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Runoff Water Quality Impact of Variable Rate Sidedress Nitrogen Application*

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Abstract. In recent years, precision agriculture has received attention from producers, agribusiness, and governmental agencies in an effort to increase profitability and protect the environment. Many aspects of precision agriculture, such as soil fertility, application technology, and economic factors, have received substantial research attention; however, other aspects of precision agriculture have not been well documented. One important issue that warrants increased attention is water quality. Because of precision application technology, variable rate fertilizer application based on within-field heterogeneity has the potential to decrease negative water quality impacts. Therefore, the objective of this paired watershed study was to evaluate the impact of variable rate nitrogen (N) fertilizer application on surface water quality. The variable rate (VR) field was divided into management units designated as poor, moderate, and high based on measured yield potential and received 100–160 kg/ha of N fertilizer. A portion of the N application was uniformly applied pre-plant or at planting, and rest was sidedressed at variable rates. The uniform rate (UR) field received uniform N application at 135 kg/ha. Surface water runoff and water quality were monitored for each field, and collected samples were analyzed for N and phosphorus (P) constituents. During the 2-year monitoring period with 22 storm sampling events, variable rate N application resulted in few water quality differences compared to uniform rate application, but overall median $NO_3 + NO_2$–N concentrations were significantly lower for the variable rate field in the second year of variable rate N application. Overall and event mean $NO_3 + NO_2$–N concentrations from the variable rate field tended to be higher, but median concentrations from the uniform rate field tended to be higher.

Keywords: water quality, variable rate fertilizer application

Introduction

Nutrient transport from agricultural lands is frequently identified as a major contributor to degradation of surface and ground water resources. Cropland, pastureland, and rangeland contribute 6.2 million metric tons of nitrogen (N) to US surface waters annually (USEPA, 2000). This link between agriculture and water quality degradation has placed increased pressure on agriculture to incorporate improved practices to sustain agricultural productivity and enhance environmental quality.

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While many of these practices are widely used in production agriculture, the persistence of water quality problems suggests a need for further development and implementation. Because practices such as precision farming may increase profitability and reduce environmental threat, they have the potential for widespread support from agricultural and environmental interests. In recent years, precision agriculture has received attention from producers, agribusiness, and governmental agencies. This attention can be attributed to improved computer and sensor technology and to innovative efforts to increase producer profitability and protect water supplies from chemical and fertilizer contamination (Pierce and Nowak, 1999; Schepers and Francis, 1998; Stafford, 2000).

Precision agriculture, which includes components such as site-specific management and variable rate technology, can be simply defined as input application across a field based on variable requirements for that input (Prato and Kang, 1998; Vanden Heuvel, 1996). With variable rate fertilizer application, the field is divided into relatively small homogeneous units with similar soil, fertility, or crop yield characteristics. Fertilizer is then applied at variable rates across the field based on these characteristics. Precision farming techniques, specifically variable rate fertilizer application in this study, consider spatial variability of crop and soil conditions. In contrast, traditional farming treats each field as a homogeneous unit with a uniform fertilizer application rate to meet a single yield goal for the entire field. Since producers do not want yields to be limited by nutrients, fertilizer over-application can occur in lower producing areas of the field. In contrast, variable rate application can capture and respond to highly variable crop yield and soil characteristics, which may result in more efficient fertilizer use by the crop (but not necessarily reduced total application). According to Hergert *et al.* (1997), variable rate application presents one of the greatest challenges and opportunities for improving fertilizer efficiency since the adoption of soil testing in the 1950s and 1960s. Increased fertilizer efficiency creates a potential reduction in nutrient losses which threaten downstream water resources. Pierce and Nowak (1999) indicate that variable rate fertilizer application should have a greater expectation for profitability and/or environmental benefit on crops which require high N inputs.

Several recent modeling studies such as Rejesus and Hornbaker (1999), Prato and Kang (1998), and Larson *et al.* (1997) have demonstrated the potential of variable rate application to provide environmental enhancement through reduction of nutrient movement offsite and increased profitability due to improved fertilizer management. However, few field studies have documented these potential environmental benefits probably because precision agriculture is a relatively recent concept and because of the significant commitment required to monitor water quality in the field. The following research has provided valuable data, but additional research is needed. Redulla *et al.* (1996) integrated yield mapping and variable N application technology and compared N use efficiency on two irrigated corn fields in south central Kansas. Results indicated no statistical difference in N use efficiency between the variable and uniform N treatment. Hergert *et al.* (1996) compared corn yields and N use efficiency on irrigated corn fields in Nebraska. They observed no significant yield difference between fixed and variable rate N, but variable rate N application showed a potential for improving N use efficiency and for decreasing long-term nitrate leaching. Dampney *et al.* (1999) compared the economical and environmental benefits of uniform rate N application and variable rate N application on two winter wheat fields in England. They found no significant difference in grain yield between the treatments but did observe reduced NO_3–N leaching from the variable rate application. Long *et al.* (1996) conducted three trials on dryland wheat fields in northern Montana. They determined that the potential exists for increased profits from variable rate N application. Malzer *et al.* (1996) evaluated the potential economic benefit of site-specific N rate management on four dryland corn fields in Minnesota. They determined that the potential added value for site-specific N management was 10–20% of the current N profitability estimates. Yang *et al.* (1999) compared crop yields from three irrigated grain sorghum fields in Texas. No difference was observed between two uniform fertilizer treatments, but the variable rate treatment produced a significantly higher yield.

The combined potential for increased profitability and environmental benefits makes variable rate fertilizer application a promising technique for agriculture. While many aspects of precision agriculture have suspected benefits, field scale research evaluation of the environmental and production performance is limited (Hatfield, 2000; Pierce and Nowak, 1999; Vanden Heuvel, 1996). This study was designed with the objective of evaluating the impact of variable rate N fertilizer application on surface runoff quality in the Texas Blackland Prairie, an important crop production area of over 11 million acres. This hypothesis was evaluated in a paired watershed study by comparing water quality from two adjacent fields, one with variable rate N application and the other with uniform N application.

Procedures

Site description

The study was conducted in Bell County, Texas, approximately 3 km east of Temple. The site was divided into two fields with one receiving uniform rate N fertilizer and the other receiving variable rate N application at three rates. A detailed field survey was conducted within each field using a Differential Global Positioning System (DGPS), and data were subsequently entered into a geographic information system (GIS) database. These GIS files were used to determine subwatershed boundaries within the fields and to delineate flow accumulation pathways. A summary of subwatershed characteristics within each field is presented in Table 1. Soils series at the study site are Heiden clay (fine, smetitic, thermic Udic Haplustert), Houston Black clay (fine, smectitic, thermic Udic Haplustert), and Ferris clay (fine, smectitic, thermic Chromic Udic Haplustert); all of which are heavy clays with a strong shrink/swell potential.

Prior to the initiation of variable rate application in 1999, a combine with a DGPS receiver and a grain yield monitor were used to collect corn (*Zea mays* L.) yield information under uniform rate fertilizer management for the 1997 and 1998 crop years. This information was used to quantify yield potentials and to divide the variable rate field into three yield potential units, poor (6.0 mg/ha), moderate (7.4 mg/ha), and best (8.7 mg/ha) as shown in Figure 1. The producer's traditional corn yield goal for

Table 1. Subwatershed characteristics within the variable rate and uniform rate fields

	Variable rate field	Uniform rate field
Area	9.1 ha	5.7 ha
Maximum Flow Length	500 m	542 m
Average Slope	3%	3%
Conservation Practices	Broad-based terraces, grassed waterway	
Cropping	Continuous corn, no winter cover crop	

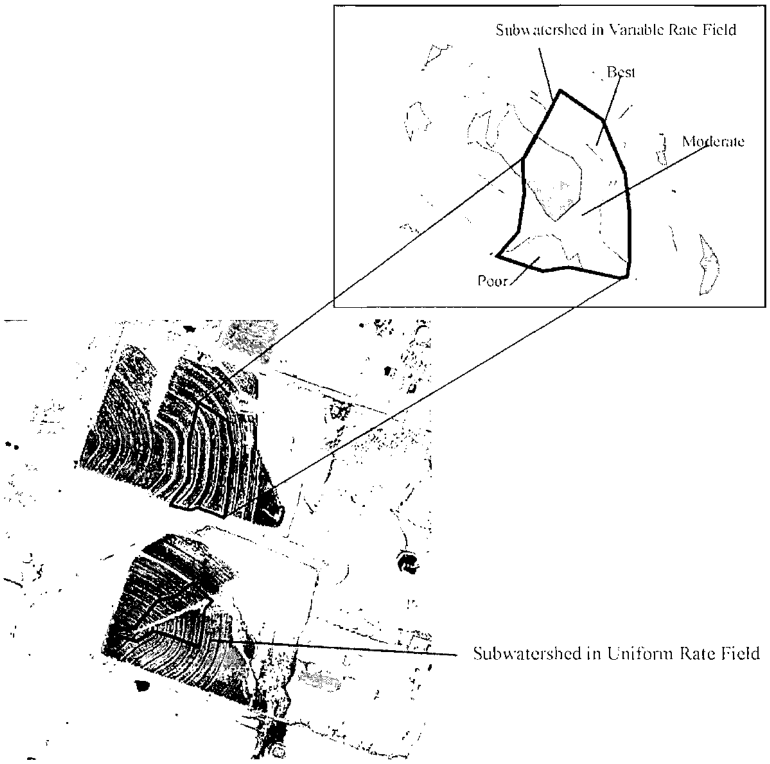

Figure 1. Yield potential units for the variable rate field.

these fields (7.5 mg/ha) was used to select appropriate fertilizer management. A detailed schedule of cropping and fertilizer application for both fields is shown in Table 2.

Flow measurement and water quality sampling

To monitor surface runoff and water quality, a 0.61 m H-flume equipped with an ISCO 4230/3700 flow meter and sampler system[4] (ISCO, Inc., Lincoln, NE) was

Table 2. Cropping and fertilizer application dates

Date	Variable rate field	Uniform rate field
1999 crop year		
26-Feb-99	Surface applied 83 kg/ha N as liquid 32-0-0, prepared seedbed	Surface applied 83 kg/ha N as liquid 32-0-0, prepared seedbed
2-Mar-99	Planted corn, knifed in 12 kg/ha N and 39 kg/ha P as mixture of liquid 32-0-0 and 11-37-0 at planting	Planted corn, knifed in 12 kg/ha N and 39 kg/ha P as mixtureof liquid 32-0-0 and 11-37-0 at planting
17-Apr-99	Knifed in variable rate N (13, 37, 60 kg/ha) as liquid 32-0-0	Knifed in 39 kg/ha N as liquid 32-0-0
16-Jul-99	Harvested corn	Harvested corn
2000 crop year		
9-Mar-00	Surface applied 64 kg/ha N and 39 kg/ha P as mixture of liquid 32-0-0 and 11-37-00, prepared seedbed	Surface applied 64 kg/ha N and 39 kg/ha P as mixture of liquid 32-0-0 and 11-37-00, prepared seedbed
10-Mar-00	Planted corn	Planted corn
26-Apr-00	Knifed in variable rate N (48, 76, 99 kg/ha) as liquid 32-0-0	Knifed in 71 kg/ha N as liquid 32-0-0
3-Aug-00	Harvested corn	Harvested corn

installed at the subwatershed outlet of each field. In each field, a broad-base terrace directed runoff flow into a waterway vegetated with coastal Bermuda grass. Runoff flowed down the waterway to the subwatershed field outlet where a small berm was constructed to channel runoff into flow monitoring devices. An ISCO 674 rain gauge (ISCO, Inc., Lincoln, NE) and two HOBO rain event recorders (Onset Computer Corporation, Pocasset, MA) were also installed on site to record rainfall data.

Monitoring began in March 1999 and continued through March 2001. During this two-year period, flow rates were recorded every 5 min during runoff events. Variable time-weighted, composite water quality samples were collected for every significant runoff event (depth greater than 38.1 mm or 0.94 l/s in the flume). Four consecutive samples were composited into a single bottle. To provide adequate resolution in short duration events and adequate sampling capacity for longer events, samples were taken at 5-min intervals for the first 65-min, 15-min intervals for the next 660-min, and 30-min intervals for the following 1200 min. Samples were collected from the field within 48 h of the runoff event. Collected samples were then acidified, iced, and transported to the laboratory for analysis of soluble and sediment-bound N and P constituents.

Water quality analysis

Samples were stored at 4 °C prior to analysis and analyzed within 30 days of collection. Samples were analyzed for dissolved nitrate plus nitrite nitrogen ($NO_3 + NO_2 - N$), ammonium nitrogen (NH_4–N), and *ortho*-phosphate (PO_4–P) concentrations using a Technicon Autoanalyzer IIC (Technicon Instruments Corp., Tarrytown, NY) and colorimetric methods published by Technicon Industrial Systems (1973a, 1973b, 1976). Dissolved nutrient loads were determined by multiplying nutrient concentrations by corresponding flow volumes and summing these incremental loads for the duration of the runoff event.

The sediment in each runoff sample was separated from solution, dried, and weighed. Sediment concentrations were determined from this mass and the total measured volume of collected runoff sample. As with dissolved nutrients, the sediment load for each storm event was estimated as the sum of incremental runoff volumes multiplied by the corresponding sediment concentrations. Sediment-bound nutrient loads were determined by multiplying sediment masses by the corresponding sediment-bound nutrient concentrations. Sediment-bound total Kjeldahl N (TKN) and P (TKP) levels were determined by a salicylic acid modification of a semimicro-Kjeldahl digestion procedure (Technicon Industrial Systems, 1976) and colorimetric methods published by Technicon Industrial Systems (1973a, 1973b, 1976).

To evaluate possible differences in nutrient loss from the variable rate and uniform rate fields, we compared: (1) nutrient event mean concentrations (EMCs), which are average flow-weighted concentrations for each storm, (2) concentrations of every individual sample collected within runoff events, and (3) annual nutrient loads. For these parameters, differences in means were evaluated with *t*-tests and differences in medians with the Mann–Whitney test, all at $\alpha = 0.05$ (Helsel and Hirsch, 1993).

Results and Discussion

Rainfall, runoff, and erosion

Rainfall variability experienced during the study provided an opportunity to evaluate water quality impacts over a range of climatic conditions. Rainfall for the 1999 crop year was 461 mm, which is well below the 877 mm annual average based on 1913–1999 records from the USDA Grassland Soil and Water Research Laboratory in Temple, Texas (Figure 2). During this period, only seven rainfall events produced adequate runoff to obtain water quality samples from both fields (Table 3).

In contrast, the 765 mm rainfall total for the 2000 crop year was near the long-term average (Figure 2). Rainfall early in the year exceeded normal amounts and produced two sampling events, but the summer drought produced little rainfall. This dry period with no sampling events was followed by an extremely wet period from October 2000 through March 2001 that produced 13 sampling events (Table 3). Sampling events in the second year were generally of much greater flow magnitude than events sampled in the first year.

It is important in paired watershed studies of water quality that the watersheds be hydrologically similar, so that water quality differences can be attributed to treatment effects. No significant difference was found between mean rainfall depth at two

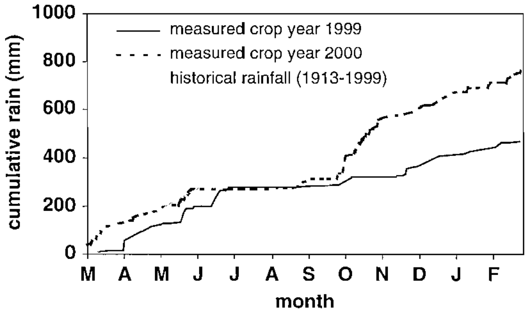

Figure 2. Cumulative rainfall for 1999 and 2000 crop years (March 15 through March 14).

Table 3. Rainfall and runoff depths for sampling events

	Variable rate field			Uniform rate field		
Date	Rainfall (mm)	Runoff (mm)	Runoff rainfall ratio (%)	Rainfall (mm)	Runoff (mm)	Runoff rainfall ratio (%)
1999 crop year						
26-Apr-99	39.6	0.3	0.8	42.5	2.8	6.6
10-May-99	35.1	0.2	0.6	37.1	0.1	0.3
15-Jun-99	15.5	0.1	0.6	15.4	0.01	0.1
12-Jul-99	25.7	1.7	6.6	25.8	1.7	6.6
8-Jan-00	45.5	6.2	13.6	42.5	1.1	2.6
22-Feb-00	23.9	1.8	7.5	22.9	3.8	16.6
26-Feb-00	18.8	2.3	12.2	20.1	3.4	16.9
2000 crop year						
26-Mar-00	8.9	0.1	1.1	7.8	0.02	0.3
11-Apr-00	51.3	23.3	45.4	49.5	23.3	47.1
3-Nov-00	62.7	23.8	38.0	62.7	15.9	25.4
8-Nov-00	11.9	5.5	46.2	11.9	4.1	34.5
12-Nov-00	15.5	0.8	5.2	15.5	1.0	6.5
17-Nov-00	24.6	18.0	73.2	25.9	12.2	47.2
23-Nov-00	11.9	4.9	41.2	11.9	4.4	37.0
25-Dec-00	44.7	35.9	80.3	31.8	25.4	79.9
10-Jan-01	22.4	7.9	35.3	26.2	7.1	27.1
16-Jan-01	26.9	21.1	78.4	25.4	19.3	76.0
29-Jan-01	12.2	4.9	40.2	13.2	3.8	28.8
16-Feb-01	19.8	1.3	6.6	19.8	1.0	5.1
03-Mar-01	17.3	2.7	15.6	13.0	1.9	14.6
08-Mar-01	17.8	6.0	33.7	19.1	4.1	21.5
12-Mar-01	8.9	1.9	21.3	9.4	1.5	16.0
Sampling event totals =	561	171	Ave = 27.4	549	138	Ave = 23.5

fields; however, runoff depth and the runoff/rainfall means were significantly different based on a paired t-test at $\alpha = 0.05$ (Table 3). The impact of this runoff difference will be discussed below. Because of erosion control measures (residue management, contour farming, terraces, and vegetated waterways), annual sediment losses from both fields were low. For the variable rate field, 167 and 449 kg/ha of soil were eroded in 1999 and 2000, respectively; and for the uniform rate field, 446 and 765 kg/ha of soil were eroded for the two years. Mean soil loss was not significantly different ($\alpha = 0.05$).

Nitrogen application and corn yield

Prior to the 1999 crop year, fertilizer was applied at a uniform N rate of 135 kg/ha on both fields. Different fertilizer application methods began in 1999, as variable rate N was applied on one field based on yield monitoring results between 1997 and 1998. Variable rate N application resulted in average N rates of 125 and 129 kg/ha applied within the variable rate subwatershed, which is 4–7% less than would have been applied under uniform N rate application (Table 4). Variable rate fertilizer application will not always result in reduced total fertilizer application over a field as was the case in this study. The field selected for variable rate application contains a higher proportion of poor yield potential areas compared to best potential areas; therefore, less overall fertilizer was applied to the field. Corn yields were similar between the two fields for 1998–2000 (Table 4). Based on results of a paired t-test, no significant difference existed between corn yields under variable rate and uniform rate N application.

Nitrogen losses in surface runoff

Under conditions experienced in this study, runoff water quality was generally similar for the variable rate and uniform rate N application fields; however, one significant difference was found. This statistically significant difference, median

Table 4. Fertilizer amounts and corn yields from subwatersheds within each field

	Fertilizer N applied Average over field (kg/ha)		Corn yield[b] ± 1 standard deviation (mg/ha)	
Year	Variable rate field	Uniform rate field	Variable rate field	Uniform rate field
1997	135[a]	135[a]	6.7 ± 1.7	Not measured
1998	135[a]	135[a]	2.5 ± 0.5	2.5 ± 0.7
1999	125	134	7.7 ± 1.3	7.9 ± 1.3
2000	129	135	5.5 ± 1.3	5.4 ± 1.3

[a] All fertilizer applied in cropping years 1997 and 1998 was uniformly applied. Variable rate N application began in 1999.

[b] Possible differences in average corn yield were evaluated with a paired t-test at $\alpha = 0.05$.

Table 5. Nutrient concentrations for the variable rate and uniform rate fields (mg/l)

	Variable rate field			Uniform rate field		
	n	Mean	Median	*n*	Mean	Median
Event mean conc. $NO_3 + NO_2$–N						
1999 crop year	7	5.4	1.2	7	5.9	2.0
2000 crop year	15	3.0	1.3	15	2.1	1.7
Total	22	3.7	1.3	22	3.3	1.9
All samples $NO_3 + NO_2$–N						
1999 crop year	60	7.3	5.1	37	7.9	7.4
2000 crop year	308	4.2	0.9[a]	262	3.8	1.5[a]
Total	368	4.7	1.2	299	4.3	1.6
Event mean conc. PO_4–P						
1999 crop year	7	0.3	0.3	7	0.4	0.4
2000 crop year	15	0.1	0.1	15	0.1	0.1
Total	22	0.2	0.1	22	0.2	0.1
All samples PO_4–P						
1999 crop year	60	0.3	0.2	37	0.4	0.4
2000 crop year	308	0.1	0.1	262	0.1	0.1
Total	368	0.1	0.1	299	0.1	0.1

[a] Significant difference (determined with the Mann–Whitney test, $\alpha = 0.05$).

$NO_3 + NO_2 - N$ concentration was lower for the variable rate field compared to the uniform rate field, occurred in the second year of variable rate application (Table 5). This result could indicate a potential for water quality enhancement under repeated variable rate N application as variable N rates attempt to match soil and crop variability within the field; however, the difference may also be attributed to dilution from increased runoff volume for the VR field. Overall and event mean $NO_3 + NO_2 - N$ concentrations from the variable rate field tended to be higher (due to a greater number of atypical positive outliers), but median concentrations from the uniform rate field tended to be higher. As shown in Figure 3, $NO_3 + NO_2 - N$ was the dominant dissolved N form. For the 22 sampling events, event mean dissolved $NO_3 + NO_2$–N concentrations ranged from 0.0 to 22.0 mg/l (mean = 3.7 mg/l; median = 1.3 mg/l) for the variable rate field and from 0.0 to 15.8 mg/l (mean = 3.3 mg/l; median = 1.9 mg/l) for the uniform rate field. In contrast, event mean concentrations for NH_4–N were all well below 1.0 mg/l. $NO_3 + NO_2$–N concentrations were generally higher in the first year with relatively low rainfall; however, high $NO_3 + NO_2$–N concentrations were also measured in the first major runoff event in the second year (Figure 4).

Total N loads (includes dissolved $NO_3 + NO_2$–N, dissolved NH_4–N, and sediment-bound TKN) were similar between the variable rate and uniform rate fields for most storms and varied greatly based on rainfall (Figure 4). One exception was the April 11, 2000 storm, in which the N load from the VR field was almost twice the N load from the UR field (Figure 5). The difference in loads

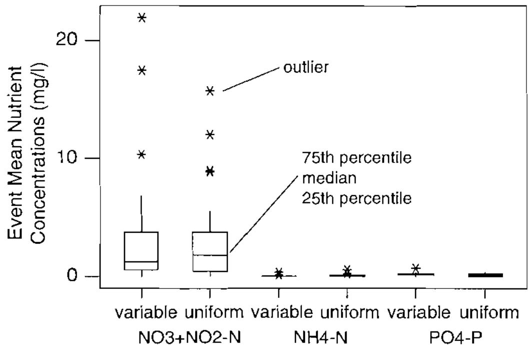

Figure 3. Event mean nutrient concentrations for the 22 runoff events.

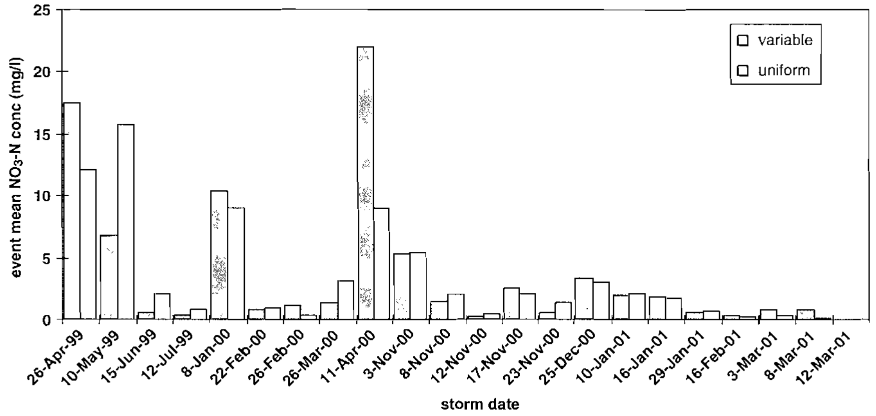

Figure 4. Event mean NO_3 + NO_2–N concentrations for the 22 runoff events.

was caused by a much higher event mean NO_3 + NO_2–N concentration from the VR field (22 mg/l) compared to the UR field (10 mg/l) because runoff volumes were the same from both fields (23 mm). This difference in storm concentrations on April 11, 2000 cannot be attributed to fertilizer application because the VR and UR sideress application was not made until April 26, 2000. Following that storm N loads and concentrations were nearly identical for the remainder of the study. Even with the large load difference on April 11, 2000, no significant differences in mean and median dissolved and sediment-bound N storm loads were found between the VR and UR fields using paired *t*-tests and nonparametric Mann–Whitney tests (Table 6). N losses in the 1999 crop year represent 0.8% of applied N from the variable rate field and 0.9% from the uniform rate field. In the 2000 crop year, N losses were 7.0% of applied N from the variable rate field and 4.2% from the uniform rate field. Dissolved forms of N contributed 70–90% of the total N loss.

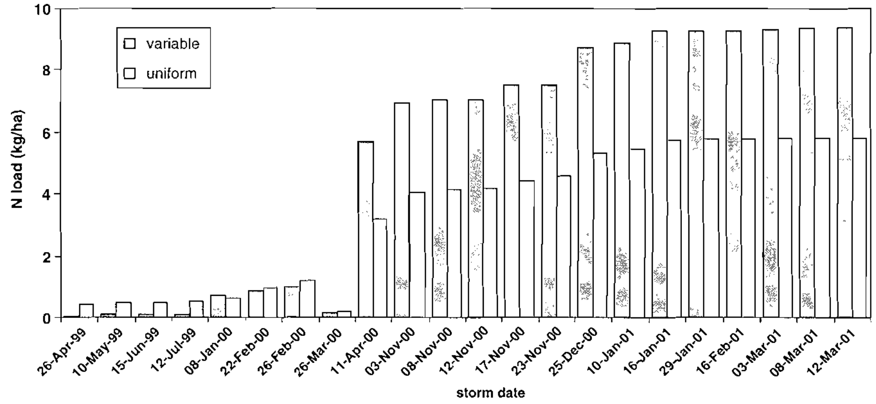

Figure 5. Cumulative annual N loads for the two year monitoring period, by year (Mar–Feb).

Table 6. Annual total, dissolved, and sediment-bound nutrient loads (kg/ha)

	Variable rate field			Uniform rate field		
	Total N	Dissolved N	Sediment N	Total N	Dissolved N	Sediment N
1999 crop year	1.01	0.77	0.24	1.21	0.55	0.67
2000 crop year	9.22	8.64	0.59	5.61	4.47	1.14
2-year total	10.23	9.41	0.83	6.83	5.02	1.81
	Variable rate field			Uniform rate field		
	Total P	Dissolved P	Sediment P	Total P	Dissolved P	Sediment P
1999 crop year	0.11	0.03	0.08	0.24	0.04	0.20
2000 crop year	0.37	0.15	0.22	0.52	0.13	0.39
2-year total	0.47	0.18	0.29	0.76	0.17	0.59

Phosphorus losses in surface runoff

Dissolved PO_4–P concentrations and total P loads (includes dissolved PO_4–P and sediment-bound TKP) were similar for both fields (Tables 5 and 6). These results were expected since P application schemes were the same for the two fields. No significant differences in event mean or overall P concentrations or in mean and median dissolved and sediment-bound P loads were found between the variable rate and uniform rate fields using *t*-tests and nonparametric Mann–Whitney tests. Dissolved PO_4–P concentrations were all well below 1.0 mg/l for both fields (Figure 3). Less than 2% of applied P was lost in runoff from both fields each year. In contrast to N, in which losses were predominately in the dissolved form, 60–80% of P was lost with eroded soil. Similar to NO_3 + NO_2–N concentrations, dissolved PO_4–P concentrations were higher in dry year 1999 than in the wetter year of 2000

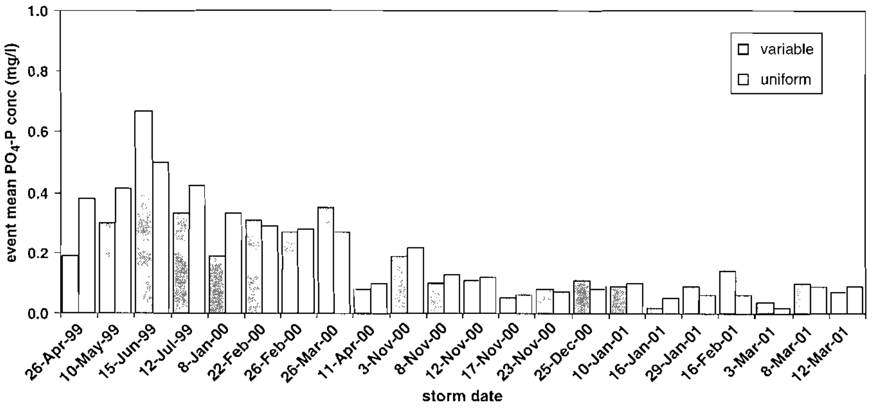

Figure 6. Event mean PO_4–P concentrations for the 22 runoff events.

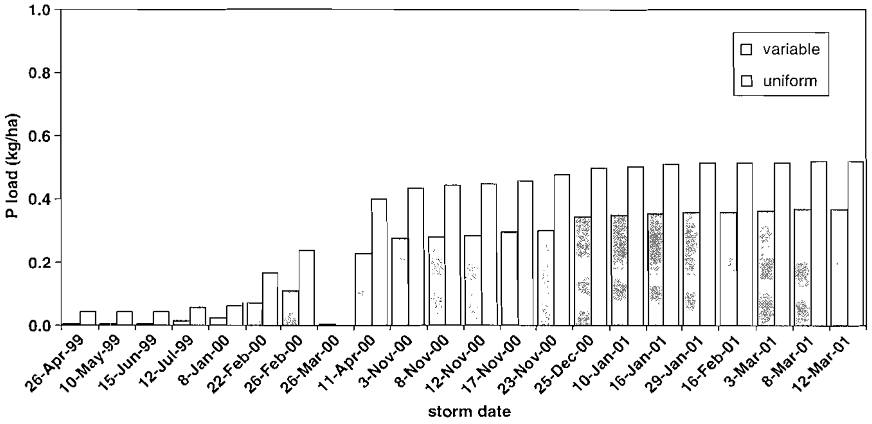

Figure 7. Cumulative annual P loads for the two year monitoring period, by year (Mar–Feb).

(Figure 6). However, annual P loads were greater in the second year of the study due to increased runoff volume (Figure 7).

Conclusions

In recent years, precision agriculture has received attention from the agricultural and environmental community because of its suspected potential to increase producer profitability and protect water resources. This attention led to preliminary research results indicating that variable rate application of agricultural fertilizers and chemicals is potentially a promising management practice for abating nonpoint source pollution from cultivated lands while enhancing producer profits. In this paired watershed study, variable rate N application impacts on surface water quality were evaluated. Rainfall variability experienced during the study provided an opportunity to quantify water quality impacts during a range of climatic conditions in the Texas Blackland Prairie, an important crop production area of over 11 million acres. In terms of crop yields, corn production was similar for the two fields even though less N was applied on the variable rate field. Under variable rate application, 4–7% less N was applied than would have been applied under uniform N application. This promising result demonstrates the potential for improved profitability under variable rate fertilizer management because of improved fertilizer management; in this case similar yields with less N input.

Under the climatic conditions experienced, variable rate N applied post-emergence did not drastically impact runoff water quality compared to uniform N application; however, the median NO_3 + NO_2–N concentration was significantly lower for the variable rate field in the second year of variable rate application. During the 2-year water quality portion of this study, 22 storm events of sufficient magnitude for storm sampling were monitored. For these sampling events, event mean dissolved NO_3 + NO_2–N concentrations averaged 3.7 mg/l for the variable rate field and averaged 3.3 mg/l for the uniform rate field. Whereas overall and event mean NO_3 + NO_2–N concentrations from the variable rate field tended to be higher, median concentrations from the uniform rate field tended to be higher than for the variable rate field. Event mean concentrations of NH_4–N and PO_4–P were all well below 1.0 mg/l. No significant differences in N or P loads were determined between the variable rate and uniform rate fields.

These results showing similar N loads and concentrations in surface runoff for variable and uniform rate N application are important findings, but they do not confirm or disprove the common assumption that VR nutrient application can lead to improved water quality. However, the reduction in NO_3 + NO_2–N concentration in the second year of VR application and the lack of significant load increase for the VR field even though runoff was greater may indicate a potential for improved water quality under VR nutrient application. Further field-scale research should be conducted to evaluate the proposed environmental benefits of precision agriculture even though intensive, field-scale water quality research requires a significant financial and personnel commitment. However, this commitment is necessary within the agricultural community because the real world impacts of precision agriculture and variable rate application may indeed lead to great advances on crop production, producer sustainability, and environmental enhancement.

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