FARM NUTRIENT MANAGEMENT PRACTICES IN TWO GEOGRAPHICALLY DIVERSE WATERSHEDS IN THE COTTONWOOD RIVER WATERSHED OF MINNESOTA, USA

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Abstract. The characteristics of a river are shaped by the quality of the tributaries that flow into it and each of the tributaries in turn reflects the management practices that occur on the soils and landscapes in their drainage areas. In the Cottonwood River of Minnesota, USA and many of its tributaries, nutrient enrichment [primarily nitrogen (N) and phosphorus (P)] and suspended sediments contribute to nonpoint source pollution. Our objective was to assess farm characteristics and nutrient management practices among producer/operators in two southwestern Minnesota watersheds, and relate these characteristics to soil and landscape differences as reflected by agroecoregions. Producer/operators were interviewed in a face-to-face interview during summer 2002 about agricultural production management practices in two tributaries of the Cottonwood River. The Sleepy Eye Creek watershed (SECW) is located in gently rolling to flat soils formed in glacial till. The Highwater-Dutch Charley Creek watershed (HDCCW) is located in moderately steep, 2–6% slope, soils formed in glacial moraine. Nitrogen and P rates applied to corn were significantly greater in the SECW than the HDCCW, and more of the N was applied in the fall in the SECW than in the HDCCW, where more was applied in spring. More farmers tested soil for plant available P in the SECW than in the HDCCW. Results from both watershed indicated that forty-seven (29%) fields with soil test phosphorus records exceeded 25 ppm (Bray 1) or 20 ppm (Olsen). Nineteen (7.4%) fields received applications of both manure and N fertilizer, and 13 (5.1%) fields received applications of both manure and phosphate (P) fertilizer. Nitrogen and P application rates ranged from 234 to 315 kg N ha^{-1} and 134 to 168 kg P_2O_5 ha^{-1} for fields receiving both manure and fertilizer. Strategies for improving nutrient management practices in these two watershed areas should take into consideration soil and landscape differences that influence which nutrient management practices are most risky and which are most likely to improve water quality.

Keywords: agroecoregion, nutrient management, nonpoint source pollution, water quality

1. Introduction

Increased food production and alterations in land use have caused eutrophication of numerous lakes, rivers, and coastal marine waters in Europe and North America (Haycock *et al.*, 1993; Caraco and Cole, 1994; Antweiler *et al.*, 1995; Howarth *et al.*, 1996; Rabalais *et al.*, 1996; Carpenter *et al.*, 1998; Rabalais *et al.*, 2001). Clean

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water resources are important for drinking water supplies, supporting biodiversity, industrial, irrigation, and recreational uses.

Under section 303(d) of the 1972 Clean Water Act, states, territories, and authorized tribes are required to develop lists of impaired waters. These impaired waters do not meet water quality standards. The law also requires that these jurisdictions develop Total Maximum Daily Loads (TMDLs) for these waters. To protect and improve the quality of all water resources within the European Union (EU), the Water Framework Directive was adopted in 2000 by the European Commission (European Commission, 2000). Within the scope of this directive, countries are required to protect and enhance the status of aquatic ecosystems and promote sustainable water use.

Management and policy decisions concerning soil and water resources are often made that only address short-term or single goals, while ignoring the complexity of coupled terrestrial-aquatic ecosystems. To solve complex environmental problems, such as sustainable use of soil and water resources, it is necessary to apply a multidimensional approach that incorporates management and conservation of terrestrial and aquatic ecosystems, instructional programs designed to educate land operators about agricultural pollution and potential solutions, and incentive programs that support conservation and stewardship of soil and water resources.

Eutrophication, caused by inputs of nitrogen and phosphorus, is a common problem in lakes and rivers (Carpenter *et al.*, 1998). Management practices on agricultural lands have been shown to affect hydrology and water quality (Gilliam *et al.*, 1999; Castillo *et al.*, 2000). It is also widely accepted that in-field and edge of field practices can be modified to improve water quality through nutrient and residue management (Dinnes *et al.*, 2002), crop rotation (Randall *et al.*, 1997), and the use of biological filters (Jaynes *et al.*, 2004).

The need for more regionally based assessments of soil and water resources has benefited from the development and application of ecoregion concepts (Omernik, 1987; Omernik and Bailey, 1997; Cohen *et al.*, 1998; Edwards *et al.*, 2000; Hatch *et al.*, 2001; Dovciak and Perry, 2002). Recently, Hatch *et al.* (2001) and Birr and Mulla (2002) have advocated targeted adoption of BMPs on the basis of soil or landscape factors and management practices that vary within watersheds in the Minnesota River Basin (MRB). About 80% of the Cottonwood River Major Watershed, located in the MRB, is composed of two agroecoregions, the Coteau and the Dryer Blue Earth Till (Hatch *et al.*, 2001). The Coteau is characterized by steeper well-drained soils formed in glacial moraine, while the Dryer Blue Earth Till is characterized by flatter poorly drained soils formed in glacial till. Soil erosion potentials are much greater in the Coteau than in the Dryer Blue Earth Till.

A 1999 report prepared by the Redwood-Cottonwood Rivers Control Area (RCRCA) identified two priority watershed areas, Sleepy Eye Creek (primarily in the Dryer Blue Earth Till agroecoregion) and the Highwater and Dutch Charley streams (primarily in the Coteau agroecoregion), in the Cottonwood River Major Watershed (CRMW) as contributing a considerable share of the nonpoint source pollutant load to the Cottonwood River. Annual nitrate-N loading from Sleepy

Eye Creek (in the Dryer Blue Earth Till) during 1997 and 1998 was estimated to be 1.2 $\mathrm{Mg\,km^{-2}}$ and 0.9 $\mathrm{Mg\,km^{-2}}$ from Highwater and Dutch Charley Creeks (RCRCA, 1999). During the same period, Highwater and Dutch Charley Creeks (in the Coteau region) exhibited the largest sediment yield of all sampled Cottonwood River tributaries, annually delivering 47 $\mathrm{Mg\,km^{-2}}$ along with 0.08 Mg total P $\mathrm{km^{-2}}$ whereas sediment and total P loading from Sleepy Eye Creek were estimated to be 10 $\mathrm{Mg\,km^{-2}}$ and 0.02 $\mathrm{Mg\,km^{-2}}$, respectively (RCRCA, 1999).

The selection of the study watershed areas was influenced by the nonpoint source pollution potential of row crop production within the Coteau and Dryer Blue Earth Till agroecoregions. The landscape characteristics affecting soil erosion and water quality between the two watershed areas included: precipitation, soil geomorphology and internal drainage, slope, and crop productivity. A greater potential for water erosion and runoff is generally associated with greater land slope. Consequently, land that has the higher potential for erosion has the potential to degrade water quality from sediment and phosphorus pollution. For example, the Coteau agroecoregion has an estimated weighted mean erodibility index of 10.1 $\mathrm{Mg\,ha^{-1}\,yr^{-1}}$, in contrast to the Dryer Blue Earth Till agroecoregion that has an estimated weighted mean erodibility index of 4.3 $\mathrm{Mg\,ha^{-1}\,yr^{-1}}$ (Hatch *et al.*, 2001).

The effectiveness of management practices intended to improve the environment may vary from site to site in watersheds due to differences in soil type, topography and climate, as well as the labor, machine, and managerial resources of the farm. Consequently, the application of uniform policies and management strategies across a watershed may be less effective than targeted, farm specific approaches in improving water quality.

The purpose of this article is to present the findings of a survey designed to assess farm characteristics and nutrient management practices among producer/operators in these two geographically diverse areas. The findings are discussed in the context of differences between the agroecoregions, and recommendations are made to reduce nonpoint source pollution within the study watersheds.

2. Methods

2.1. DESCRIPTION OF STUDY AREA

The Cottonwood River originates on top of the Coteau des Prairies or “Highland of the Prairies,” a glacial moraine. About 84% of the Coteau is characterized by landscapes with long northeast facing slopes of moderate slope (2–6%) and characterized by well drained soils (86% of the area). After flowing off the moraine, the river flows along the base of the Coteau and receives water from many tributaries that also originate on the moraine. Leaving the base of the Coteau, the river enters the Dryer Blue Earth Till Plain. Lands within the Dryer Blue Earth Till Plain are a complex mixture of gently sloping (2–6%) well-drained loamy soils (61% of the area) and nearly level (0–2%) poorly drained loamy soils (39% of the area).

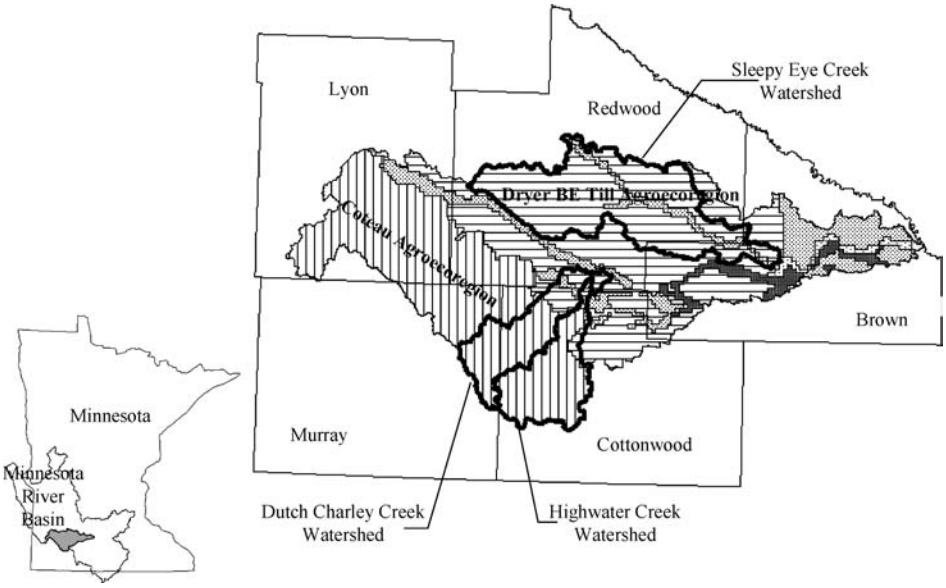

Figure 1. Map showing boundaries of survey watersheds and agroecoregions in the Cottonwood River Major Watershed, Minnesota, USA.

Annual precipitation ranges from about 610 mm in the western watershed to 711 mm in the eastern portion of the watershed, with more than two thirds of this precipitation falling between May and September. Average annual runoff was estimated to be approximately 76 mm yr^{-1}, largely in response to patterns in precipitation, land use, slope, and soil freezing (USDA-SCS, 1979). Average monthly temperatures range from $-12\,^{\circ}\mathrm{C}$ in January to $22\,^{\circ}\mathrm{C}$ in July.

The study region was composed of three tributaries of the Cottonwood River located in southwest Minnesota, USA (Figure 1). For the purposes of this investigation, the priority watersheds were separated into two distinct areas. Sleepy Eye Creek watershed was identified as one watershed and the Coteau streams, Highwater and Dutch Charley Creeks, were considered to be one watershed since Highwater Creek converges with Dutch Charley before flowing into the Cottonwood River. Corn and soybean [*Glycine max* (L.) Merr.] are grown on approximately 92% of cropped land in the Cottonwood Watershed; small grains, hay, and grasslands enrolled in the Conservation Reserve Program (CRP) make up the majority of the balance.

2.2. DATA COLLECTION

Data were collected during the summer of 2002 using a structured questionnaire that requested information about agricultural production systems and practices in use at the time of the survey. The questionnaire was based on a survey developed by the Minnesota Department of Agriculture (MDA) to aid in the design of effective educational programs and to provide baseline agricultural production system and management data to determine educational program effectiveness over time (Montgomery and Bruening, 1997).

Data were collected from participants using face-to-face interviews. Each face-to-face interview required 3–6 h of time to complete the survey, consequently, there were only adequate resources to interview 40 producer/operators for this survey. Detailed maps outlining township boundaries of the study regions were used to guide participant selection. We used two-stage sampling where each farm was the primary sampling unit and fields within a farm were subunits. One potential participant was randomly selected from the southwest quarter of every tenth section within the watersheds until 40 producer/operators were selected. No names or identifying information were included on the questionnaire which made it impossible for the investigators to identify the respondents. The survey design used a "blind analysis" approach. A specialist from MDA contacted potential questionnaire participants and conducted the survey. Every attempt was made to ensure that the researchers were not aware of the survey participant identities to avoid any preconceptions from influencing the results, analysis, and interpretation. Field management data were collected for all fields farmed by the interviewee located entirely within the boundaries of the study regions. This sampling design resulted in a wide spatial distribution of participants within the priority watershed boundaries.

2.3. DATA ANALYSIS

Questions regarding fertilizer and manure management were included in the questionnaire. These data were used to make comparisons of farm nutrient management practices between the two watershed areas using descriptive statistics. Statistical analysis was performed using the GLM procedure SAS for unbalanced data (SAS, 2002). The *t* test was used to compare differences between agroecoregions.

3. Results and Discussion

The Sleepy Eye Creek subwatershed (SECW) drainage area is 71,000 ha and the Highwater/Dutch Charlie Creeks subwatersheds (HDCCW) drainage area is 54,050 ha, combined. Landscape characteristics of the priority watersheds (Table I) showed differences in soil geomorphology, slope, soil internal drainage, and crop productivity between SECW and HDCCW. Descriptive findings and characteristics of the priority watersheds (Table II) showed that the number of farms surveyed, number of farms with livestock, size of operation, number of fields inventoried, and total land area surveyed between the two watershed areas were similar.

In the CRMW, cropland was dominated by row crop production consisting of predominantly a corn – soybean rotation accounting for 93% of all crop land

TABLE I

Landscape characteristics of Sleepy Eye and Highwater/Dutch Charlie Creek Watersheds

Characteristic	Sleepy Eye Creek	Highwater Dutch Charley Creek
Agroecoregion	Dryer Blue Earth Till	Coteau
Soil geomorphic class	Glacial till	Glacial moraine
Slope Steepness class		
0–2% (%)	36.2	13.6
2–6% (%)	59.4	84.4
2–12% (%)	1.8	1.5
6–12% (%)	2.6	0.5
Internal drainage class		
Poor (%)	31.9	11.6
Poor, tiled (%)	7.1	2.0
Well drained (%)	61.0	86.4
Crop productivity class		
Low (%)	4.5	2.6
Medium (%)	93.1	97.3
High (%)	2.4	0.1

TABLE II

Characteristics of surveyed population

Characteristic	Sleepy Eye Creek	Highwater Dutch Charley Creek
Farms in watershed	195	113
Farms surveyed	19	21
Farms surveyed – livestock	5	5
Land area surveyed (ha)	2971	3416
Number fields surveyed	113	139
Farm area surveyed (ha)		
Mean	172	234
Minimum	32	32
Maximum	437	384
Farm area operated (ha)		
Mean	258	312
Minimum	32	97
Maximum	573	546

TABLE III

Distribution of crop types and area (ha) across inventoried farms in Sleepy Eye Creek and Highwater-Dutch Charley Creek watersheds

Type	SECW	HDCCW
Corn	1481 (50%)	1630 (48%)
Soybeans	1335 (45%)	1478 (43%)
Alfalfa	76 (2.6%)	129 (3.8%)
Grasses/Pasture	13 (<1%)	127 (3.7%)
Small Grains	21 (<1%)	51 (1.5%)
Other crops[†]	43 (1.4%)	0 (0%)

[†] Other crops included peas and sweet corn.

surveyed. Major crops and corresponding land area inventoried in the CRMW for the 2002 cropping season (Table III) showed the diversity of crops and the land area devoted to growing the two major crops was similar between the two watersheds. The percentage of area on which corn was grown was similar for both the SECW and HDCCW watersheds, but slightly greater percentages of alfalfa and small grains were grown in the HDCCW than in the SECW.

Aggregated row crop and row crop-livestock nutrient application results showed statistically significant differences in N application rate for corn and N and P application rates for soybean between SECW and HDCCW (Table IV). Findings showed that SECW had the highest mean use rate of nutrients for corn and soybean. However, reported yields indicated that no statistically significant increase in corn yield was attained with the additional nutrients applied in SECW compared to HDCCW (Table V).

3.1. ROW CROP ONLY OPERATIONS

3.1.1. *Commercial Fertilizer Nitrogen*

Commercial N was applied to 2,610 ha of inventoried cropland in SECW and 3,160 ha in HDCCW, the majority of this was applied to corn fields. All field corn received either commercial N fertilizer, animal manure, or a combination of both sources of fertilizer. A total of 490.7 Mg of commercial fertilizer N was applied to inventoried fields in the CRMW (Table VI). Fields in the SECW and HDCCW received 244.3 Mg and 246.4 Mg of commercial N fertilizer, respectively (Table IV).

Commercial fertilizer N application for corn ranged from 112 to 211 and 78 to 192 kg N ha^{-1} for cropland in SECW and HDCCW, respectively. With the exception of one field that received only fertilizer N, fields with N rates greater than 196 kg N ha^{-1} received both livestock manure and fertilizer N during 2002. Farmer

TABLE IV

Nitrogen and phosphate application rates (kg ha^{-1}) for corn and soybean in Sleepy Eye and Highwater/Dutch Charley Creek watersheds during 2002

Nutrient applied	SECW	HDCCW
Nutrients applied – corn	($n = 60$)	($n = 62$)
Nitrogen		
Mean[†]	150a	133b
Median	150	139
SD	31	29
Phosphorus as P_2O_5		
Mean	63a	60a
Median	70	47
SD	33	37
Nutrients applied – soybean	($n = 43$)	($n = 51$)
Nitrogen		
Mean	7a	0.7b
Median	0	0
SD	17	3
Phosphate		
Mean	12a	2b
Median	0	0
SD	30	8

[†] Means within a row followed by the same letter are not different (*t* test, $\alpha = 0.05$).

TABLE V

Corn and soybean yields (Mg ha^{-1}) for Sleepy Eye and Highwater/Dutch Charley Creek watersheds during 2002

Crop	SECW	HDCCW
Corn	($n = 60$)	($n = 62$)
Mean[†]	9.4a	9.3a
SD	1.9	0.6
Soybean	($n = 43$)	($n = 51$)
Mean	3.1a	2.9a
SD	0.3	0.1

[†] Means within a row followed by the same letter are not different (*t* test, $\alpha = 0.05$).

TABLE VI

Commercial nitrogen (kg N) applied to crops

Timing	Corn	Soybean	Other crops
SECW			
Autumn	161179 (70%)	1734 (37%)	3118 (29%)
Spring preplant	60126 (26%)	2999 (63%)	5093 (48%)
Spring planting	1510 (<1%)	0	0
Sidedress	6141 (2.7%)	0	2433 (23%)
HDCCW			
Autumn	112190 (46%)	612 (44%)	343 (18%)
Spring preplant	106963 (44%)	796 (56%)	1193 (63%)
Spring planting	2614 (1.1%)	0	102 (5.4%)
Sidedress	21348 (8.8%)	0	245 (13%)

expected corn yield and historic yield across inventoried farms averaged 9.6 and 9.5 Mg ha^{-1}, respectively. Surveyed farmers from SECW reported average corn yield of 9.6 Mg ha^{-1} (range 8.5 to 11.3 Mg ha^{-1}) while farmers from HDCCW reported average corn yield of 9.3 Mg ha^{-1} (range 7.5 to 10.3 Mg ha^{-1}). Surveyed farmers appeared to have realistic yield expectations for field corn based on the similarity between expected and historic yields. According to current University recommendations for corn following soybean, 134 kg N ha^{-1} is required to achieve an expected yield between 9.4 and 10.9 Mg ha^{-1}.

Nitrogen rate versus percent inventoried corn area that received commercial N fertilizer, manure N, or both showed that higher rates of N were applied to more cropland in SECW than in HDCCW (Figure 2). More than 85% of SECW and 70% of HDCCW areas inventoried and planted to corn received N in excess of University of Minnesota recommendations for expected yields between 9.4 and 10.9 Mg ha^{-1} (Figure 2). Rates of N applied were considerably greater in the SECW than in the HDCCW. Thus, we would expect greater environmental losses of nitrate-N in SECW than in the HDCCW. This was verified by water quality monitoring data showing annual nitrate-N loading from Sleepy Eye Creek (1.2 Mg km^{-2}) to be 0.3 Mg km^{-2} greater than from Highwater and Dutch Charley Creeks (RCRCA, 1999). In some cases, producers apply extra “insurance” N that they believe may provide protection against weather conditions that might accentuate N loss and reduce crop yield or alternatively that might provide added yield and economic return in years with optimal growing conditions and high N requirements. There is little economic advantage to the producer from using an insurance N approach since the added fertilizer cost is unlikely to be offset by an equivalent or greater increase in crop receipts (Bock and Hergert, 1991). This practice can lead to increased residual soil nitrate levels and increased nitrate N leaching (Gast *et al.*, 1978). Over

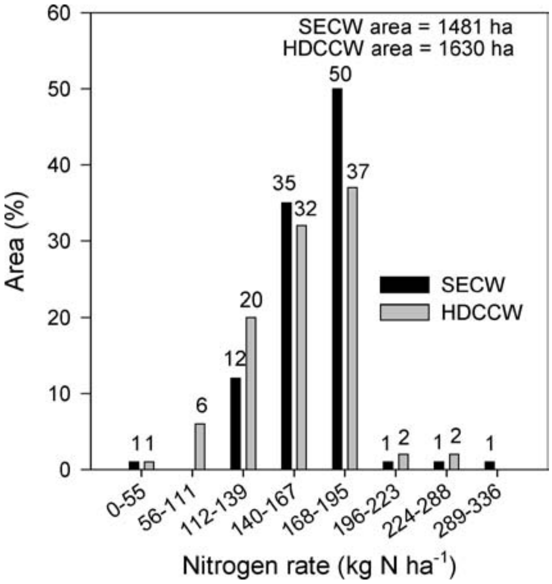

Figure 2. Nitrogen application rate for inventoried crop land planted to corn and receiving commercial fertilizer and manure nitrogen in Sleepy Eye and Highwater/Dutch Charley Creek watersheds during 2002.

application of N may be the result of ignoring N credits from livestock manure, legumes, and P fertilizers that contain N.

The concept of insurance N may be viewed differently when the timing decision of application is considered, and particularly when multiple applications are considered. Uncontrolled variables, especially weather, influence the yield response to N. So at any point in time, the yield response is actually an expected probability distribution of yields. It follows that more is known about growing conditions in the spring than in the fall, and more is known post-plant than preplant. Thus, when multiple applications are a consideration, insurance N decisions may be delayed until the spring pre-plant period or post-plant period when more is known about the potential yield response. The economic and environmental benefits of these sequential decision-making strategies must, of course, be weighed against increased application costs, both in terms of operating expenses and the competition for the farm's fixed resources.

A total of 57% (279.6 Mg) of commercial N was applied to all inventoried crop land during autumn and 36% (177.2 Mg) was applied as a spring preplant application (Table III). Nitrogen applied at planting accounted for 0.9% (4.2 Mg) and 6% (30.2 Mg) applied as a sidedress application (Table VI). Sixty-eight percent (166.0 Mg) of the N applied to surveyed crop land in the SECW was applied in the autumn and 28% (68.2 Mg) as a spring preplant application (Table VI). In the HDCCW, 46% (113.1 Mg) of N was applied in autumn and 44% (180.9 Mg) was applied in spring as preplant applications (Table VI). Thus, greater proportions of N were applied in autumn in the SECW than in the HDCCW. Randall *et al.* (2003) compared corn yield after autumn (no nitrification inhibitor), spring preplant, and sidedress N application in southern Minnesota and showed that autumn application resulted in lower corn grain yield and greater leaching losses of nitrate-N than spring preplant or sidedress applications. Spring preplant application is the recommended BMP for N in SW Minnesota. In situations where autumn applied N is used, recommendations suggest delaying application until the daily soil temperature is below 10 °C at the 15 cm depth.

Economic considerations related to the timing of nitrogen application are influenced by conditions in the fertilizer market, the use of custom application services, and the availability of labor and machine services, as well as the yield response. Suppliers may discount nitrogen prices in the autumn, potentially offsetting the added operating capital cost resulting from the earlier incidence of this cash expense. Application of N may serve as a primary tillage operation. By hiring custom application, labor and machine resources may be used to complete other field operations in a more timely way. On the other hand, if fertilizer application is delayed until spring, field work, including planting may be delayed, particularly in years when field working days are low because of poor weather conditions. Since it derives from the seasonal demand for and availability of fixed farm resources, this timeliness cost will become more critical as crop land area increases.

3.1.2. *Commercial Fertilizer Phosphorus*

There are considerable differences in the philosophy used by land managers, fertilizer dealers, producers, and University researchers regarding P fertilizer recommendations. As a result, the amounts of P fertilizer recommended and/or applied for crop production vary greatly. The University of Minnesota uses a correlation and calibration approach to make fertilizer recommendations for corn (Rehm *et al.*, 2000) and soybean (Rehm *et al.*, 2001). A second approach for making P fertilizer recommendations is based on crop removal. Crop removal values for corn grain and soybean vary, but the most widely used values in Minnesota are 4.6 kg P_2O_5 m^{-3} for corn and 11.3 kg m^{-3} for soybean. The crop removal approach can have negative economic and agronomic consequences if used on soils with very high concentrations of plant available phosphorus. For example, when soil test values are in the medium to very high ranges, excessive amounts of nutrients like P produce no added yield which is not cost effective. Phosphate application based on crop removal may be too low if soil test values are in the very low range. This shortage of P will result in lowered yield thereby reducing profits.

Soil test records were collected for 160 of 254 inventoried fields. Soil test information was collected from producers or from the producer's fertilizer dealer records. A much greater percentage of fields had soil test P records in SECW than in HDCCW. Of inventoried fields, there were 91 fields with soil test P records

TABLE VII

Soil test phosphorus categories for all inventoried crop land in Sleepy Eye and Highwater/Dutch Charley Creek watersheds during 2002

	Area (%)	
Category[†]	SECW	HDCCW
Very low	3	0
Low	11	6
Medium	21	23
High	23	19
Very high	42	52
No soil test	16	47

[†] No soil test available category included all survey land (SECW = 2971 ha and HDCCW = 3416 ha). Other soil test categories based on surveyed land with soil test *P* values (SECW = 2509 ha and HDCCW = 1806 ha).

from SECW and 69 fields with records from HDCCW. There were no soil test P records available for 16% (476 ha) of the land area inventoried in the SECW and 47% (1605 ha) of the land area inventoried in the HDCCW (Table VII). No phosphate fertilizer is recommended for either broadcast or starter application when soil test P is higher than 25 ppm Bray1 or 20 ppm Olsen and conventional tillage systems are used (Rehm *et al.*, 2000). Forty-seven (29%) of the 160 fields with soil test P values tested greater than or equal to 25 ppm Bray or 20 ppm Olsen.

Broadcast application of phosphate fertilizer would have a low probability of increasing corn yields for 65% of the inventoried land area with soil P tests in the SECW and 71% of the inventoried land area with soil P tests in the HDCCW because soil test P levels were in the high or very high category (Table VII). Application of phosphate fertilizer for soybean would not be recommended for 86% of the inventoried land area with available soil test P records in the SECW because soil test P levels were medium or higher (Table VII). Correspondingly, in the HDCCW, phosphate fertilizer for soybean would not be recommended for 94% of the land area inventoried with available soil test P records (Table VII).

A total of 179.1 Mg of P_2O_5 fertilizer was applied to crop land planted to corn, 19.1 Mg was applied to soybean, and the remaining 11.0 Mg was applied to other crops during 2002 (Table VIII). Commercial fertilizer phosphate application ranged from 16 to 112 and 7 to 123 kg P_2O_5 ha^{-1} for cropland in SECW and HDCCW, respectively. Fields with P rates greater than 134 kg P_2O_5 ha^{-1} were from combined livestock-crop production operations and received livestock manure and fertilizer P during 2002.

TABLE VIII

Commercial phosphate applied (kg P_2O_5) to crops

	SECW			HDCCW		
Timing	Corn	Soybean	Other crops	Corn	Soybean	Other crops
Autumn	60657 (72%)	7622 (49%)	177 (6.5%)	54171 (57%)	1565 (43%)	876 (16%)
Spring preplant	19650 (23%)	7893 (51%)	2542 (93%)	32945 (35%)	2034 (57%)	1057 (19%)
Spring planting	4530 (5.3%)	0	0	8262 (8.7%)	0	714 (13%)
Sidedress	0	0		0	0	2939 (53%)

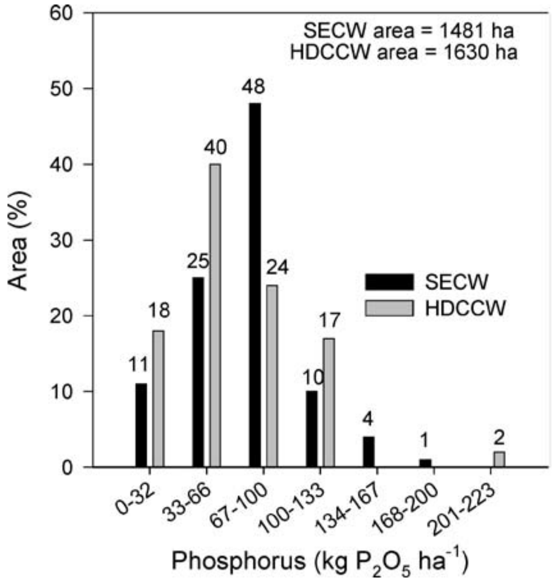

Figure 3. Phosphorus application rate for inventoried crop land planted to corn and receiving commercial fertilizer and manure phosphate in Sleepy Eye and Highwater/Dutch Charley Creek watersheds during 2002.

Phosphorus fertilizer rate versus percent area of inventoried crop land that received commercial P fertilizer, manure P, or both during 2002 showed that higher rates of P_2O_5 were applied to more cropland in SECW than in HDCCW (Figure 3). This was a surprising result given that a greater percentage of fields had soil test P records in SECW than in HDCCW. Additionally, of those fields with soil test records in SECW, 65% had high or very high soil test values (Table VII). These fields would have a low probability of increasing crop yield with additional P fertilizer. One explanation for the disagreement between soil test P findings and fertilizer P rate is that soil test P results were used to monitor changes in soil test P rather than as a predictive tool for making fertilizer P recommendations.

Inventoried farms in the CRMW applied a wide range of phosphate rates. Survey participants were not specifically questioned about their P management philosophy; however, their philosophy was assumed based on application rate. It would seem that a crop removal philosophy of P management was used on crop land represented by fields receiving 67 to 133 kg P_2O_5 ha^{-1}. Assuming this presumption was correct then a crop removal strategy was practiced on 49 and 37% of inventoried crop land in SECW and HDCCW, respectively. In contrast, assuming that a philosophy based on University of Minnesota recommendations was represented by crop land receiving 0 to 66 kg P_2O_5 ha^{-1}, then it appears that this approach to P management was practiced on 39 and 58% of inventoried crop land in SECW and HDCCW, respectively. Thus, considerably larger areas of land in SECW than in HDCCW had P application rates that were much higher than University recommendations. Crop land receiving 0 to 66 kg P_2O_5 ha^{-1} could be receiving P above University of Minnesota recommendations if soil tests for P were high or very high. Regardless of application philosophy, over application of phosphate fertilizer on crop land with high and very high soil test P levels have potentially negative economic and environmental consequences. First, over application of phosphate fertilizer will reduce profitability. Second, surface runoff and soil erosion from soil with high and very high soil test P levels can lead to eutrophication of surface water. Runoff erosion from crop land with low soil test P levels also contributes to eutrophication, but soluble P in runoff generally increases as soil test P increases.

3.2. ROW CROP-LIVESTOCK OPERATIONS

Ten inventoried farm operations, 25% of total surveyed farm operations, included livestock and applied manure on surveyed crop land. Nutrient losses from collection and storage of manure were estimated from published guidelines for individual storage systems (Midwest Plan Service, 1993). Nutrient losses from land application of manure were estimated from published guidelines for Minnesota (Schmitt, 1999). Manure collected but not spread on crop land specified in the survey is not considered in the collected amounts. Two additional farmers purchased swine manure and applied it to surveyed crop land. Surveyed livestock numbers represent the livestock on hand from fall 2001 to summer 2002. This was the livestock that would contribute manure to 2002 crops. Additional data on livestock operations from 2001 official county feedlot inventories were collected to assess the representativeness of the survey data since there were a limited number of livestock operations represented in the survey. According to survey results, type and density of livestock within both watershed areas was representative of the type and density calculated from official county livestock surveys (Table IX). Swine (*Sus scrofa domesticus*) production was the dominant livestock enterprise among inventoried farms. Feeder cattle (*Bos taurus* L.) and sheep (*Ovis aries*) production were also important according to the survey.

TABLE IX

Total livestock numbers and density from survey data and county feedlot inventories for Dutch Charlie, Highwater, and Sleepy Eye Creek watersheds in 2002[†]

	Survey		County feedlot inventory	
Livestock type	Number	Animals/ha	Number	Animals/ha
Dairy				
Cows	190	0.03	2726	0.02
Calves/heifers	335	0.05	576	0.00
Swine				
Sows/boars	105	0.02	3817	0.03
Nursery	2000	0.32	18110	0.14
Finishing	3000	0.47	58145	0.46
Beef				
Cows/bulls	43	0.01	472	0.00
Feeders[‡]	1006	0.17	18993	0.15
Sheep				
Ewes/rams/lambs	1085	0.17	5980	0.05
Poultry				
All	0	0.00	11951	0.10

[†] Survey area = 6387 ha and county feedlot inventory = 125,050 ha.

[‡] Feeders include dairy and beef feeders.

Manure was applied to a total of 526 ha of inventoried cropland in the CRMW of which 261 ha were in the SECW and 265 ha were in the HDCCW. Swine manure was spread on 44% of the inventoried crop land receiving manure during 2002. Dairy manure was applied to 33%, beef 15%, and sheep 8% of the remaining manured crop land.

3.2.1. *Manure Nitrogen*

An estimated 92.7 Mg N was collected from livestock during 2002 (Table X). After adjustments for storage system losses and manure not collected from pastured livestock, an estimated 65.8 Mg N was available for application from livestock during 2002 (Table X). After adjusting the amount of manure available for application for purchased manure, manure produced on surveyed farms but applied outside the inventoried area, and application method losses, 25.4 Mg N was available to the crop during 2002 (Table X).

Six fields that represented 8.5% (252 ha) of all surveyed cropland in SECW and 13 fields that represented 6.2% (212 ha) of all surveyed cropland in HDCCW

TABLE X

Manure nitrogen and phosphorus collected, available for application, applied, and available for crop production for inventoried livestock producers during 2002

		Nitrogen (kg N)			Phosphate (kg P_2O_5)		
Livestock type	Livestock number	Collected	Available for application	Available to crop	Collected	Available for application	Available to crop
Beef	819	24090	16863	3155	17686	15917	9538
Dairy	755	52490	36743	5359	21001	19395	11926
Sheep	1,085	2542	1180	235	1171	1054	557
Swine[†]	5,105	13592	10493	16667	9578	9578	16813

[†] Swine manure nitrogen and phosphorus applied and available to crop include purchased manure.

received both manure and N fertilizer. Fields that received manure applications in SECW received 4.6 Mg N from manure and an additional 17.0 Mg N from fertilizer. Similarly, 6.7 Mg N from manure and 26.8 Mg N from fertilizer was applied to fields in HDCCW during 2002. Fields in HDDCW received 1.6 times more N from manure and fertilizer than fields in SECW. Two fields in SECW and four fields in HDCCW received manure and fertilizer N in excess of 224 kg N ha^{-1}. Nitrogen application rates ranged from 234 to 315 kg N ha^{-1}. All of these fields were planted to corn and were preceded by soybean.

3.2.2. *Manure Phosphorus*

An estimated 49.4 Mg P_2O_5 was collected from livestock during 2002 (Table X). After adjustments for storage system losses and manure not collected from pastured livestock an estimated 45.9 Mg P_2O_5 was from livestock during 2002 (Table X). After adjusting the amount of manure available for application of purchased manure, manure produced on surveyed farms but applied outside the inventoried area, and application method losses, 38.8 Mg P_2O_5 was available to the crop during 2002.

Four fields that represented 2.3% (70 ha) of all surveyed cropland in SECW and nine fields that represented 4.4% (153 ha) of all surveyed cropland in HDCCW received P_2O_5 from manure and fertilizer. Manured fields in SECW received 9.6 Mg P_2O_5 from manure and an additional 3.9 Mg P_2O_5 from fertilizer. Similarly, 9.3 Mg P_2O_5 from manure and 9.8 Mg P_2O_5 from fertilizer were applied to fields in HDCCW during 2002. Fields in HDCCW received 2.5 times more P_2O_5 from manure and fertilizer than fields in SECW.

Two of four fields in SECW received combined manure and fertilizer P_2O_5 at rates greater than 134 kg P_2O_5 ha^{-1}. Two of the four fields had no soil test P records while the other two fields had soil test P levels greater than 25 ppm (Bray1) and 20 ppm (Olsen), respectively. Two of the four fields in SECW were planted to corn and were preceded by soybean – the other two were planted to alfalfa. Two fields in HWDCCW received combined manure and fertilizer P_2O_5 at rates greater than 168 kg P_2O_5 ha^{-1}. One field had a soil test P level greater than 25 ppm (Bray1) and the other field had a soil test P level less than 15 ppm (Bray1). These fields were planted to corn and were preceded by soybean.

3.2.3. *Manure Application Method*

More manure was broadcast without incorporation in HDCCW than in SECW. According to survey results, 51% (133 ha) of crop land that received manure in SECW and 100% (265 ha) of cropland that received manure in HDCCW was broadcast applied without incorporation. Manure was broadcast and incorporated within 12 h, according to University of Minnesota recommendations, to 49% (127 ha) of crop land receiving manure in SECW. All broadcast-incorporated manure was swine manure. None of the surveyed livestock producers used irrigation or injection systems to apply liquid manure.

Broadcast application of manure without incorporation leaves manure on the soil surface susceptible to losses of N due to volatilization and P due to surface runoff and erosion. As surface runoff and erosion increase, phosphorus loss increases. Mueller *et al.* (1984), in a field study using dairy manure, showed that P loss in surface runoff was five times higher from areas that received broadcast application of manure without incorporation compared with broadcast application of manure followed by manure incorporation from tillage. Impairments to surface water quality occur through accelerated eutrophication from nutrient inputs (primarily N and P) that stimulate algal and rooted aquatic plant growth.

3.2.4. *Manure Application Timing*

Timing of manure application versus percent area of inventoried crop land that received manure showed that more manure was year-round than during spring or autumn combined (Table XI). Of all surveyed cropland receiving manure, 47% (249 ha) received year-round application, 25% (131 ha) received manure in spring, and 17% (87 ha) received manure in autumn (Table XI). Manure was applied year-round to 71% (188 ha) of crop land receiving manure in HDDCW compared to 23% (60 ha) in SECW. Spring applied manure was applied to 44% (116 ha) of the crop land receiving manure in SECW, whereas only 6% (16 ha) of the crop land in HDCCW received spring manure application (Table XI). During the growing season, manure was broadcast applied to alfalfa (*Medicago sativa* L.) or recently harvested small grain fields. Of manure applied year-round, 77% (192 ha) of cropland that received manure was broadcast applied without incorporation. According to survey results, 1.3% (3 ha) of crop land that received manure year-round in SECW and 100% (189 ha) of cropland that received manure year-round in HDCCW was broadcast applied without incorporation.

TABLE XI

Manure application timing for all inventoried crop land receiving livestock manure in Sleepy Eye and Highwater/Dutch Charley Creek watersheds during 2002

	Area (%)	
Timing	SECW	HDCCW
Winter	18	0
Spring	44	6
Summer	5	0
Autumn	10	23
Year-round	23	71

[†]SECW area = 261 ha; HDCCW area = 265 ha.

3.3. BEST MANAGEMENT PRACTICES BY AGROECOREGION FOR SECW AND HDCCW

Nutrient management practices among producer/operators in SECW were in contrast with nutrient management practices among producer/operators and HDCCW. A difference in management practices between the two watersheds was not unexpected since they occupy two distinct agroecoregions.

Characteristics of SECW were low soil erodibility estimates (Hatch *et al.*, 2001), improved drainage on poorly drained soil (survey data not shown), water quality data (RCRCA, 1999) that indicated nitrate-N was a key non-point source pollutant, survey data that showed very high soil test P values, and nutrient management practices data that showed high rates of N and P were being applied to surveyed fields. Stakeholders in the Dryer Blue Earth Till agroecoregion, such as SECW, or in other agroecoregions with similar soil and topographic conditions and management characteristics, may achieve desirable environmental results by adopting and implementing specific BMPs for managing nitrate-N losses. Practices might include controlled drainage, following recommended N rates, and applying N fertilizer in spring.

Characteristics of HDCCW were high soil erodibility estimates (Hatch *et al.*, 2001), water quality data (RCRCA, 1999) that indicated suspended sediment and phosphorus were key non-point source pollutants, survey data that showed very high soil test P values and a lack of soil testing for P, and substandard manure management practices. Stakeholders in the Coteau agroecoregion, such as HWDCCW, or in other agroecoregions with similar soil and topographic conditions and management characteristics, may achieve desirable environmental results by adopting and implementing specific BMPs for sediment and P losses. Practices might include residue management, manure management, and soil testing for P.

4. Conclusions

The majority of fertilizer N applied in the watersheds studied was put on to satisfy corn N demands. Farmer/operators generally followed University guidelines for late autumn N application timing. However, results of this study also provided evidence that over 85% of inventoried land planted to corn in SECW and 70% in HDCCW received N applications in excess of recommended rates which could increase the potential risk of nitrate leaching. Soil test records from SECW and HDCCW showed that over 65% of inventoried land would have a low probability of increasing crop yield with broadcast P fertilizer. Despite this result, 49% of inventoried land in SECW and 37% in HDCCW received P applications over $67\,\mathrm{kg\,P_2O_5\,ha^{-1}}$ which could increase the risk of P loss in surface erosion and runoff.

According to this study, the most serious cases of nutrient mismanagement were the direct result of application of fertilizer N and P in combination with livestock manure in the same field and poor manure management after field application. Combined manure and fertilizer N rates in some fields were in excess of $224\,\mathrm{kg\,N\,ha^{-1}}$. Similarly, combined livestock manure and fertilizer P rates in some fields were in excess of $134\,\mathrm{kg\,P_2O_5\,ha^{-1}}$. Livestock manure was broadcast without incorporation on 75% of the land receiving manure which could lead to important agronomic, economic, and environmental losses. Surveyed row crop-livestock operators, particularly in HDCCW, have the potential to make significant improvements in nutrient management decisions. For example, incorporation of manure after application, proper manure crediting, reduced rates of manure application, and changes in manure handling would result in better economic return and less potential environmental impact.

Environmental benefits and water quality improvement for the specific agroecoregions in these watersheds may be enhanced by targeting BMPs in areas that generate the most pollution. Best management practices can be developed for the specific agroecoregions in these watersheds along with complementary educational programming, personal advice, bulletins, and on-farm demonstrations to enhance adoption and implementation. Approaches include using good record keeping systems, developing and following integrated manure and nutrient management plans, following nutrient management recommendations, soil testing for N and P, where appropriate, and plant N testing.

The information gained from this research will be useful in assessing various strategies for controlling nutrient losses in the Cottonwood River, the Minnesota River Basin, and throughout the Upper Midwest. This survey information combined with ongoing field and watershed scale modeling and economic analysis will be used to generate valuable information concerning the long-term probabilities of N, P and sediment loadings to the Cottonwood River for various types of agricultural management practices and specific combinations of soils, landscapes, and climate.

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