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Nitrogen and water management strategies to reduce nitrate leaching under irrigated maize

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Abstract

Cropping systems that fail to integrate nitrogen (N) water management are frequently associated with elevated concentrations of nitrate-N in soil and groundwater. Examples of poorly integrated management practices are abundant, especially where irrigation is used to minimize the effects of drought and N fertilizer is inexpensive. Two maize fields under improved water and N management practices at the Nebraska Management Systems Evaluation Area (MSEA) project were compared with an adjacent field under conventional furrow irrigation that followed management guidelines mandated by the local Natural Resources District. Surge-flow furrow irrigation with laser grading and a runoff-water recovery system reduced water application by 45–69% compared to conventional furrow irrigation over the three years of this study. Center-pivot sprinkler irrigation reduced water application by 60–72% compared to conventional furrow irrigation. Uniformity of water application was improved with the surge-flow and sprinkler irrigation systems, which made it reasonable to consider adding fertilizer N in the water (fertigation) to meet crop needs. The spoon-feeding strategy, based on chlorophyll meter readings to schedule fertigation, saved 168 kg ha^{-1} N the first year and 105 kg ha^{-1} N the second year without reducing yields. Near total reliance of fertigation to meet crop N needs resulted in a 15% yield reduction the second year because spatial variability in soil N status made it difficult to collect representative chlorophyll meter data. Plot studies showed chlorophyll meter readings and yields were consistently higher for maize following soybean than where maize was grown in monoculture.

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1. Introduction

Nitrogen management strategies frequently involve a one year or longer time frame. In reality, most N management strategies would probably be more environmentally sound if they also involved a number of short-term decisions that accounted for plant growth, water availability, soil physical factors and climatic conditions. Producer commitment to any one factor depends on the urgency of the situation, the availability of technical expertise and the economic consequences of making a reasonable vs. an improper decision. When put in perspective, more frequent decisions are required when attempting to manage for environmental protection and profitability than when inputs are relatively inexpensive and environmental considerations are not an issue.

Long-term N management strategies tend to change over time in response to economic pressures, climatic conditions, and more recently because of environmental concerns. Nonetheless, the scientific principles responsible for the dynamics of the N cycle and water movement in soils continue to function and express themselves in various ways (Schepers and Mosier, 1991). As with any input to a cropping system, too much of a good thing (i.e. fertilizers, pesticides, water, etc.) can lead to environmental problems. For example, excessive or poorly timed applications of irrigation water can accentuate the need for N fertilizers because of the increased potential for leaching and/or denitrification losses. This is not to imply that natural conditions are immune from such losses, but to simply indicate that excessive water from any source can adversely impact the environment. For these reasons, it is essential to simultaneously consider water management whenever N management decisions are made.

Nitrogen management practices that target efficient use of N fertilizer are not always the most profitable for producers. This is because profitability is usually assessed over the entire cropping system rather than for individual components such as the incremental increase in profit that can be gained by each additional increment of N fertilizer. The first increment of N fertilizer usually results in the greatest crop response and nutrient uptake efficiency. Applications of additional increments of fertilizer may still be profitable as long as the last increment of fertilizer costs less than the corresponding increase in crop value. Nonetheless, nutrient uptake efficiency may be vary low for the last increment of fertilizer. This type of simple economic assessment does not consider the environmental consequences of farming operations. More specifically, the cost of remediating impaired ground- and surface water quality has not been factored into the cost of N fertilizers or irrigation water. If such costs could be determined and then assessed to agriculture, it would seem the charges for remediation or treatment should be distributed to the various sources of N that contribute to crop growth. Likewise, it could be argued that irrigation should be assessed a remediation fee because of the increased potential for nitrate leaching and runoff. Such logic is based on the premise that only fertilization and/or irrigation are responsible for the nonpoint source contamination of our water resources. In reality, crops use N from many sources, all of which contribute to the occurrence of nitrate in our water resources (Olson et al., 1973). Also, sources other than agriculture may contribute significantly to nonpoint pollution.

The major N related problem facing agriculture is that society frequently seems insensitive to the fact that natural processes contribute to nitrate leaching and can even accentuate water quality problems. This perhaps explains why the public seems intent on assigning the cost of remediating nonpoint source contamination problems to agriculture. The implications are that proposed constraints and restrictions on agricultural inputs (i.e. fertilizer, irrigation, etc.) and producer operations will be expected to compensate for naturally occurring processes that also degrade water quality unless compromises can be reached. This is why producers must be prepared to do what they can to integrate management practices that can reduce the potential for nitrate leaching.

The time delay between implementation of new agricultural technologies and when the practices might impact the environment in either a positive or negative way will always be a concern. For this reason, formulation of N management strategies should strive to address the smallest reasonable unit of time that is practical and technically possible so as to minimize environmental and economic risks.

It is commonly perceived that maize producers are reluctant to assume the risk of lower crop yields caused by an N deficiency. Therefore, the concept of insurance N will likely remain prevalent unless methods are available to easily detect and remediate an N stress before it reduces yields. In the past, the challenge has been to develop a fast, easy and inexpensive way for producers to evaluate crop N status during the growing season. Previously, Inada (1965) reported that chlorophyll meter readings were highly correlated with leaf chlorophyll content. More recently, Girardin et al. (1985) demonstrated a strong relationship between crop N deficiency, photosynthetic activity and leaf chlorophyll content. Lohry (1989) found that both leaf chlorophyll content and N concentration could effectively be used to monitor the N status of maize, which was highly correlated with yield. Combining such tissue testing procedures with the potential for fertigation (injecting N fertilizer into irrigation water) would seem to address both producer concerns. Blackmer and Schepers (1995) demonstrated chlorophyll meters could be used to schedule fertigation of maize and maintain productivity on research plots using this strategy. The objective of this research was to expand the fertigation concept to a whole-field basis and evaluate the effect of several integrated N and water management strategies on maize production and the implied impact on groundwater quality.

2. Methods and materials

This research was conducted at the Management Systems Evaluation Area (MSEA) project site that is located in the second terrace of the Platte River Valley near Shelton, Nebraska, U.S.A. The alluvial soils in the area form a nearly level landscape that has been graded to facilitate furrow irrigation. The Hall (fine-silty, mixed, mesic pachic Argiustoll) and Hord (fine-silty, mixed, mesic cumulic Haplustoll) surface soils overlay sand and gravel at 1.2–1.8-m depth. Groundwater used for irrigation is pumped from an aquifer with its water table at 5–7-m depth and that extends to ~ 20-m depth. Nitrate-N concentration in groundwater used for irrigation ranges for 30–32 mg L^{-1}. Precipitation in the area averages 620 mm annually, with about one-third of it coming between 1 April and 15 June.

Two types of studies were initiated in 1991 to address different aspects of N and water management. In one case, three N fertilizer/water management scenarios for monoculture maize were established on individual 13.6-ha fields. It was not possible to replicate these large fields because of their size and the cost of installing the 41 multilevel sampling wells needed to monitor changes in groundwater quality. The second approach involved a replicated maize/soybean rotation where small plots were used to evaluate the dynamics of the N cycle as influenced by fertilizer rate and crop residues.

2.1. *Monoculture maize*

Three square 13.6-ha irrigated maize fields with individual irrigation wells were established in 1990. These adjacent fields had been under maize or soybean production for over two decades. Each of the fields received a preplant application of 168 kg ha^{-1} N as anhydrous ammonia in 1990 and was planted to maize that received 33 kg ha^{-1} N as a starter fertilizer at planting. Flow meters were installed on the wells and fields were furrow irrigated (~ 380-m length of run) according to traditional producer practices. Average grain yields were similar for all three fields and averaged 12.3 Mg ha^{-1}. Irrigation application ranged from 91 to 122 cm in 1990, which far exceeded the 20–40 cm require to meet crop needs. Clearly, improved water management would be required before improved fertilizer N management could be effective.

In the fall of 1990 and spring of 1991 two of the fields were modified to accommodate different types of irrigation systems. The first was a modestly priced improved furrow irrigation system (surge-flow) that offered some opportunities for improved N management, including fertigation. The second was a more costly sprinkler irrigation system (center pivot) that offered maximum flexibility in terms of N management. These fields were compared to conventional furrow irrigation practices for the area. Nitrogen management strategies (i.e. preplant, sidedress and fertigation) were developed and tailored for each type of irrigation system. Prior to planting, soils from each field were sampled to a depth of 1.2 m for residual soil N.

The conventional field received preplant fertilizer as anhydrous ammonia plus a small amount of starter fertilizer (Table 1). Prior to irrigation, a dike was constructed at the lower end of the field to restrict runoff of irrigation water. Slope of this field averaged ~ 0.15%, but isolated areas were nearly level. The surge-flow-irrigated field was laser graded to a slope of 0.15% in the fall of 1990. An irrigation recovery system was installed to recycle runoff water. The center-pivot irrigation system with a corner unit to increase coverage was installed in the spring of 1991. Details of fertilizer timing and amounts are shown in Table 1. Preplant and sidedress N was applied as anhydrous ammonia (82–0–0, $N–P_2O_5–K_2O$), starter as a liquid blend (19–17–0), and urea ammonium nitrate (28–0–0) was used during fertigation.

An expected yield of 12.5 Mg ha^{-1} was considered reasonable and attainable for this site. According to University of Nebraska recommendations, the crop requirement for this level of production is 240 kg ha^{-1} N. The actual fertilizer N recommendation was considerably less (113 kg ha^{-1} N) after crediting for residual soil nitrate and estimated nitrate contained in the irrigation water. The conventional cropping system is common to the area, which is under a N management program imposed on producers by the Central Platte Natural Resource District (CPNRD). Residual soil N (nitrate) prior to planting, fertilizer applications and nitrate contained in irrigation water are shown in Table 1.

Table 1
Nitrogen and water applications and yield at the Nebraska MSEA site for three years

Year: Irrigation	Residual N [a] (kg ha^{-1})	Starter N (kg ha^{-1})	Other N (kg ha^{-1})	Total fertilizer N (kg ha^{-1})	Recommended fertilizer N [b] (kg ha^{-1})	Irrigation N [c] (kg ha^{-1})	Water applied (cm)	Growing season precipitation (cm)	Grain yield (Mg ha^{-1})
1991:									
Conventional	106	33	168 (preplant)	201	113	301	94	7.5	12.53
Surge-flow	173	33	90 (sidedress)	123	46	144	45	7.5	12.33
Center-pivot	95	33	0 (fertigation)	33	124	109	34	7.5	12.17
1992:									
Conventional	121	21	157 (preplant)	178	98	237	74	31.5	13.03
Surge-flow	135	21	52 (fertigation)	73	84	74	23	31.5	12.59
Center-pivot	78	21	26 (fertigation)	47	141	67	21	31.5	11.02
1993:									
Conventional	67	30	157 (preplant)	187	152	73	20	76.2	8.92
Surge-flow	58	30	58 (preplant) 69 (fertigation)	157	161	43	11	76.2	8.04
Center-pivot	24	30	58 (preplant) 67 (fertigation)	155	195	28	8	76.2	8.17

[a] Total residual N (nitrate-N) to a depth of 0.9 m.

[b] Crop N requirement, kg ha^{-1} = (16.128, kg N/Mg of yield $\times$ expected yield, Mg ha^{-1})/(1 $-$ 0.01274 $\times$ expected yield, Mg ha^{-1}). Fertilizer N recommendation, kg ha^{-1} Crop N requirement + 56 $-$ credits (residual soil N, water, etc.). Estimated nitrate-N in irrigation water assuming 24-cm average application at 32 mg L^{-1} nitrate-N = 77 kg ha^{-1} N.

[c] Irrigation water contained an average of 32 mg L^{-1} nitrate-N (3.2 kg ha^{-1} N/cm depth).

Even though the recommended fertilizer N rate in 1991 was 113 kg ha^{-1} N, the producer felt that it would require 168 kg ha^{-1} N to maintain his past level of production. He based this decision on past experiences, knowledge about the soil and concern that nitrate contained in the irrigation water may be applied too late in the growing season to be of much value to the crop. It was stipulated in the contract with the producer that the project would be responsible for yield reduction caused by the various management practices. The producer agreed it was reasonable to establish reference areas in each field that received the same N rate as the conventional field. Therefore, three adequately fertilized test strips (six rows wide receiving 168 kg ha^{-1} as sidedress N) were established in the surge-flow- and sprinkler-irrigated fields to compare yields and evaluate crop N status during the growing season.

Chlorophyll meters (SPAD 502® manufactured by Minolta Corp.) were used to routinely monitor crop N status (Dwyer et al., 1991; Schepers et al., 1992; Piekielek and Fox, 1992; Peterson et al., 1993). Replicated plot data (J.S. Schepers, unpublished data, 1994) indicate that chlorophyll meter readings (average of 30 per plot) have an uncertainty of ±3% or greater, but ±5% is common. A crop N sufficiency index was calculated by dividing the average chlorophyll meter reading for the bulk field by the average value from the adequately fertilized reference strips. Sufficiency index values generated from leaf N concentration data (Schepers et al., 1990) showed that a 95% value at the initial tassel stage (VT) according to Hanway (1971) reduced maize yields by ~ 5%. Plots with sufficiency index values above 95% had statistically similar yields but grain protein content increased with the sufficiency index. Based on the above considerations, a sufficiency index value of 95% was used to trigger fertigation in this study.

The checkbook method was used to schedule irrigation on the surge-flow- and sprinkler-irrigated fields. Irrigation was initiated when 50% of the plant available water was depleted. A neutron probe was used to measure soil water at select locations in each field. Hand sampling provided additional information about the water status for other parts of the field. Irrigation of the conventional field was scheduled by the producer.

2.2. *Maize / soybean rotation*

This study was initiated in 1991 under a linear-drive irrigation system to accommodate comparisons between monoculture maize, a maize/soybean rotation (each crop grown each year) and monoculture soybean. Maize stalks from the previous growing season were shredded and the entire area was disked twice before planting. Four maize hybrids differing in yield potential, maturity and stay green characteristics were selected for use in both the monoculture and rotation systems in combination with five N fertilizer rates (0, 40, 80, 120 and 160 kg ha^{-1} N) plus an "as needed" treatment to simulate fertigation. All hybrids were planted on 15 May 1991, 25 April 1992 and 4 May 1993 in 8-row plots using a 91-cm row spacing at ~ 74,000 seeds/ha. Soybean in the soybean/maize rotation was planted at the same time as the maize in 1991, on 15 May 1992 and 24 May 1993. In early June, N fertilizer as NH_4NO_3 was broadcast on the soil surface and immediately incorporated with 6–7 mm irrigation water. In-season N status was monitored on a weekly basis using chlorophyll meters starting at the V9 stage (nine exposed leaves) and continuing through R2 (soft dough). Chlorophyll meter readings were taken from the uppermost mature leaf until the VT growth stage (23 July). After that stage the ear leaf was measured. All measurements were taken on 30 plants within each plot. Final grain yield was determined at physiological maturity.

3. Results and discussion

Opportunities for making management decisions that are reactive to crop N needs depend on the flexibility of the cropping system. It stands to reason that cropping systems with limited opportunities to correct a N deficiency must rely on other approaches to N management that minimize the potential for a problem. Such cropping systems emphasize past experiences and incorporate a risk factor to compensate for atypical climatic conditions that could result in a N deficiency and lower yields.

The conventional furrow irrigation system for monoculture maize at the Nebraska MSEA site falls into the above category in that it involves no opportunity to correct a N deficiency and therefore a relatively large amount of preplant N fertilizer is applied to this field (Table 1). Soil testing indicated that other nutrients were adequate, so P fertilizer was only applied to replace that removed in the grain. This management system requires the producer to be highly proactive and make a number of assumptions such as how much irrigation will be required, when will irrigation be required, how much N credit should be given for nitrate in the irrigation water, will mineralization follow normal patterns, and to what extent will leaching and denitrification reduce crop N availability. The integrated response to these questions addresses the concern about synchrony between soil N availability and crop needs. Uncertainties associated with these assumptions are usually translated into higher preplant fertilizer N application rates. For example, the producer applied 88, 170 and 35 kg ha^{-1} more fertilizer N than recommended in 1991, 1992 and 1993, respectively. Since the producer applied similar amounts of fertilizer on this field each year (178–201 kg ha^{-1} N), one must question the confidence he placed on the availability of other N sources (i.e. soil and water).

Producers in this area acknowledge that groundwater used for irrigation can be a valuable source of crop N ($\sim$ 3.2 kg ha^{-1} N/cm depth), but giving much credit to this source of N prior to planting involves considerable uncertainty. This concern is illustrated in 1993 when precipitation was nearly adequate to meet crop needs and need for irrigation was limited. In contrast, precipitation in 1991 was below normal and irrigation provided $\sim$ 300 kg ha^{-1} N to the crop. This amount of N in the water was well above the 77-kg-ha^{-1}-N credit recommended by the University of Nebraska for this location. Because irrigation with high nitrate water serves the same function as fertigation, the water in this case could provide at least 50% of crop N needs ($<$ 5 kg ha^{-1} day^{-1}) in July and August, assuming evapotranspiration of $\sim$ 0.8 cm day^{-1}.

Maize yields for the conventional furrow irrigation system in 1991 and 1992 (Table 1) were comparable to maximum yields for the surrounding community. Limited yellowing of lower leaves with the approach of senescence usually suggests an adequate to excessive supply of N throughout the growing season. The relatively large application of irrigation water and associated nitrate contributed to crop N availability during grain fill. This apparent over-irrigation is attributed to the furrow irrigation system that provided adequate water to all parts of the field, but resulted in excessive applications to some areas because a dike at the lower end ensured no water was allowed to leave the field. Grain yields in 1993 were about one-third lower than normal because of stalk breakage caused by a very strong wind on 8 July.

The surge-flow furrow-irrigated system provided moderate flexibility to the producer in terms of N management options because sidedress N application was used in 1991, fertigation in 1992 and limited preplant application plus fertigation in 1993. These approaches adjusted to the situation (i.e. residual soil N and climatic conditions) and minimized the opportunity for early season nitrate leaching while providing adequate N to the crop. The sidedress option requires the N application amount be determined by mid-June, which is about two months later than the preplant application for the conventional management system. Sidedress N applications allow producers to evaluate early season mineralization, compensate for spring leaching and denitrification, and assess crop appearance before deciding how much fertilizer N to apply. The fertigation option used in 1992 and 1993 was not available in 1991. While fertigation allows producers to delay the decision to apply N fertilizer until it is needed by the crop, it can also increase the risk of encountering a N deficiency if excessive precipitation limits the opportunity for furrow irrigation. This situation could necessitate fertigation of an adequately moist soil, which would promote nitrate leaching.

The center-pivot sprinkler-irrigated field produced an average yield that was comparable to the conventional management system in 1991 (Table 1) with considerably lower N fertilizer and water inputs. Difficulties with the irrigation system delayed the first sprinkler application, which probably caused the slight yield differences. Reduced N fertilizer and water application rates resulted in a gradual decline in residual soil N over time prior to planting. Lower amounts of residual N after harvest should result in less nitrate leaching over the winter months.

An important component of any effective N management system is coordinating N availability with crop N needs. Achieving reasonable synchrony requires a technique to evaluate N status of the growing crop so that a N deficiency can be detected early enough to allow addition of fertilizer N to correct the apparent problem. The chlorophyll meter used to monitor crop N status indicated no apparent N deficiency for the surge-flow- or center-pivot-irrigated field in 1991. Aerial photographs taken at silking failed to identify the three adequately fertilized reference strips in either field that received additional N fertilizer. The slightly lower average yield from the surge-flow-irrigated field compared to the conventional field (Table 1) is attributed to a small portion of the field where topsoil was removed during the laser-grading operation. The same N deficient area was identified in a 1992 aerial photograph at silking, but the adequately fertilized test strips were still difficult to identify. Earlier in the 1992 growing season chlorophyll meters indicated an approaching N deficiency, which triggered the fertigation treatment.

Chlorophyll meter readings collected weekly from the sprinkler-irrigated field during the 1992 growing season showed mixed signs of a N deficiency for the three sets of reference strips. Fertigation was only applied once to this field in 1992. Aerial photographs taken at silking were not available for examination until after harvest, but for the first time revealed considerable spatial variability in terms of crop N status for this field. The photograph also revealed an old test strip established in 1991 that was adjacent to one of the 1992 test strips. The intent was to use the same area for the test strips year after year. Comparison of chlorophyll meter readings between the 1991 and 1992 test strips resulted in non-representative information that in turn failed to trigger the need for fertigation. Significant yield reductions for the sprinkler-irrigated system in 1992 illustrate the implied risk to profitability of maize production associated with a N deficiency.

Evidence to support the spatial variability observed in the aerial photograph of the sprinkler-irrigated field was provided with data generated by grid sampling the soil (30 × 30 m) in the spring of 1991. Although differences in surface soil color were not apparent, depth to sand varied from 50 to > 150 cm. Differences in root zone depth would affect N mineralization and crop nutrient availability.

Application of additional N fertilizer to reference strips has been shown to be a reasonable way to calibrate chlorophyll meters over time (Schepers et al., 1992; Peterson et al., 1993). However, these data illustrate the importance of selecting representative areas of the field when making relative comparisons to evaluate crop N status. One caution when using a chlorophyll meter to measure crop N status is that other nutrients can also affect leaf chlorophyll content. Since N is the nutrient most closely associated with chlorophyll, adequate P was provided in the starter fertilizer, and previous crops did not exhibit any nutrient deficiencies, it suggests that the lighter green areas in the field in 1992 can be attributed to an N deficiency. The combined use of chlorophyll meters and aerial photographs seems to provide adequate information for making intelligent decisions regarding the need for fertigation.

The inability of a cropping system to respond to fluctuations in N availability caused by the dynamics of the N cycle usually forces producers to adapt longer-term N management strategies. Climatic factors that affect N losses typically have a similar effect on cropping systems. Long-term N management strategies tend to be more "proactive" out of necessity because opportunities to be "reactive" are frequently limited. The reactive features of N management within a cropping system are likely to be the most obvious under situations where climatic conditions or management practices lead to extreme situations. This is because atypical climatic conditions can result in everything from above normal mineralization rates to excessive soil water that can lead to large N losses by denitrification and leaching.

Crop rotations involving legumes frequently show signs of enhanced nutrient availability, hence the recognition and assignment of legume credits when making N fertilizer recommendations. The term "legume N credits" may actually be a misnomer in that comparison is usually made to monocrop systems that involve different kinds and amounts of residue. Therefore, mineralization rates are likely to be different for rotation and monocrop production systems. Soils containing legume residues tend to become "net mineralizers" before those with maize, sorghum, or wheat residues (Schepers and Mosier, 1991). These differences affect synchronization of N availability with crop N needs and therefore affect the way producers manage their N fertilizers.

Results from the crop rotation study will feature the 1992 data because 1991 was the first year of the study that contained both crops. The 1993 chlorophyll meter readings

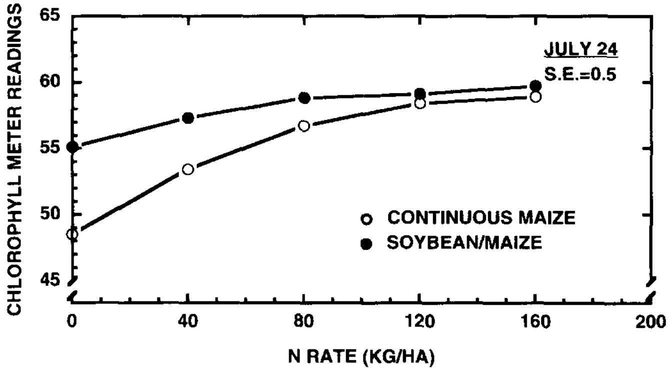

Fig. 1. Effect of N rate on chlorophyll meter readings for an irrigated maize/soybean rotation and monoculture maize at silking.

and yields for the various maize hybrids were differentially affected by the wind damage. Maize following soybean and monoculture maize receiving high rates of fertilizer N showed up to 50% stalk breakage. Each hybrid used in the crop rotation study in 1992 responded similarly to applied N as indicated by chlorophyll meter readings and grain yield (Table 2), but average values for both parameters were consistently greater for the rotation system than for continuous maize. Higher chlorophyll meter readings at silking (23 July) demonstrate the enhanced N status of maize following soybean compared to continuous maize (Fig. 1). The highest rate of N fertilizer (160 kg ha^{-1} N applied shortly after planting) under continuous maize showed comparable N status to much lower N rates under the rotation system. These differences were evident throughout the growing season and only began to converge near senescence.

A time sequence of chlorophyll meter readings for the check plot and the 120-kg-ha^{-1}-N rate illustrates the dynamics of N availability for cropping systems involving

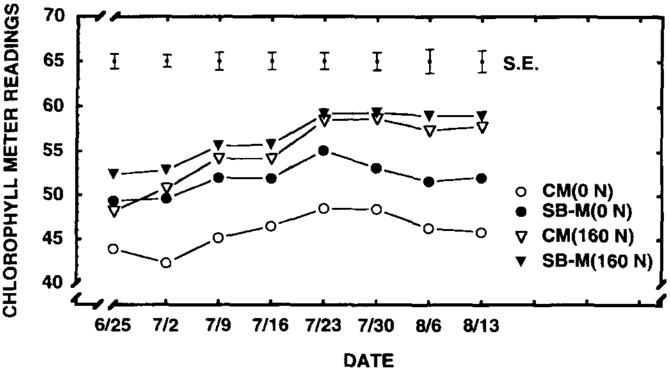

Fig. 2. Changes in chlorophyll meter readings during the growing season for an irrigated maize/soybean rotation and monoculture maize at two fertilizer N rates.

Table 2
Influence of N fertilizer on average in-season chlorophyll meter readings and grain yield of four irrigated maize hybrid in monoculture and soybean–maize cropping systems at Shelton, Nebraska, in 1992

N rate	Chlorophyll meter readings						Grain yield (Mg ha^{-1})	
(kg ha^{-1})	2 July		16 July		30 July		CM	SB/M
	CM	SB/M	CM	SB/M	CM	SB/M		
0	42.3	49.6	46.4	51.9	48.4	53.1	7.9	10.7
40	46.7	51.2	50.5	53.9	53.1	56.6	9.3	11.3
80	49.7	53.1	52.7	54.9	56.7	58.7	10.3	11.9
120	50.7	52.8	54.1	55.7	58.7	59.3	10.5	11.8
160	51.5	53.6	54.2	55.5	59.3	59.5	10.8	11.7
Mean	$\overline{48.2}$	$\overline{52.0}$	$\overline{51.6}$	$\overline{54.4}$	$\overline{55.2}$	$\overline{57.4}$	$\overline{9.8}$	$\overline{11.5}$
S.E.	0.45		0.43		0.50		0.20	

CM = continuous maize; SB/M = soybean/maize; S.E. = standard error.

legume rotations (Fig. 2). Residue from the previous soybean crop probably mineralized sooner than maize residue and apparently was better synchronized with N need of the subsequent maize crop. These findings could also be related to improved soil tilth following the soybean crop, which is thought to promote more extensive rooting, fewer plant pathogens and more vigorous plant growth.

The net positive effect of the previous soybean crop on chlorophyll meter readings existed throughout the growing season for the check plots. Early season benefits of the previous soybean crop were detected with the chlorophyll meter even at the 120-kg-ha^{-1}-N fertilizer rate. By midseason the benefit of the previous soybean crop had disappeared in the presence of adequate N fertilizer; however, grain yield at the 120-kg-ha^{-1}-N rate was greater for the maize/soybean rotation. These data illustrate the importance of adequate early season N nutrition on maize yields.

4. Conclusions

The focus of this study was to document the effect of improved N and water management practices on groundwater quality. This report illustrates that irrigation management practices that provide for uniform water distribution and for non-excessive application rates are essential when striving to minimize nitrate leaching. Many options are available to improve N management once water percolation below the root zone can be minimized. Reducing fertilizer N application rates to meet crop needs proved to be a noble goal, but difficult to achieve when limited to techniques that only provide for uniform applications of crop nutrients. Improved N management practices including fertigation were able to reduce carry-over N to the next growing season.

The implications of reduced irrigation and fertilizer N application rates on groundwater quality are encouraging, even though they are largely intuitive. Data not provided in this paper indicate that after three years these practices reduced the concentration of nitrate-N leaching beneath the root zone and entering the aquifer. The extent to which nitrate leaching can be reduced will depend on the extent to which producers are able to deal with temporal variability in climate and spatial variability in soil. Cropping systems that allow producers to make N management decisions and apply N fertilizer during the growing season reduce the number of assumptions that go into cropping strategies that are limited to preplant fertilizer applications. Interactive decision making opportunities that integrate nutrient availability, crop growth and climatic conditions allow producers to sustain profitability and minimize the risk of environmental contamination by nitrate.

References

Blackmer, T.M. and Schepers, J.S., 1995. Use of a chlorophyll meter to monitor N status and schedule fertigation for corn. J. Prod. Agric., 8: 56–60.

Dwyer, L.M., Tollenaar, M. and Houwing, L., 1991. A nondestructive method to monitor leaf greenness in corn. Can. J. Plant Sci., 71: 505–509.

Girardin, P., Tollenaar, M. and Muldon, J.F., 1985. The effect of temporary N starvation on leaf photosynthetic rate and chlorophyll content in maize. Can. J. Plant Sci., 65: 491–500.

Hanway, J., 1971. How a corn plant develops. Iowa State Univ., Ames, IA, Spec. Rep. No. 48.

Inada, K., 1965. Studies for a method for determining the deepness of green colour and chlorophyll content of intact crop leaves and its practical application, 2. Photoelectric characters of chlorophyllometer and correlation between the reading and chlorophyll content in leaves. Proc. Crop Sci. Soc. Jpn., 33: 301–308.

Lohry, R.D., 1989. Effect of N fertilizer rate and nitrapyrin on leaf chlorophyll, leaf N concentration, and yield of three irrigated maize hybrids in Nebraska. Ph.D. Dissertation, University of Nebraska, Lincoln, NE.

Olson, R.A., Seim, E.C. and Muir, J., 1973. Influence of agricultural practices on water quality in Nebraska: A survey of streams, ground water, and precipitation. Water Resour. Bull., 9(2): 301–311.

Peterson, T.A., Blackmer, T.M., Francis, D.D. and Schepers, J.S., 1993. Using a chlorophyll meter to improve N management. Univ. Nebr., Lincoln, NE, Nebr. Coop. Ext. Ser., NebGuide G93-1171A.

Piekielek, W.P. and Fox, R.H., 1992. Use of a chlorophyll meter to predict sidedress N requirements for maize. Agron. J., 84: 59–65.

Schepers, J.S. and Mosier, A.R., 1991. Accounting for N in nonequilibrium soil–crop systems. In: R.F. Follett, D.R. Keeney and R.M. Cruse (Editors), Nitrogen Management for Ground Water Protection and Farm Profitability, Ch. 6. Soil Sci. Soc. Am., Madison, WI, pp. 125–138. .

Schepers, J.S., Francis, D.D. and Clausen, C., 1990. Techniques to evaluate N status of corn. Agron. Abstr., p.268.

Schepers, J.S., Blackmer, T.M. and Francis, D.D., 1992. Predicting N fertilizer needs for corn in humid regions: using chlorophyll meters. In: B.R. Bock and K.R. Kelley (Editors), Predicting N Fertilizer Needs for Maize in Humid Regions. Natl. Fert. Environ. Res. Cent., Tenn. Valley Auth., Muscle Shoals, AL, Bull. Y-226, pp. 105–114.