leaching for Elston sandy loams under irrigated seed maize production appears to be in the 12 to 15 kg N ha^{-1} yr^{-1}. The 101 N and VNR treatments displayed a pattern of NO_3–N leaching from 1990 to 1994 similar to the control treatment, with decreasing amounts of NO_3–N lost to leaching from 1990 to 1993. During the 1993–1995 period, the 101 N and the VNR lysimeters lost respectively 52 and 53 kg N ha^{-1} to deep leaching. These quantities are nearly identical in spite of the fact that the 101 N treatment received 77 kg N ha^{-1} more than the VNR treatment during the 2-yr period (Table 6). These results concur with previous studies that report that maize N fertilization only tends to generate N leaching problems when applications are in excess of plant uptake (Angle et al., 1993; Gast et al., 1978). Hence, Gast et al. (1978) reported little NO_3–N leaching differences between hybrid maize fields receiving from 22 to 112 kg N ha^{-1}. Similar results were reported by Sexton et al. (1996), who estimated N leaching rates of 21, 30, and 78 kg N ha^{-1} yr^{-1} corresponding to fertilizer application of 20, 100, and 180 kg N ha^{-1}, respectively. The baseline of NO_3–N leaching reached during the 1993 to 1995 period under 101 N and VNR treatments proved greater than the zero N control by only 13 kg N ha^{-1} yr^{-1}. Preplant application of 202 kg N ha^{-1} resulted in average annual NO_3–N losses by deep leaching of 60 kg N ha^{-1} yr^{-1} for the1993 to 1995 period, which represents an additional 34 kg N ha^{-1} yr^{-1} compared with the 101 N or VNR treatments. During an 11-yr period in Minnesota, Randall and Iragavarapu (1995) report that an N fertilization rate of 200 kg N ha^{-1} was sufficient to produce average grain yields of 8.6 Mg ha^{-1}, while maintaining average annual leaching rates at 40 kg N ha^{-1}. In our study, grain yields of the mid-season variety were not significantly different between the 101 N and the 202 N treatments. These findings concur with the results of Peterson and Corak (1993) who reported that, when inbreds respond to N fertilization, grain yields reach a plateau at fertilization rates of 100 to 110 kg N ha^{-1}. Our study demonstrates an obvious environmental and economical disadvantage to apply 202 kg N ha^{-1} to the P38 inbred variety on a Elston sandy loam, compared with a split application of 101 kg N ha^{-1}.

Nitrate leaching mostly occurred in the fall and early winter of each year (Fig. 1). This indicates that after the winter flush, little NO_3–N remained to be leached in the spring. Low NO_3–N leaching during the summer probably resulted from the high evaporative demand and NO_3–N uptake of the growing maize crop. This seasonal leaching pattern must be considered when implementing techniques for reducing leaching. For example, cover crops will only be effective for removing NO_3–N from the soil profile when substantial plant growth can be reached by early fall. This implies that cover crops planted for the purpose of scavenging excessive NO_3–N should be interseeded with maize early in the growing season.

After four growing seasons, the 101 N treatment displayed a positive soil N balance, which suggests that 101 kg N ha^{-1} became sufficient to replenish the soil supplies in mineral and easily mineralizable N. Nevertheless, grain yields were low for the 1994 growing season, which might explain the slightly positive soil N balance of the 101 N. For this treatment, average ear (grain and cob) export was 82 kg N ha^{-1}, and NO_3–N leaching loss tended toward an equilibrium of 26 kg N ha^{-1} yr^{-1} for the two last growing seasons. Therefore, total N removed from the soil by ear export and deep leaching was 108 kg N ha^{-1} yr^{-1}. This indicates that the 101 kg N ha^{-1} rate was slightly deficient, and that a split application of about 108 kg N ha^{-1} yr^{-1} would provide sufficient N for continuous production of the P38 inbred without long-term depletion of the N pool of these soils. This rate of 108 kg N ha^{-1} is substantially lower than the average N amount applied by local growers in 1991 of 161 kg N ha^{-1}. Therefore, reducing N fertilization rates by about 50 kg N ha^{-1} is expected to substantially decrease nitrate leaching without negatively impacting seed yields. Application of 108 kg N ha^{-1} yr^{-1} for an expected yield of about 5.6 Mg ha^{-1} represents a slightly lower ratio of fertilizer N to grain yield than what is generally reported in the literature for hybrid maize. Optimum economical N fertilization of hybrid maize was 168 to 180 kg N ha^{-1} for expected yields ranging from 7.5 to 8.8 Mg ha^{-1} (Schlegel and Havlin, 1995; Williams et al., 1992), and of 275 kg N ha^{-1} for expected yields of 10.5 Mg ha^{-1} (Liang and MacKenzie, 1994). A negative soil N balance for the zero N control indicates that the soil organic matter had not yet reached an equilibrium 6 yr after shifting from grass–alfalfa mixture to inbred maize production. Nevertheless, the time series from 1990 to 1994 presented a distinctive trend toward equilibrium. The zero N control produced similar yields to the 101 N or 202 N treatments for the initial years of the study, but appeared to induce soil N depletion, which eventually resulted in significant yield loss for the 1994 growing season.

CONCLUSIONS

This study advocates an adjustment of N fertilization rates of inbred maize based on reasonable ranges of expected yield. Analyses of yield, NO_3–N leaching and soil N balance indicated that the appropriate fertilization of the P38 mid-season inbred approximates 108 kg N ha^{-1}. This research indicates that applying 202 kg N ha^{-1} before planting is not an appropriate fertilization practice for some moderate-yield inbreds, such as P38 and T10, grown on the sandy soils of southwest Michigan. Residual NO_3–N remaining in the soil profile after harvest was quickly lost to deep leaching in the fall, which potentially renders fall-planted cover crops ineffective at scavenging residual NO_3–N. We conclude that minimum ground water contamination is best achieved by tailoring N fertilization rates to inbred line needs.

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