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Spatial and temporal processes affecting nitrogen availability at the landscape scale

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Abstract

Nitrogen dynamics in soils are affected by spatial and temporal processes. Drainage class is generally regarded to be the most significant source of variability for N in temperate humid climates. A 5-year study was conducted including four rates of N fertilizer and three drainage classes within a 15 ha maize (*Zea mays* L.) field. Variance component analysis showed that N response was minimally affected by drainage class, but showed strong yearly variations, apparently related to early-season precipitation. Annual field-averaged economic optimum N rates had a range of 65 kg ha^{-1} with lower rates being associated with years with low early-season precipitation. A calibrated LEACHMN model and site-specific weather data were used to evaluate the effects of early-season weather conditions on N rate and availability. During wet years, soil N availability was reduced by approximately 35–50 kg ha^{-1} compared to dry years, largely independent of drainage class. For well-drained soils, most losses were attributed to leaching (especially in years with wet early-season), while poorly drained soils mainly experienced denitrification. It is concluded that limited benefits may be gained from spatially variable N applications within fields based on drainage class or soil type, but considerable economic and environmental gains are possible from yearly adjustment of supplemental N rates based on model simulations of N dynamics using information on early-season weather conditions.

Keywords: Soil variability; Spatial variability; Temporal variability; Nitrogen; Maize; Drainage class; Weather; LEACHMN

1. Introduction

1.1. Nitrogen management

For a sustainable agriculture, efficient input use is crucial (De Koeijer and Oomen, 1997), and for the sake of both the environment and the economy, it is important to balance the allocation of consumable inputs with crop requirements as precise as possible (Ostergaard, 1997). Nitrogen fertilizer will continue to be used to sustain maize grain production all over the world. However, current environmental and economic concerns demand improved N use efficiency and many studies (e.g., Roth and Fox, 1990; Saragoni et al., 1991; Yiridoe et al., 1997; Randall et al., 1997; Sogbedji et al., 2000) have been conducted with this objective. These research efforts are useful for assessing the ecological and economic impact of agricultural management practices, but their applications, at least to some extent may not be appropriate because both crop yield and the impact of farming on the environment are complex functions of weather, soil,

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cultivar and management. Under such circumstances, precision agriculture may be the appropriate farming strategy. Most of the recent research efforts in precision agriculture (Robertson et al., 1994; Kitchen et al., 1995; Everett and Pierce, 1996; King et al., 1996; Johnson et al., 1999; Wendroth et al., 1999) have focused on site-specific fertilization. However, in their study relating the temporal and spatial variability of maize grain yield to soil properties, Timlin et al. (1999) found that the year-to-year differences in weather had the largest effect on yield. The dynamics of plant N uptake is quite complex as plants absorb more nutrients at certain growth stages than others. Under such circumstances, site-specific fertilization is not enough because the factor of time also needs to be considered (Zhang and Solberg, 1996). Plant available stored soil water and seasonal precipitation quantity and distribution generally have the greatest effect on rainfed crop yields (Runge and Hons, 1999). It appears therefore that accounting for variation in both space (site-specific-based) and time (primarily as defined by variation in weather conditions) in the use of N fertilizer is necessary from both economic and ecological points of view. The equipment for such a management strategy is available, but there are many open questions concerning the correct way to address the rate of N in the soil–plant–atmosphere system (Engel, 1997). Most current methods for determining fertilizer rates are based on an expected (average) yield response based on information on yield goal, soil type, cropping history, etc. This approach implicitly neglects the annual variations in yield response to N and may result in overfertilization in some years (leading to excess residual soil nitrate) and underfertilization in other years (leading to unattained yield goals). Annual variations are accounted for in the more recently adapted late-spring soil nitrate tests (Magdoff, 1991; Durieux et al., 1995), but short timing between soil testing and fertilizer application, higher labor requirements, and generally high prediction errors limit the adoption of this method by farmers. Computer simulation models may be applied to extending N rate predictions to various soil and weather scenarios and estimate the need for modification of N fertilizer recommendations (Magdoff, 1991). The application of such models is facilitated by recent advances in the quality of site-specific weather information.

1.2. Nitrogen modeling

As many physical, chemical, and biological processes affecting soil N can happen at once, any attempt at a simultaneous description of the process requires an explicit computer-based model (Addiscott et al., 1991). Nitrogen models range in degree of sophistication from simple empirical equations to complex mechanistic computer simulation models. LEACHM (Hutson and Wagenet, 1992) is a process-based model that simulates water and solute movement, and related chemical and biological processes, in the unsaturated soil. LEACHMN, the version of LEACHM that addresses N dynamics, was selected for this study because it has subroutines to calculate water flow, NO_3 leaching, evapotranspiration, heat flow, rate constant adjustments for temperature and water content, N transformations and uptake. Mineralization, nitrification, denitrification, and volatilization are the major N transformation processes modeled by LEACHMN. Slight changes in model rate constants for nitrification, denitrification, and volatilization have been shown to affect N transformations and mass leached (Hutson and Wagenet, 1992).

The LEACHM model has been evaluated in several model simulation studies. Lotse et al. (1992) used LEACHMN to predict leachate nitrate concentrations, soil nitrate distribution, and maize N uptake in non-manured and manured field sites in southern Pennsylvania. Jabro et al. (1994) tested LEACHM predictions of bromide leaching against field-measured data collected from soils located in a karst region of southeastern Pennsylvania. Jemison et al. (1994) found that when calibrated for each treatment and year, LEACHMN-predicted and observed NO_3–N leaching losses were similar. The model can accurately predict drainage, and when calibrated for each year and soil type, satisfactorily simulate soil profile NO_3–N, NO_3–N leaching and maize N uptake (Sogbedji et al., 2000b,c).

The objectives of this paper were (1) to determine the effects of variable drainage class and yearly variation in weather on economic optimum N fertilizer rates of application for maize, and (2) to evaluate the effects of early-season weather on soil N availability to crops using the LEACHMN model for the purpose of adjusting N fertilizer recommendations.

2. Materials and methods

2.1. Experimental site

A field study was conducted on a 15 ha field at the Cornell University Experimental Farm at Aurora, NY (42°45′N, 76°35′W) for a 5-year period from 1978 to 1982 under three different drainage classes grown to maize. Nitrogen fertilizer trials were conducted on a moderately well-drained Honeoye-Lima soil (fine-loamy, mixed, active, mesic Glossic Hapludalf and Oxyaquic Hapludalf, USDA; Calcaric Luvisols, WRB-FAO), a somewhat poorly drained Kendaia soil (fine-loamy, mixed, active, nonacid, mesic Aeric Epiaquept; Gleyic Luvisol WRB-FAO), and a poorly to very poorly drained Lyons soil (fine-loamy, mixed, active, nonacid, mesic Mollic Endoaquept, Gleyic Luvisol and Calcaric Gleysol, WRB-FAO) developed from glacial tills of limestone and calcareous shales. The experiment was laid out as a completely randomized multiway split plot design in time with years as whole plots, N rate of application as subplots and soil drainage as sub-subplots. The sub-subplots were 3 m × 15 m in size with five replicates each.

2.2. Crop and soil management

The experimental site was under continuous maize crop production prior to this study. In each of the 5 years of study, the experimental site was moldboard plowed, disked, and planted to maize (CV. Pioneer 3958) at a density of 70,000 kernels ha^{-1}, all in the month of May. Pest management practices included the use of 5.7 l of Sutan+ (*S*-ethyl diisobutylthiocarbamate) and 1.4 kg of atrazine (2-chloro,4-ethylamino,6-isopropylamino-s-triazine) per hectare for weed control, and the use of phorate (0,0-diethyl *S*-[ethylthiomethyl]) in planter for rootworm control. Starter fertilization (in planter) consisted of 276 kg ha^{-1} of 6–24–24 in a 5 × 5 cm^2 band.

For the 5 consecutive years, four rates of sidedress N including 0, 55, 110, and 220 kg N ha^{-1} were incorporated as urea ammonium nitrate (UAN) between alternate maize rows using a John Blue (Huntsville, AL) injector approximately 6 weeks after planting (when maize was approximately 15–25 cm in height). Maize grain yields were determined from two 6 m-long rows of maize that were harvested from the center of each sub-subplot. A subsample of 10 years was then taken and the yield was adjusted to 15.5% moisture content.

2.3. Economic optimum N rate of application

Maize grain yield response data were used to determine economic optimum fertilizer rates. Several models have been used to describe maize yield response to N fertilizer and to determine economic optimum N rates of application. The linear-plus-plateau, exponential, and square root models are inferior to the quadratic and quadratic-plus-plateau models, but the quadratic model is inferior to the quadratic-plus-plateau model for data that reach a plateau (Blackmer and Cerrato, 1990). Based on their data set, Bullock and Bullock (1994) concluded that the quadratic-plus-plateau model is preferable in all cases to the quadratic model for predicting N fertilizer requirements of maize. For this study, however, the quadratic-plus-plateau model could not be used due to both the limited number and wide range of fertilization rates, leading to inappropriate model fits. Another factor that prevented the use of the quadratic-plus-plateau model relates to the fact that some of the measured yield data sets did not reach a plateau. Therefore, estimates of economic optimum fertilizer rates were obtained by using the quadratic model defined as follows:

$$Y = a + bX + cX^2$$

where Y is the yield of grain (Mg ha^{-1}), and X the rate of N application (kg ha^{-1}); a (intercept), b (linear coefficient), and c (quadratic coefficient) the regression parameters. PROC NLIN procedures (SAS Institute, 1999) were used to fit the model to measured data. Predicted economic optimum rates of fertilization were calculated by equating the first derivatives of the response equations to a fertilizer-to-maize price ratio of 3.3 and solving for X (National Academy of Sciences–National Research Council, 1961; Nelson et al., 1985). A variance component analysis was performed using the VARCOMP Procedure (SAS Institute, 1999) to evaluate the relative magnitude of variance components of year effects, drainage effects, and their interaction. Variance component estimates (VCEs) were normalized into coefficient of variation estimates (CVs) by (van Es et al., 1999):

$$CV = \frac{[(VCE)^{1/2} \times 100]}{m}$$

where m is the grand mean of economic optimum N rates in this study.

2.4. The LEACHMN model simulations

In each of the 5 years of study, LEACHMN model simulations were executed for the period from 1 March to 30 June while maize crop was growing. Soil-related input parameters for the model were collected from the experimental site under each of the three drainage classes. Daily precipitation, total weekly potential evapotranspiration, mean weekly air temperature, and mean weekly amplitude of air temperature are weather input data for the model, and were collected at the research farm meteorological station. The free drainage boundary conditions option was used for the simulations. This assumes that once the bottom layer of the soil profile is at saturation, any further water percolate that reaches this layer is subject to drainage. Simulations covered soil profiles of 80 cm for the Honeoye-Lima soil type, and 70 cm for the Kendaia and Lyons soil types, which corresponded to maize crop rooting depth at each site as determined from neutron moisture measurements (data not shown).

In evaluating the LEACHMN model, Jemison et al. (1994) concluded that the model transpose adequately and performed when calibrated for critical N transformation rate constants including those for nitrification, denitrification, and volatilization. The model outputs were less sensitive to changes in the mineralization rate constant (Hutson and Wagenet, 1992; Lotse et al., 1992). In a related study (Sogbedji et al., 2000b), we calibrated the LEACHMN model from lysimeter studies for nitrification, denitrification and volatilization rate constants under loamy sand and clay loam soils for the weather conditions of New York for a 3-year period following sod plowdown. Best-estimate values for rate constants were used in this study based on the second and third year calibration effort, and accounting for expected differences among the soil types. These values are presented in Table 1. The soil physical properties of each drainage class are presented in Table 2, and other model parameter input values used for the simulations are presented in Table 3. Environmental N losses through denitrification and leaching, and the end-of-June available mineral N were estimated for each drainage class–year combination.

Table 1
N transformation rate constants used during the simulations

Drainage class	Rate constant (per day)		
	Nitrification	Denitrification	Volatilization
Honeoye-Lima	0.280	0.040	0.000
Kendaia	0.280	0.080	0.000
Lyons	0.280	0.100	0.000

3. Results and discussions

3.1. Maize grain yields and economic optimum N rates

Maize grain yields for 1978, 1979 and 1981 under the three drainage classes were generally higher compared to those for 1980 and 1982 (Fig. 1a–c). Within each of the 5 years of study, maize grain yields were generally similar for each of the three drainage classes and were responsive to N fertilizer rate of application. Although the response curves under the three drainage classes were generally similar *within* each year, they varied *among* years (Fig. 1a–c). In 1978, 1979, and 1981, yields under all drainage classes were approximately 4–5 Mg ha^{-1} for the 0 kg ha^{-1} sidedress rate, while the check yields for 1980 and 1982 were only about 2 Mg ha^{-1}. For the former 3 years, yield was less responsive to N fertilizer rate above a threshold level of about 110 kg ha^{-1}, while 1980 and 1982 showed significant yield grains at higher rates (Fig. 1a–c). Between N rates of 0 and 110 kg ha^{-1}, the 1980 and 1982 years experienced a yield depression of about 2.5 Mg ha^{-1} compared to yields in the other three years.

The April–October period precipitation (Table 4) showed that cumulative precipitation for the period was higher in the 1978, 1979, and 1981 years compared to that in 1980 and 1982. The higher cumulative precipitation in 1978, 1979, and 1981 resulted from their higher August–October period precipitation. On the other hand, the early-season period (May–June)

Table 2
Physical properties for each of the three drainage classes

Depth (cm)	Bulk density ($Mg\ m^{-3}$)		Saturated hydraulic conductivity (mm per day)	Water content, $m^3\ m^{-3}$ at pressures (kPa)					
	Mean	S.D.		1	10	40	100	300	1500
Honeoye-Lima									
5	1.25	0.10	10163	0.45	0.25	0.21	0.15	0.08	0.07
15	1.52	0.16	24614	0.38	0.25	0.22	0.10	0.09	0.08
25	1.55	0.10	5346	0.35	0.23	0.21	0.09	0.07	0.06
35	1.69	0.02	5228	0.28	0.17	0.15	0.09	0.07	0.06
45	1.51	0.20	826	0.32	0.24	0.22	0.17	0.14	0.12
55	1.50	0.17	4314	0.35	0.25	0.23	0.18	0.14	0.13
65	1.54	0.05	3554	0.41	0.30	0.29	0.25	0.21	0.16
75	1.56	0.12	289	0.44	0.41	0.40	0.36	0.32	0.29
Kendaia									
5	1.25	0.09	7456	0.46	0.30	0.26	0.17	0.14	0.11
15	1.47	0.11	13507	0.40	0.28	0.226	0.20	0.17	0.13
25	1.53	0.08	2694	0.43	0.34	0.32	0.28	0.22	0.18
35	1.58	0.11	2476	0.43	0.41	0.35	0.31	0.27	0.23
45	1.50	0.13	606	0.41	0.38	0.35	0.32	0.29	0.25
55	1.50	0.12	1971	0.44	0.41	0.38	0.34	0.31	0.28
65	1.52	0.06	622	0.44	0.41	0.38	0.36	0.34	0.30
Lyons									
5	1.16	0.07	5471	0.47	0.34	0.32	0.23	0.19	0.17
15	1.43	0.02	7413	0.40	0.36	0.34	0.28	0.24	0.22
25	1.53	0.06	1360	0.43	0.39	0.38	0.35	0.31	0.27
35	1.49	0.06	1176	0.45	0.43	0.41	0.39	0.34	0.31
45	1.51	0.04	446	0.42	0.40	0.38	0.36	0.34	0.31
55	1.51	0.05	905	0.45	0.43	0.42	0.41	0.37	0.34
65	1.52	0.07	109	0.44	0.42	0.41	0.40	0.38	0.34

precipitation (particularly in June) was higher in 1980 and 1982. This, presumably, led to higher environmental N losses in those 2 years and resulted in a different response to N fertilization.

Table 3
LEACHMN parameter input values used in the simulations

Parameter[a]	Input values
Partition coefficient, NH_4–N ($l\ kg^{-1}$)	3.0
Partition coefficient, NO_3–N ($l\ kg^{-1}$)	0.0
Denitrification half saturation constant ($mg\ l^{-1}$)	10
Litter mineralization rate constant (per day)	0.01
Humus mineralization rate constant	7×10^{-5}
Q10 factor	2.0
C:N ratio for biomass and humus	10.0
Maximum NO_3^-/NH_4^+ ratio in solution to control nitrification rate	8.0

[a] All parameter values in the simulations came from Hutson and Wagenet (1992), Jansson and Andersson (1988), or Johnsson et al. (1987).

The estimated economic optimum N rate values are almost certainly overestimated due to the fact that the study involved only four N rates ranging from 0 to 220 kg N ha^{-1} and a lack of data points between 110

Table 4
Monthly precipitation (mm) at the experimental site

Month	Year				
	1978	1979	1980	1981	1982
April	68	87	89	70	34
May	55	82	25	49	74
June	*112*	*64*	*144*	*97*	*137*
July	47	59	82	103	32
August	119	107	72	110	47
September	90	133	73	176	93
October	87	107	87	136	31
Total					
April–October	*578*	*639*	*572*	*741*	*448*
May–June	*167*	*146*	*169*	*146*	*211*

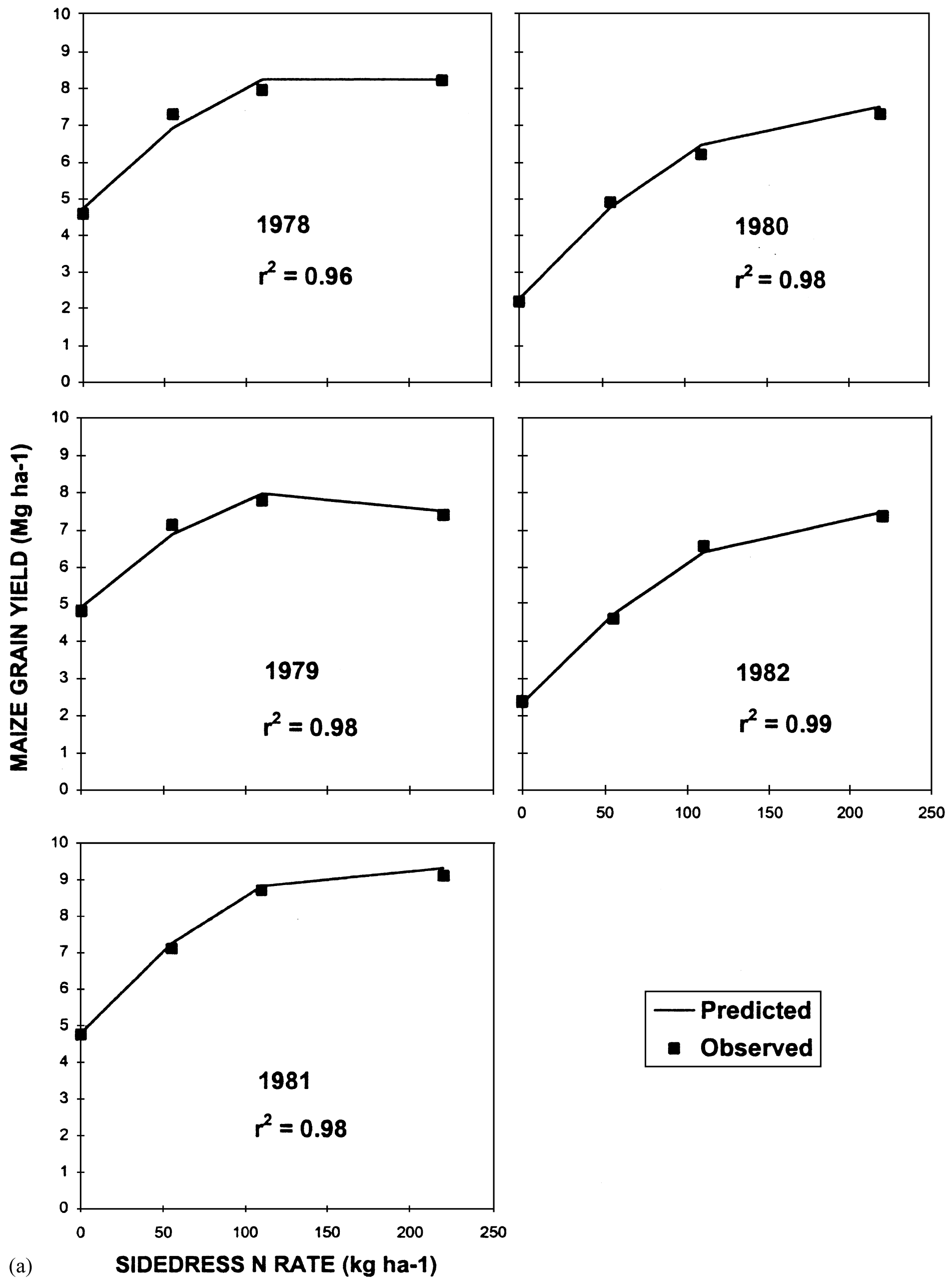

Fig. 1. Maize grain yield response curves to N fertilizer for 5 years (1978–1982) under the Honeoye-Lima (a), Kendaia (b), and Lyons (c) soils.

and 220 kg ha^{-1}. Within each of the 5 years, economic optimum rates for the three drainage classes were generally similar (Table 5), which suggest that the rates were minimally affected by drainage-related field variability. Generally, the optimum rates were similar for the 1978, 1979, and 1981 years, ranging between 148 and 165 kg N ha^{-1} for all drainage classes. In 1980 and 1982, optimum N rates were much higher, ranging from 190 to over 200 kg N ha^{-1} (Table 5), indicating that in these 2 years, significantly more N was needed

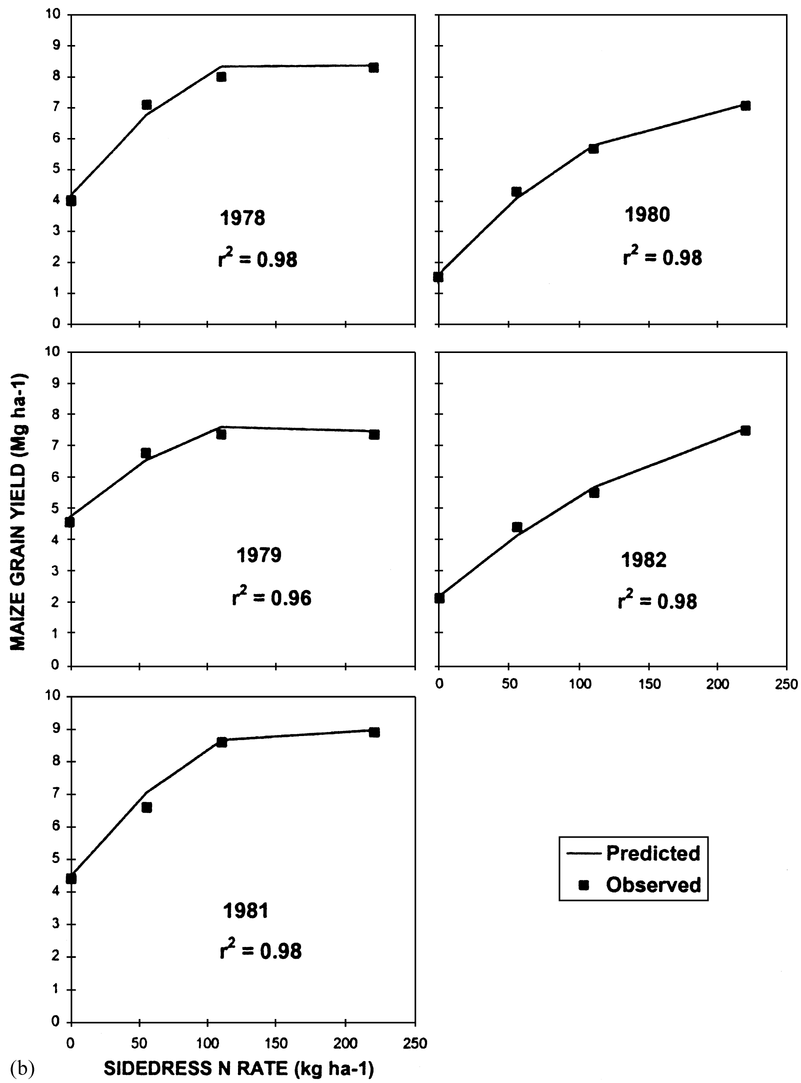

Fig. 1. (*Continued*).

to maintain maize yield. Deviation from the grand mean economic optimum N rate for all 5 years showed negative values (−11 to −22 kg ha^{-1}) for 1978, 1979 and 1981 and positive values (17 and 39 kg ha^{-1}) for the other years that experienced wet early-season weather (Table 5). For the 5-year period of this study, the field-averaged economic optimum N rates had a range of 65 kg ha^{-1}, with precise quantification being constrained by the limitations of the data set.

The variance component analysis (Table 6) showed that the effects of field variability from drainage class on economic optimum N rates were insignificant, but that the latter was affected by year effects, with higher optimum N rates for years with wet early-season weather. A small year × drainage class interaction is explained by a minor effect of drainage class in these wet early-season years, especially in 1982.

3.2. *The LEACHMN model simulations*

Soil N availability for crop use is a function of mineralization of soil organic N, denitrification and

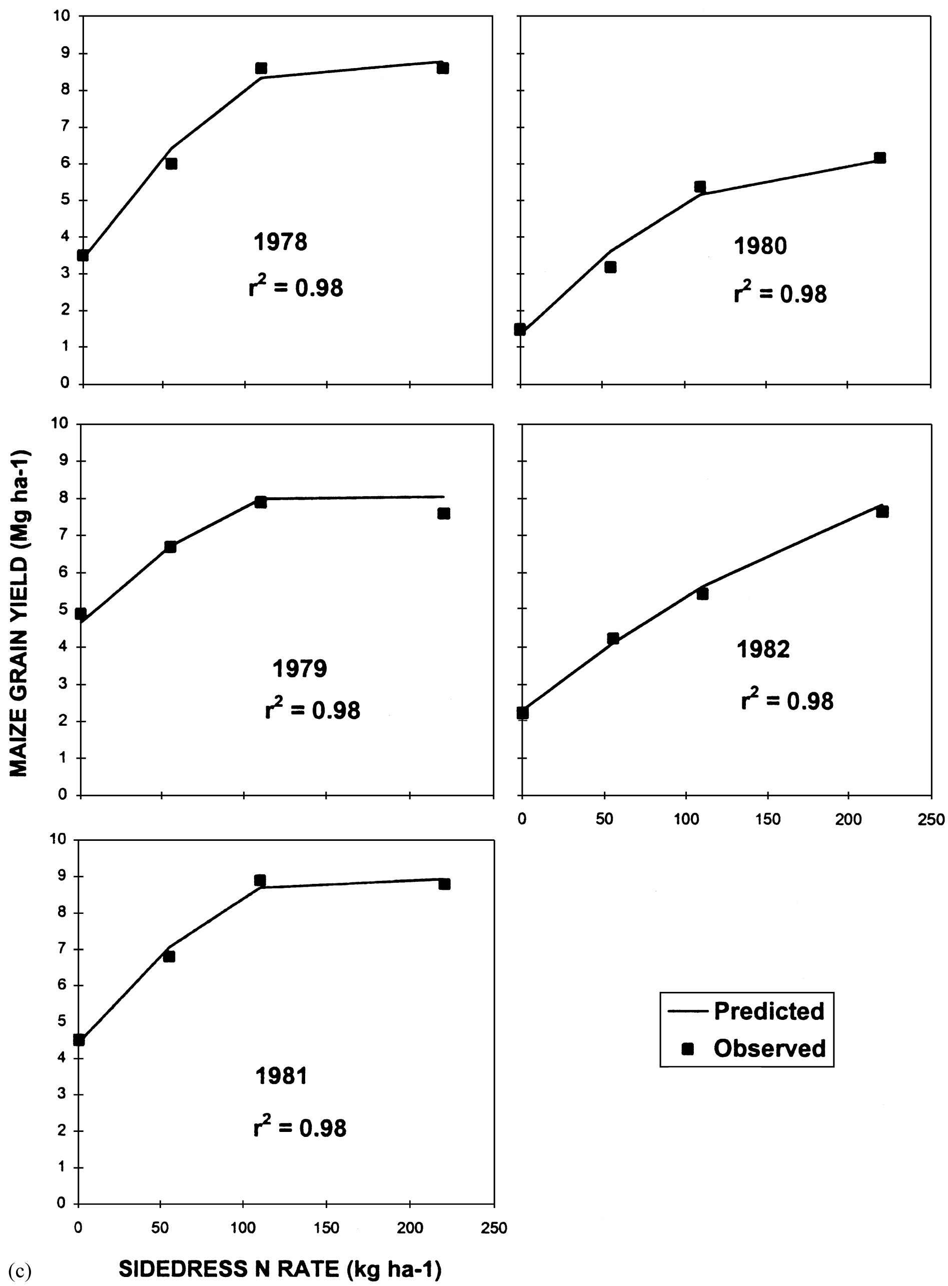

Fig. 1. (*Continued*).

leaching losses, and N applied in fertilizer. The simulation results (Table 7) show that mineralized N within each soil type was similar for each of the 5 years. Among soil types, estimated mineralization rates increased from well-drained to poorly drained.

Denitrification and leaching losses were affected by both drainage class and year. In each of the 5 years, denitrified N was similar for the Kendaia and Lyons soils, but higher compared to that for the Honeoye-Lima soil (Table 7). Leaching losses were generally

Table 5
Economic optimum rates of N fertilization (kg N ha^{-1}) at a fertilizer-to-maize grain price ratio of 3.3 as determined using the quadratic model for each drainage class–year combination, and their deviations from the overall mean value

Drainage class	Year										Mean deviation
	1978		1979		1980		1981		1982		
	N rate	Deviation from mean	N rate	Deviation from mean	N rate	Deviation from mean	N rate	Deviation from mean	N rate	Deviation from mean	
Honeoye-Lima	162	−15	147	−29	190	13	160	−17	192	15	−6.6
Kendaia	158	−19	148	−28	203	26	163	−14	231[a]	54	3.8
Lyons	165	−12	157	−20	189	12	162	−15	225[a]	48	2.6
Mean deviation		−15		−26		17		−15		39	

[a] Estimated economic optimum N rate is beyond the data range.

Table 6
Variance component analysis for economic optimum N rates

Variance component	Estimate (kg^2 ha^{-2})	CV (%)
Var(year)	501	12.6
Var(drainage class)	0	0
Var(year × drainage class)	73	4.8

similar for the three drainage classes in 1978, 1979 and 1981, but in the other two years that experienced a wet early-season, losses were much higher for the Honeoye-Lima compared to those for the Kendaia and Lyons soils. On an annual basis, both denitrified and leached N within the same drainage class were similar for the 1978, 1979, and 1981 years, but much lower compared to those for 1980 and 1982 (Table 7). The total environmental losses (denitrified and leached N) were in general minimally affected by drainage class with losses being similar for the Kendaia and Lyons soils, but quantitatively slightly higher compared to those for the Honeoye soil. The year effects, again, were strong, with environmental losses being much

Table 7
Simulated mineralized, denitrified, maize uptake, and leached N, and ground water nitrate levels, and drainage and precipitation (for 1 March–30 June period) for each drainage class in each year

Drainage class	Mineralized N (kg ha^{-1})	Denitrified N (1) (kg ha^{-1})	Leached N (2) (kg ha^{-1})	Environmental loss (1 + 2) (kg ha^{-1})	Maize N uptake (kg ha^{-1})	Drainage (mm)	Precipitation (mm)
Honeoye-Lima							
1978	36.0	9.0	13.0	22.3	27.0	211	290
1979	36.0	8.9	13.6	22.5	27.0	212	286
1980	38.0	23.0	30.0	53.0	16.0	254	355
1981	36.0	10.0	11.0	21.0	27.0	155	227
1982	33.0	24.0	28.0	52.0	15.0	162	258
Kendaia							
1978	42.0	13.3	11.0	24.3	27.0	138	290
1979	44.0	15.0	11.3	26.3	27.2	138	286
1980	43.0	49.2	15.0	64.2	22.2	178	355
1981	47.0	16.1	7.1	23.2	27.0	81	227
1982	46.0	54.0	11.5	65.5	22.3	83	258
Lyons							
1978	50.0	16.0	9.4	25.4	27.0	102	290
1979	51.0	16.1	10.0	26.1	27.0	106	286
1980	50.0	52.5	15.0	67.5	22.0	164	355
1981	53.0	20.3	5.0	25.3	28.0	50	227
1982	52.0	56.1	12.0	68.1	22.0	83	258

Table 8
Simulated end-of-June available soil N within the top 70 cm depth for the Honeoye-Lima and 80 cm for the Kendaia and Lyons soils, and soil NO_3–N concentrations within the top 30 cm depth for the three drainage classes

Drainage class	End-of-June available soil N components (kg ha^{-1})					End-of-June soil NO_3–N concentration within 30 cm (mg kg^{-1})
	NH_4^+ (a)	NO_3–N (b)	Total (a + b)	Potential mineral N	Total mineral N	
Honeoye-Lima						
1978	13.4	41.0	54.4	36.0	90.4	3.7
1979	10.4	44.4	54.8	36.0	90.8	4.1
1980	3.0	11.0	14.0	36.0	50.0	0.02
1981	11.4	47.6	59.0	36.0	95.0	5.7
1982	3.0	13.8	16.8	36.0	52.8	0.02
Kendaia						
1978	12.3	49.4	61.7	37.6	99.3	7.3
1979	10.1	52.2	62.3	37.6	100.0	8.9
1980	5.4	22.6	28.0	37.6	65.6	2.4
1981	11.0	60.6	71.6	37.6	109.2	10.0
1982	6.0	26.6	32.6	37.6	70.2	1.5
Lyons						
1978	11.3	47.4	58.7	47.0	105.7	4.5
1979	11.5	49.0	60.5	47.0	107.5	5.2
1980	5.0	19.0	24.0	47.5	71.5	0.4
1981	12.0	53.5	65.5	47.5	113.0	6.7
1982	5.2	21.4	26.6	47.5	71.1	0.5

higher for the 1980 and 1982 years compared to those for the other 3 years.

Simulated end-of-June available soil N components are presented in Table 8. Total mineral N appeared to be slightly affected by drainage only between the two extreme classes (Honeoye-Lima and Lyons), suggesting that end-of-June available mineral N was in general minimally affected by drainage class. The year effects on end-of-June plant available soil N on the other hand were evident. Under the three drainage classes, total mineral N was much lower for the 1980 and 1982 years compared to that for 1978, 1979, and 1981 with differences typically ranging from 35 to 50 kg N ha^{-1} (Table 8). The lower level of available N for the 1980 and 1982 years primarily resulted from the higher environmental N losses that they experienced, and presumably resulted in the yield depression and higher economic optimum N rates observed for those years in the field study. This corroborates the notion that additional N is needed to maintain maize grain yields in years with wet early growing seasons due to considerable denitrification and leaching losses. Estimated end-of-June soil nitrate levels (Table 8) show the same pattern of lower values during those years, which would be reflected in low values for late-spring soil nitrate tests (Magdoff, 1991).

4. Conclusions

This study showed that economic optimum N rates were minimally affected by field variability from drainage class, but strongly affected by annual fluctuations as a result of varying early-season weather. This suggests that accounting for year-to-year variation in weather conditions in N fertilizer recommendations deserves more attention than it has received in the past and that spatially variable N application has less benefit in temperate humid climates. Annual field-averaged economic optimum N rates suggest annual adjustment of recommended N fertilizer rates within a range of 65 kg N ha^{-1}. LEACHMN simulations generally corroborated this pattern that in years with wet early-seasons, soil N availability was significantly reduced as a result of denitrification and leaching. Estimated environmental losses for wet years were

35–50 kg N ha^{-1} over those of dry years, which is slightly lower than those indicated by the annual field-averaged economic optimum N rates. The LEACHMN model proved to be capable of simulating N availability in field scenarios.

References

Addiscott, T.M., Whitmore, A.P., Powlson, D.S., 1991. Farming, Fertilizer, and the Nitrate Problem. CAB International, Wallingford, UK.

Blackmer, A.M., Cerrato, M.E., 1990. Comparison of models for describing corn yield response to nitrogen fertilizer. Agron. J. 82, 138–143.

Bullock, D.G., Bullock, D.S., 1994. Quadratic and quadratic-plus-plateau models for predicting optimal nitrogen rate of corn: a comparison. Agron. J. 86, 191–195.

De Koeijer, T.J., Oomen, G.J., 1997. Environmental and economic effects of site specific and weather adapted nitrogen fertilization for a Dutch field crop rotation. In: Stafford, J.V. (Ed.), Precision Agriculture'97, Vol. I, Spatial Variability in Soil and Crop. BIOS Scientific Publishers, Oxford, UK, pp. 379–386.

Durieux, R.P., Brown, H.J., Stewart, E.J., Zhao, J.Q., Jokela, W.E., Magdoff, F.R., 1995. Implications of nitrogen management strategies for nitrate leaching potential — roles of nitrogen-source and fertilizer recommendation system. Agron. J. 87, 884–887.

Engel, T., 1997. Use of nitrogen simulation models for site-specific nitrogen fertilization. In: Stafford, J.V. (Ed.), Precision Agriculture'97, Vol. I, Spatial Variability in Soil and Crop. BIOS Scientific Publishers, Oxford, UK, pp. 361–369.

Everett, M.W., Pierce, F.J., 1996. Variability of corn yield and soil profile nitrates in relation to site-specific N management. In: Robert, P.C., et al. (Eds.), Proceedings of the Third International Conference on Precision Agriculture. ASA, CSSA, SSSA, Madison, WI.

Hutson, J.L., Wagenet, R.J., 1992. LEACHM. Leaching estimation and chemistry model: a process-based model of water and solute movement, transformations, plant uptake, and chemical reactions in the unsaturated zone, Version 3. Research Series 92-3. Department of Soil, Crop, and Atmospheric Sciences, Cornell University, Ithaca, NY.

Jabro, J.D., Lotse, E.G., Fritton, D.D., Baker, D.E., 1994. Estimation of preferential movement of bromide tracer under field conditions. J. Hydrol. 156, 61–71.

Jansson, P., Andersson, R., 1988. Simulation of runoff and nitrate leaching from an agricultural district in Sweden. J. Hydrol. 99, 33–47.

Jemison Jr., J.M., Jabro, J.D., Fox, R.H., 1994. LEACHM evaluation. II: Simulation of nitrate leaching from nitrogen-fertilized and manured corn. Agron. J. 86, 852–859.

Johnson, R.M., Bradow, J.M., Bauer, P.J., Sadler, E.J., 1999. Spatial variability of cotton fiber yield and quality in relation to soil variability. In: Robert, P.C., et al. (Eds.), Proceedings of the Fourth International Conference on Precision Agriculture. ASA, CSSA, SSSA, Madison, WI.

Johnsson, H., Bergstrom, L., Jansson, P., Paustian, K., 1987. Simulated nitrogen dynamics and losses in a layered agricultural soil. Agric. Ecosyst. Environ. 18, 333–356.

King, B.A., Stark, J.C., McCann, I.R., Westerman, D.T., 1996. Spatially varied nitrogen application through a center pivot irrigation system. In: Robert, P.C., et al. (Eds.), Proceedings of the Third International Conference on Precision Agriculture. ASA, CSSA, SSSA, Madison, WI.

Kitchen, N.R., Hughes, D.F., Sudduth, K.A., Birrell, S.J., 1995. Comparison of variable rate to single rate nitrogen fertilizer application: corn production and residual NO_3–N. In: Robert, P.C., et al. (Eds.), Site-specific Management for Agricultural Systems. ASA, CSSA, SSSA, Madison, WI, pp. 427–439.

Lotse, E.G., Jabro, J.D., Simmons, K.E., Baker, D.E., 1992. Simulation of nitrogen dynamics and leaching from arable soils. J. Contam. Hydrol. 10, 183–196.

Magdoff, F.R., 1991. Understanding the corn pre-sidedress nitrate test: a step towards environmentally sound N management. J. Prod. Agric. 4, 297–305.

National Academy of Sciences–National Research Council, 1961. Statistical methods of research in economic and agronomic aspects of fertilizer response and use. Committee on Economic of Fertilizer Use of the Agricultural Board, NAS–NRC Publication No. 918. NAS–NRC, Washington, DC.

Nelson, L.A., Voss, R.D., Pesek, J.T., 1985. Agronomic and statistical evaluation of fertilizer response. In: Angelstad, O.P. (Ed.), Fertilizer Technology and Use, 3rd Edition. ASA, Madison, WI, pp. 53–90.

Ostergaard, H.S., 1997. Agronomic consequences of variable N fertilization. In: Stafford, J.V. (Ed.), Precision Agriculture'97, Vol. I, Spatial Variability in Soil and Crop. BIOS Scientific Publishers, Oxford, UK, pp. 315–320.

Randall, G.W., Huggins, D.R., Russelle, M.P., Fuchs, D.J., Nelson, W.W., Anderson, J.L., 1997. Nitrate loss through subsurface tile drainage in conservation reserve program, alfalfa, and row crop systems. J. Environ. Qual. 26, 1240–1247.

Robertson, G.P., Crum, J.R., Ellis, B.G., 1994. The spatial variability of soil resources following long-term disturbance. Oecologia 96, 451–456.

Roth, G.W., Fox, R.H., 1990. Soil nitrate accumulations following corn fertilized at various N rates in Pennsylvania. J. Environ. Qual. 19, 243–248.

Runge, E.C.A., Hons, F.M., 1999. Precision agriculture-development of hierarchy of variables influencing crop yields. In: Robert, P.C., et al. (Eds.), Proceedings of the Fourth International Conference on Precision Agriculture. ASA, CSSA, SSSA, Madison, WI.

Saragoni, H., Olivier, R., Poss, R., 1991. Dynamique et lixiviation des elements mineraux. Agron. Trop. 45 (4), 259–273.

SAS Institute, 1999. SAS User's Guide, Version 7-1. SAS Institute, Cary, NC.

Sogbedji, J.M., van Es, H.M., Yang, C.L., Geohring, L.D., Magdoff, F.R., 2000. Nitrate leaching and N budget as affected by maize N fertilizer rate and soil type. J. Environ. Qual. 29, 1813–1820.

Sogbedji, J.M., van Es, H.M., Hutson, J.L., 2000b. N rate and transport under variable cropping history and fertilizer rate on loamy sand and clay loam soils: I. Calibration of the LEACHMN model. Plant and Soil, in press.

Sogbedji, J.M., van Es, H.M., Hutson, J.L., 2000c. N rate and transport under variable cropping history and fertilizer rate on loamy sand and clay loam soils: II. Validation of the LEACHMN model using different calibration scenarios. Plant and Soil, in press.

Timlin, D.J., Pachepsky, Y.A., Snyder, V.A., Bryant, R.B., 1999. Soil surface curvature and the spatial and temporal variability of corn grain yields on a hillslope. In: Robert, P.C., et al. (Eds.), Proceedings of the Fourth International Conference on Precision Agriculture. ASA, CSSA, SSSA, Madison, WI.

van Es, H.M., Ogden, C.B., Hill, R.L., Schindelbeck, R.R., Tsegaye, T., 1999. Integrated assessment of space, time, and management-related variability of soil hydraulic properties. Soil Sci. Soc. Am. J. 63, 1599–1607.

Wendroth, O., Jurschik, P., Giebel, A., Nielsen, D.R., 1999. Spatial statistical analysis of on-site crop yield and soil observations for site-specific management. In: Robert, P.C., et al. (Eds.), Proceedings of the Fourth International Conference on Precision Agriculture. ASA, CSSA, SSSA, Madison, WI.

Yiridoe, E.K., Voroney, R.P., Weersink, A., 1997. Impact of alternative farm management practices on nitrogen pollution of groundwater: evaluation and application of CENTURY model. J. Environ. Qual. 26, 1255–1263.

Zhang, Z.M.N., Solberg, E.D., 1996. The factor of time: a new consideration in precision farming. In: Robert, P.C., et al. (Eds.), Proceedings of the Fourth International Conference on Precision Agriculture. ASA, CSSA, SSSA, Madison, WI.