Transport of phosphorus and nitrogen in surface runoff in a corn silage system: Paired watershed methodology and calibration period results

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Jokela, W. E and Casler, M. D. 2011. **Transport of phosphorus and nitrogen in surface runoff in a corn silage system: Paired watershed methodology and calibration period results**. Can. J. Soil Sci. **91**: 479–491. Transport of P, N, and sediment via runoff from crop fields, especially where manure has been applied, can contribute to eutrophication and degradation of surface waters. We established a paired-watershed field site to evaluate surface runoff losses of nutrients and sediment from different manure/crop/tillage management systems for silage corn production. During the 2-yr calibration period the four 1.6-ha watersheds, or fields, were treated identically with fall dairy manure application and chisel plowing, and runoff was monitored, sampled, and analyzed for suspended sediment (SS) and total and dissolved forms of P and N. That management was maintained as a control in one watershed, while alternative management systems were initiated on the three treatment fields. During the calibration period both concentrations and loads of SS and total and dissolved P and N varied by field and over 50% of runoff and dissolved P and N was from snowmelt runoff. Linear regressions of treatment fields against the control field were highly significant for runoff and concentrations and loads of all constituents. The estimated minimum detectable change (difference between means) was 10 to 30% for most parameters, suggesting a reasonable probability of success in detecting change in the treatment period.

Key words: Phosphorus, nitrogen, runoff, paired watershed, water quality, corn silage

Jokela, W. E. et Casler, M. D. 2011. **Transport du phosphore et de l'azote dans les eaux de ruissellement dans un système d'ensilage du maïs: méthode du double bassin et résultats de la période d'étalonnage**. Can. J. Soil Sci. **91**: 479–491. Le transport du P, du N et des sédiments par les eaux qui ruissellent des champs, surtout ceux sur lesquels on a épandu du fumier, peut concourir à l'eutrophisation et à la détérioration des eaux de surface. Les auteurs ont créé un site à double bassin sur le terrain afin d'évaluer les pertes d'éléments nutritifs et de sédiments résultant du ruissellement, pour divers systèmes de production du maïs d'ensilage (utilisation de fumier, pratiques culturales, travail du sol). Durant la période d'étalonnage de deux ans, les quatre bassins ou champs de 1,6 ha ont été traités de manière identique, avec épandage de fumier et travail du sol à la charrue à l'automne, puis les auteurs ont surveillé le ruissellement, échantillonné et analysé l'eau afin de déterminer la présence de sédiments en suspension (SS) ainsi que la quantité de P et de N totale et dissoute. Ils ont maintenu ce système de gestion dans un champ qui a joué le rôle de témoin, et appliqué d'autres systèmes aux trois champs restants. Pendant la période d'étalonnage, la concentration et la charge de SS, ainsi que la quantité totale et la quantité dissoute de P et de N varient avec le terrain. Plus de la moitié du ruissellement ainsi que du P et du N dissous surviennent à la fonte des neiges. La régression linéaire des données venant des terrains expérimentaux par rapport à celles du champ témoin est très significative pour le ruissellement, la concentration et la charge de tous les constituants. On estime que la variation la plus faible décelable (écart entre les moyennes) est de 10 à 30 % pour la majorité des paramètres, signe que la probabilité de détecter un changement durant la période de traitement est raisonnable.

Mots clés: Phosphore, azote, eaux de ruissellement, double bassin, maïs d'ensilage, qualité de l'eau

Transport of P, N, and sediment via runoff from crop fields, especially where manure has been applied, can contribute to degradation of surface waters, leading to eutrophication and potential health effects (Carpenter et al. 1998; Sharpley et al. 1994). In the dairy cropping system of Wisconsin and most of the northern USA dairy belt, the silage corn phase of the rotation is the most susceptible to runoff and erosion losses because of the lack of protective crop residue (Grande et al. 2005a) and regular applications of livestock manure (Andraski et al. 2003). A number of different best management practices (BMP) have been recommended to minimize these nutrient and sediment losses (Sharpley et al. 1994; Gilley et al. 2002; Jokela et al. 2004). These include manure incorporation and timing (Little et al. 2005), conservation tillage methods (Clausen et al. 1996; Ginting et al. 1998), cover crops (Dabney et al. 2001; Kleinman et al. 2005), and vegetative buffer strips (Uusi-Kamppa et al. 2000). The effect of combinations of manure application and tillage methods designed to reduce erosion and runoff loss of nutrients is complex because of the mulching and soil quality effects of manure and the

Abbreviations: **DRP**, dissolved reactive P; **MDC**, minimum detectable change; **TKN**, total Kjeldahl N; **TP**, total P; **SS**, suspended sediment

potential for increased erosion from tillage to incorporate manure (Mueller et al. 1984; Bundy et al. 2001; Andraski et al. 2003; Grande et al. 2005b). Also, tillage and manure management BMPs can have opposite effects on losses of total P and dissolved P in runoff (Bundy et al. 2001). Research on management effects on nutrient runoff that includes both rainfall and snowmelt runoff is limited, but has shown the importance of snowmelt, especially as a source of dissolved P (Hansen et al. 2000; Panuska et al. 2008; Tiessen et al. 2010). Most research on corn production systems has been in grain-harvest systems, which leave substantial crop residue, but limited research in silage corn systems showed increased sediment and P runoff losses compared with those with grain-harvested residue (Grande et al. 2005a, b).

Much of the research on management effects on agricultural runoff has been conducted at the field-plot or micro-plot (e.g., rainfall simulator) scale. Such results are useful for comparing relative effects of individual practices, but they may not be transferable quantitatively to the more complex hydrology and soil variability that exists on the landscape scale (Dabney 1998). An alternative approach is to use a paired-watershed design, in which the experimental units are two or more hydrologically defined land areas, which can vary in size from a portion of a field (1 to a several hectares) to a cluster of fields or a stream-based drainage area, or watershed. A calibration period in which all watersheds are managed identically, followed by a treatment period in which alternative management treatments are implemented in all but the control watershed, allows for rigorous statistical analysis (Clausen and Spooner 1993; Loftis et al. 2001). Use of the paired-watershed approach in agricultural research has been limited, but it has been used to quantify sediment loss, nutrients, and/or pesticides in surface runoff from conservation tillage (Clausen et al. 1996; Tiessen et al. 2010), riparian buffer restoration (Galeone 1999; Clausen et al. 2000; Veum et al. 2009), and combinations of BMPs (Bishop et al. 2005).

More specifically, the paired watershed technique requires two or more similar watersheds [control and treatment(s)] and two periods of study (calibration and treatment) (Clausen and Spooner 1993; Clausen et al. 1996). During the calibration period, all watersheds are treated identically and event-based data are collected for runoff parameters of interest. Regression equations developed for pairs of watersheds during the calibration period can be statistically evaluated to determine the probability of detecting a minimum detectable change (MDC) in runoff parameters during the treatment period (Clausen and Spooner 1993; Loftis et al. 2001). During the treatment period, management remains the same in the control watershed, which serves as a check on weather and other year-to-year variation, and treatments are applied to the others. Treatment and calibration regression equations are then tested statistically for differences to determine the effect of the treatment.

The overall objective of this study is to evaluate year-round field runoff losses of nutrients and sediment from different manure/crop/tillage management systems for silage corn production with the goal of developing cropping systems that minimize adverse water quality impact, while maintaining or increasing farm efficiency and productivity. The objectives of the first phase of the study reported here were: (a) to determine the limits of statistical precision of the calibration period data and our ability to detect differences during the upcoming treatment period and (b) to determine runoff loads of suspended sediment (SS), P, and N from this silage corn cropping system and potential relationships between various runoff constituents.

MATERIALS AND METHODS

We established a paired-watershed field site to monitor runoff on a field, or sublandscape, scale on a site in central Wisconsin representative of that area's dairy farm production. The 6.4-ha field site is at the University of Wisconsin/USDA-Agricultural Research Service Research Station near Stratford, WI, USA, on a somewhat poorly drained Withee silt loam soil (Fine-loamy, mixed, superactive, frigid Aquic Glossudalfs) with 1 to 3% slope. Infiltration on these soils is limited by a compacted layer at about 50-cm depth, resulting in high runoff potential as a result of saturation-excess surface runoff. Surface drainage on this site is accomplished with a series of drive-through diversion drainageways that were created in spring 2006. This surface drainage technique has been used on other fields in the area to remove excess water and improve crop production potential. The standard design was modified slightly on this field to allow runoff monitoring of four drainage areas or "watersheds", referred to in this paper as fields M1, M2, M3, and M4 (Fig. 1) and averaging 1.6 ha each in size. Also, the natural divide between the north and south fields was made slightly more pronounced by minor grading with a land plane. The drainageways extend the full length of the lower two sides of each of the four fields (south and west sides of M1 and M2; north and west sides of M3 and M4) to direct runoff into the flumes, and on the upper (east) side of M1 and M4 to divert runoff away from the study area. They are bordered on the lower side by a low berm to assure that runoff is confined to the drainageway. The overall slope (from upper end of each field to flume) was similar, about 2%, for all fields, but the lower one-third of M3 had very little slope (0.25%) and the upper two-thirds had a slope of 3%.

The direction of tillage and corn planting was north–south except for a 14-m strip (three planter passes) along the north and south ends that were planted east–west to allow turning during the planting, harvest, and other field operations. Because of the microtopography created by tillage and planting operations, the direction of

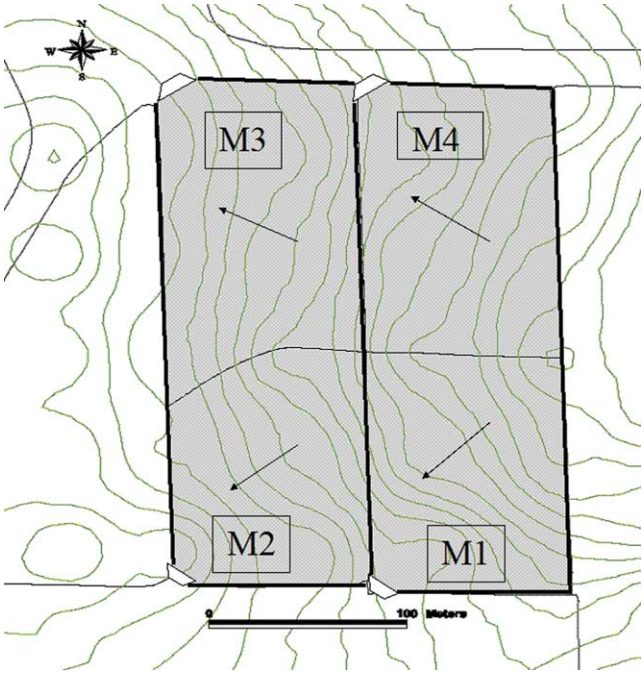

Fig. 1. Map of field site showing four drainage areas, or fields, and runoff monitoring stations. Contour lines represent 0.3 m (1 foot) elevation differences. Heavy lines indicate drainage-way-berms. Light line is divide separating north and south runoff flow. Arrows indicate downslope direction. Trapezoid symbols indicate flume/water monitoring stations.

flow over the main part of the fields for most runoff events was either north (M3 and M4) or south (M1 and M2) and then west along the field-end drainageways. The drainageways averaged 5 m in width and were about 10 to 16 cm deep across the flat middle one-third. These drainageways are managed as part of the field in terms of tillage, manure and fertilizer application, planting, and harvest operations. Slopes in the row and tillage direction and along the field-end drainage-ways averaged 1 to 2%.

Initial soil tests showed pH values of 6.0 to 6.2 and soil test P of 19 to 29 mg kg^{-1} Bray P_1. Soil test P levels from soil sampling at the end of the calibration period in fall of 2008 were 24, 23, 19, and 23 for M1, M2, M3, and M4, respectively.

The calibration period began in August 2006 with installation of runoff monitoring and sampling stations for each of the four fields. Management during the calibration period, typical of that for corn production on dairy operations in central WI, consisted of fall application of liquid dairy manure, in this case applied at a rate to meet 80% of the crop N need, chisel plowing the same day, and spring field cultivation followed by corn planting in early to mid-May. Management was identical on all four fields/watersheds. Standard production practices for planting and weed control were followed. Starter fertilizer ("2 by 2-inch" placement, or 5-cm deep and 5-cm to the side of the row) was applied at a rate to supply 15, 8, and 42 kg ha^{-1} of N, P, and K. Liquid dairy manure (approximately 150 g kg^{-1} solids) was applied at an average rate of 55 000 L ha^{-1} and supplied approximately 200 kg N ha^{-1} and 25 to 30 kg P ha^{-1} annually (Table 1). Additional N was applied as needed as a side-dress in June based on results of a pre-side-dress nitrate soil test (Laboski et al. 2006).

The calibration period ended with the start of the establishment of treatment management systems in early October 2008. On one watershed, or field (M1), the control, management remained the same as in the calibration period (fall manure, fall chisel plow). Management treatment systems for the other three fields were: (1) cover crop (fall-seeded cereal rye), spring manure and chisel plow (M2); (2) fall surface-applied manure with spring chisel plow (M3); and (3) fall manure and chisel plow with permanent vegetative field borders/grassed waterways (M4). The main focus of this paper is presentation of data and statistical analysis from the calibration period (Aug. 2006 to Oct. 2008), during which all four fields were managed similarly, to examine runoff and nutrient concentrations and loads and to assess the adequacy of the data to detect reasonable treatment effects in the treatment period. Some of the presentation, examining nutrient concentration and cumulative loads over time and the relationship between selected runoff constituents, extends beyond the calibration periods into the early treatment period, a transition period during which practices such as manure and tillage timing and buffer/waterway establishment were being implemented as part of the treatment period systems.

Runoff was monitored and sampled at gauge stations located at the natural low point of each watershed

Table 1. Manure nutrient application rates

Date	Fields	Application rate				
		Manure	Total N	NH_4-N	Total P	Total K
		(L ha^{-1})	(kg ha^{-1})			
4 Nov. 2006	All	53600	195	115	30.1	147
6 Nov. 2007	All	53600	200	105	32.4	202
9 Nov. 2008	M1, M3, M4	57300	200	96	27.9	86
8 May 2009	M2	54200	204	94	25.4	114

(Fig. 1). Flume construction and monitoring procedures were slight modifications of those used by the US Geological Survey for other monitoring stations in Wisconsin (Stuntebeck et al. 2008). At each runoff monitoring location a 60-cm fiberglass H-flume (Tracom, Inc., Alpharetta, GA) was initially attached directly to a wingwall, which directed all surface runoff through the flume. Wingwalls were constructed from overlapping sheets of treated plywood ($1.2 \times 2.4 \times 0.019$ m) placed in trenches 60-cm deep and extended approximately 3 m either side of the flume and level with the top of each flume (60-cm height). Earthen berms at the outer ends of each wingwall supported the wingwalls and ensured that all runoff passed toward the flume. In Nov. 2007, 1.8-m-long plywood approach channels (1.2 m on M4 because of proximity to access road) were installed between the wingwall and the flume to provide more uniform flow entering the flume and a greater distance for deposition of suspended sediment ahead of the flume (Brakensiek et al. 1979). Approach channels and flumes were supported at the outflow end by threaded rods attached to treated wood posts or galvanized steel pipes with turnbuckles to facilitate leveling. During the winter months the approach channel and flume were enclosed in a plywood housing with canvas curtains at the inflow and outflow ends. A 500-W quartz heater fastened to the upper surface of the housing above the flume maintained a temperature adequate to prevent freezing of sample tube inlets and flume outlet under most conditions.

The flow meter and sampling equipment for each runoff station were housed in a commercially available garden shed (Niagara model, Yardmate Series, Royal Outdoor Products, Inc. Middleburg Hts., OH) $1.8 \times 2.1 \times 2$-m high that allowed adequate space for all equipment, extra sample bottle containers, and miscellaneous supplies, as well as protection from the weather for project personnel. AC power for sampling equipment, heat tapes, and lights was supplied to all monitoring stations.

Runoff discharge was determined by measuring stage in the H flumes using an air bubbler/pressure transducer flow meter (ISCO Model 4230, Teledyne Isco, Inc., Lincoln, NE). A bubbler PVC tube (3.175 mm i.d.) was attached to the floor of the flume 40 mm back from the outlet. Staff gages were also installed on the inside wall of the H flumes to allow simultaneous comparison of stage with that from the flow meter. Time-based runoff samples were collected by an automated 24-bottle (1 L) refrigerated sampler (ISCO 6712SR, Teledyne Isco, Inc.). A sample intake tube (9.3 mm i.d.) was attached to the flume floor near the flume outlet and extended approximately 2 m to the automated sampler inside the enclosure, protected from freezing by heat tape and foam insulation. A CR10X datalogger (Campbell Scientific, Inc., Logan, UT) was used to read and store data and control the runoff sampling collection scheme. A second sample tube connected to a separate pump collected samples for pathogen analysis using a flow-through glass wool filter system (Lambertini et al. 2008) (data not reported here). Real-time, two-way radio telemetry allowed remote communication with each runoff monitoring station and the weather station. A Campbell Scientific software program, PC208W, was used to connect with the modem and communicate remotely with the field stations to read runoff data in real-time and modify the sampling program if needed. Data were loaded into Real Time Data Monitoring (RTDM) software (Campbell Scientific, Inc.) for viewing and graphical representation of data such as number and frequency of samples collected, hydrograph stage readings, and equipment status.

A meteorological station 1000 m from the site was equipped to measure and record precipitation with a tipping bucket rain gage, as well as air temperature, wind, and other standard meteorological measurements

Table 2. Monthly precipitation during the study period and long-term average precipitation for Marshfield, WI

	Monthly precipitation totals[z]				
Month	2006	2007	2008	2009	1913–2009 avg.
			(cm)		
Jan.	–	2.3	2.9	1.1	2.7
Feb.	–	2.5	2.9	1.9	2.4
Mar.	–	4.2	1.4	3.2	4.4
Apr.	–	2.7	10.7	7.3	7.1
May	–	10.3	8.4	9.4	9.8
Jun.	–	8.8	9.2	6.0	11.5
Jul.	–	7.9	10.7	1.2	9.0
Aug.	–	11.0	4.6	–	10.1
Sep.	2.2	10.3	3.8	–	9.7
Oct.	4.7	10.7	3.2	–	6.3
Nov.	2.2	0.0	3.5	–	5.1
Dec.	4.8	7.6	5.7	–	3.0
Total		78.3	67.0		81.4

[z]2006–2009 monthly totals for March to November are from field site; December to February and long-term averages are from UW Agric. Research Station (13 km from site) and include rain-equivalent snow precipitation. Precipitation before and after the measurement period (indicated by –) are not reported.

Table 3. Corn silage yields, N and P uptake, and statistical analysis

Field	Yield	P Uptake	N Uptake
	($Mg\ ha^{-1}$)	($kg\ ha^{-1}$)	
M1	16.0	32.5	185
M2	17.3	34.7	197
M3	16.6	32.4	186
M4	16.0	32.3	182
		ANOVA	
Source		*Pr > F*	
Year	0.08	0.64	0.04
Field	0.02	0.07	0.03
Year×Field	0.80	0.03	0.46
LSD	1.04	4.89	12.3
CV (%)	10.3	11.6	10.6

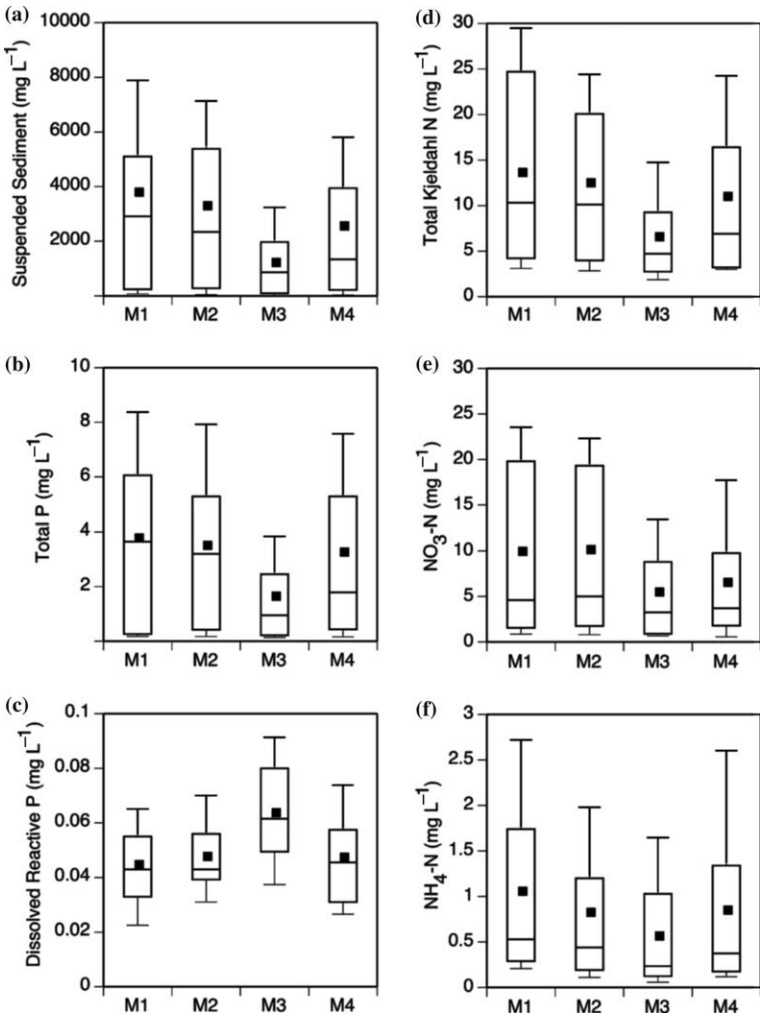

Fig. 2. Distribution of concentrations of (a) suspended sediment, (b) total P, (c) dissolved reactive P, (d) total Kjeldahl N, (e) NO_3-N, and (f) NH_4-N in runoff during calibration period from four fields – M1, M2, M3, and M4. Box plots show mean (●), 25th, 50th, and 75th percentile (lower, middle, and upper bars on each box). Whiskers indicate 10th and 90th percentiles.

not reported in this paper. Annual precipitation was slightly below the long-term average in 2007, but well below (18%) in 2008 with an especially dry period in the August through November period (Table 2).

Runoff samples from individual bottles from each runoff event were combined into a flow-weighted composite and analyzed for suspended sediment (SS; gravimetric, Method 3977-97B) (ASTM 2000), total P (TP; block digestion, Method 4500 P F) [American Public Health Association (APHA) 1995], dissolved reactive P (DRP; automated colorimetric method 4500 P F) (APHA 1995), total Kjeldhal N (TKN; block digester automated colorimetric, 4500 NH_3 G) (APHA 1995), ($NO_3^- + NO_2$-N), (automated Cd reduction; 4500 NO_3 F5) (APHA 1995), and NH_4-N (automated phenolate, 4500 NH_3 G) (APHA 1995). Values for TKN and NO_3-N were added to provide an estimate of total N, since NO_3-N is not measured in the TKN procedure.

Silage corn yields were determined by harvesting nine random 3-m row-length samples of above-ground biomass from each field (M1, M2, M3, and M4) when whole-plant DM content reached 350 g kg^{-1} (about Oct. 01). Subsamples were analyzed for N and P to determine plant nutrient concentration and uptake. Earleaf samples at silking and lower stalk samples at harvest were also collected to assess N status (data not reported here). Corn silage data were analyzed by Mixed Models Analysis using years as a replication factor with random effects and fields as a fixed effect (SAS Institute, Inc. 2010). Values of LSD for comparing field means were computed from the year × field interaction as the error term.

All runoff variables were initially transformed to log base 10 in an attempt to normalize residual values from regressions (Clausen et al. 1996; Galeone 1999). Residual plots, box plots, and normality tests indicated that the log transformation was successful in normalizing

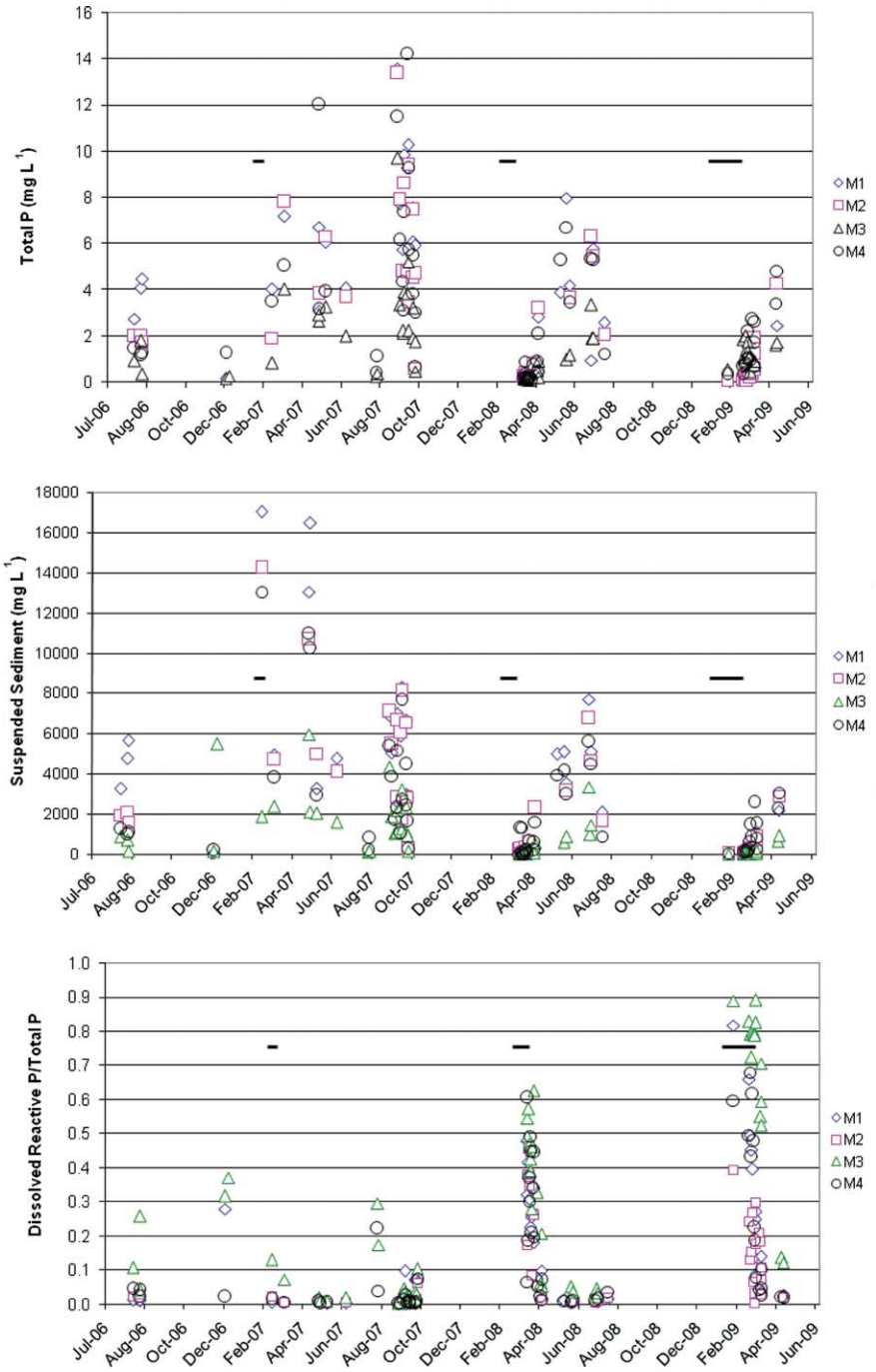

Fig. 3. Concentrations of total P (top) and suspended sediment (center) and ratio of dissolved to total P (bottom) from Aug. 2006 to Apr. 2009. Bars indicate snowmelt runoff periods.

residuals only for runoff. For simplicity, and because there was little data analysis that relied on *P* values, all variables except runoff were analyzed in their original non-transformed form. Each of the "treatment" watersheds (M2, M3, and M4) was paired with the control watershed (M1) to generate regressions of "treatment" watershed data (Y) on control watershed data (X) for the calibration period. The paired watershed data were analyzed by Mixed Models Analysis using an analysis of covariance structure to test differences in intercepts and slopes across M2, M3, and M4 watersheds (Reinhart 1967; Littell et al. 1996; SAS Institute, Inc. 2010). Mixed Models Analysis was conducted for both homogeneous and heterogeneous variances structures, across the three

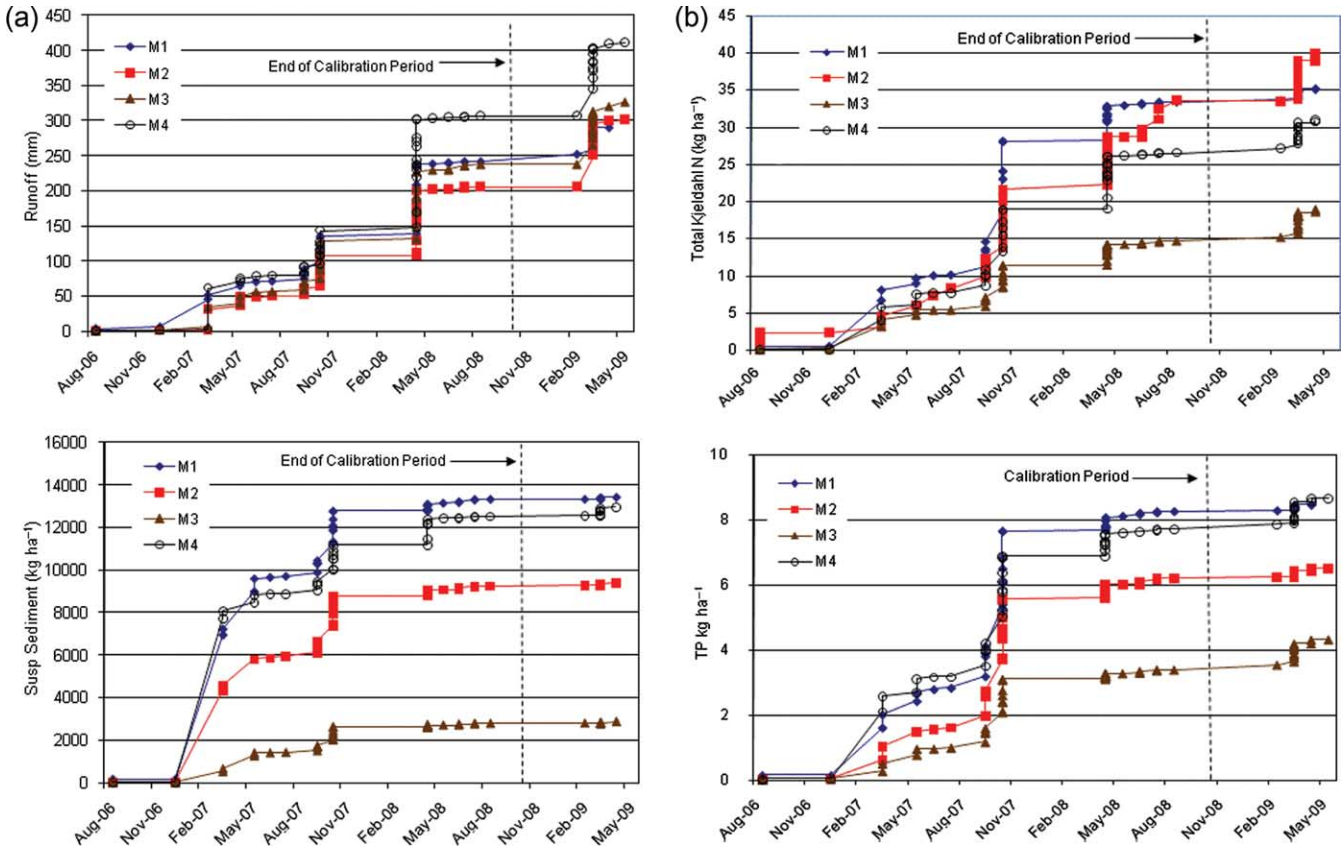

Fig. 4. (a) Cumulative runoff and suspended sediment load from four fields from Aug. 2006 to Apr. 2009. (b) Cumulative total P and total Kjeldahl N load from Aug. 2006 to Apr. 2009.

pairs of watersheds, and differences between the two structures were evaluated by Akaike's Information Criterion (Littell et al. 1996).

Using the methods of Clausen and Spooner (1993), we computed MDC for a range of possible sample sizes during the treatment period. The MDC is defined as the smallest change in a specific variable that would be considered statistically significant (Loftis et al. 2001). The purpose of computing these values is to predict a sample size necessary to detect MDC values of a particular magnitude. Values of MDC were computed as differences in intercept or mean values between treatment and control watersheds, expressed as a percentage of the mean for that variable, or in the case of runoff, the mean log of runoff values. Values of MDC were computed for treatment-period sample sizes ranging from 5 to 75 runoff events and for $P = 0.05$ or 0.10.

The relationship between total P load, total N load, and suspended sediment load was investigated using Mixed Models Analysis combined with an analysis of covariance model to test differences in slopes and intercepts between rainfall and snow events.

Table 4. Average annual runoff and loads of suspended sediment (SS), total Kjeldahl N (TKN), NH_4-N, NO_3-N, total N and P, and dissolved reactive P (DRP) from each field, and the portion from snowmelt during the calibration period

	Runoff	SS	TKN	NH_4-N	NO_3-N	Total N	Total P	DRP
	(mm)				(kg ha^{-1})			
M1	121	6676	16.7	1.85	11.9	28.6	4.20	0.059
M2	103	4645	11.7	1.27	11.0	22.7	3.10	0.054
M3	119	1450	7.3	0.81	6.6	13.9	1.69	0.085
M4	153	6274	13.2	2.19	12.4	25.7	3.85	0.078
Mean	124	4762	12.2	1.53	10.5	22.7	3.21	0.069
					Snowmelt/total ratio			
Mean	0.59	0.48	0.33	0.85	0.81	0.55	0.21	0.65

RESULTS AND DISCUSSION

Corn silage yields were typical of those for the area, averaging 16.5 t ha^{-1} across fields and years (Table 3). There were significant yield differences among fields, averaged over years, ($P = 0.02$; M2 > M1 and M4), but yields (field-year combinations) ranged only from 15 to 17.5 Mg ha^{-1}. There were some differences in nutrient uptake as evidenced by a significant main effect of field (N) and a significant field × year interaction (P). The differences among the four fields for all three corn variables point out the importance of the calibration period as the basis for our ability make comparisons across treatments following the upcoming treatment period. While a paired-watershed design will not be used to evaluate yields and nutrient uptake, these results may reflect soil differences and result in crop residue differences, both of which could affect runoff losses of nutrients.

The means, medians, and ranges for runoff concentrations of SS and most P and N constituents were fairly similar among Fields M1, M2, and M4, but M3 was lower in SS and sediment-associated TP and TKN and higher in DRP (Fig. 2). This may be explained by the lower slope in field M3 in the area approaching the flume (0.25% as discussed earlier), which led to slower movement of runoff and hydrographs that tended to have lower peaks and longer duration times than other fields, allowing more time for settling of suspended sediment and associated N and P.

Results of edge-of-field monitoring of two sites in southern WI with silage corn or low residue show a similar range of SS concentrations, slightly higher TP concentrations (5 mg L^{-1}), and much higher DRP concentrations (0.5 mg L^{-1}) (Baxter and Good 2006; L. W. Good, University of Wisconsin, personal communication). Other studies with rain simulation-generated runoff on a range of manure, tillage, and crop residue conditions showed equal or slightly higher SS, a very similar range of TP concentrations (1.5 to 5 mg L^{-1}), and DRP concentrations higher but overlapping in range (mostly 0.02 to 0.5 mg L^{-1}) (Bundy et al. 2001; Andraski et al. 2003; Grande et al. 2005a, b). The higher DRP concentrations in these studies are likely a result of much higher soil test P levels (two- to fivefold higher in most cases), which has been shown to have a direct effect on dissolved P concentrations in runoff (Bundy et al. 2001; Jokela et al. 2004).

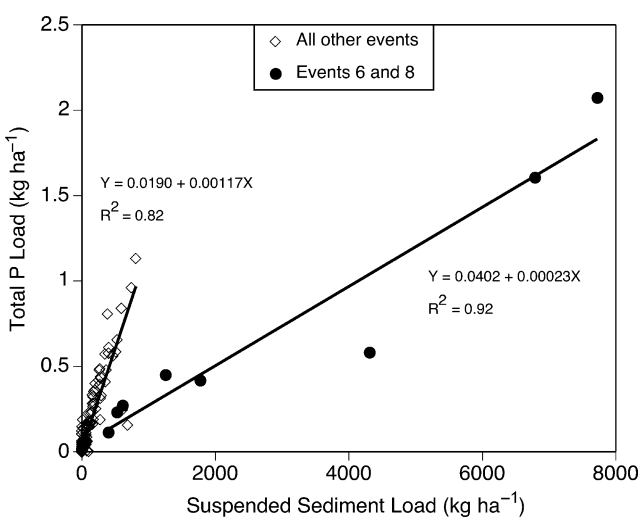

Fig. 5. Relationship between suspended sediment load and total P load in runoff for Aug. 2006 to Apr. 2009 period for events 6 (3/12/07) and 8 (5/23/07) and all other events separately.

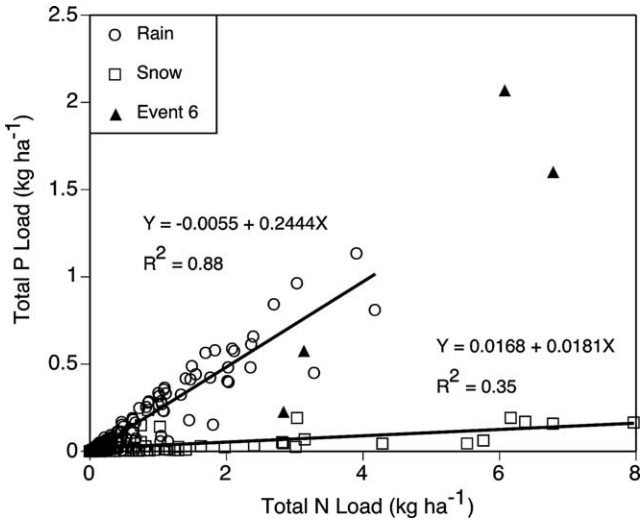

Fig. 6. Relationship between total P load and total N load in runoff for Aug. 2006 to Apr. 2009 period (event 6 deleted from regressions).

There were seasonal effects on the concentrations of SS and TP, as well as the ratio of DRP to TP, primarily related to periods of snowmelt (Fig. 3). Suspended sediment and TP concentrations were highest in fall and summer events (also in some April post-snowmelt events) and lowest in early spring snowmelt (Apr. 07 and Mar. 08), times that coincided with high DRP:TP ratios, reflecting the low SS concentration typical of most snowmelt runoff. An exception to this trend was high SS concentration in the single snowmelt event in March 2007. This was the first large runoff event after the establishment of the field site the previous August. The unusually high sediment losses resulted from faster snowmelt than is typical of snowmelt runoff, and may have been exacerbated by the multiple tillage operations (land grading of berms and rock windrowing, in addition to conventional primary and secondary tillage) performed in preparation of the site. (Deposition in the flumes resulted in some erratic peaks in the flow readings because of interference with the bubbler flow meter tube and required adjustment of the hydrographs in consultation with a US Geological Survey hydrologist.)

Table 5. Regression models, adjusted R^2, and minimum detectable change (MDC), assuming 40 treatment events for runoff and concentration and load of runoff constituents

Measurement variable	Y[z]	n	Regression model	Int.[z]	Slope[z]	Var.[z]	R^2	MDC $P=0.05$	MDC $P=0.10$
Runoff (mm)	M2	35	−0.136+1.069 log X	NS	NS	het	0.90	22	18
	M3	39	−0.038+1.007 log X				0.73	30	25
	M4	41	−0.030+1.038 log X				0.76	37	31
			Concentration (mg L^{-1})						
Suspended sediment	M2	35	110+0.854 X	<0.001	<0.001	het	0.93	13	11
	M3	39	307+0.229 X				0.51	36	30
	M4	41	44+0.707 X				0.89	17	15
Total P	M2	35	0.205+0.849 X	NS	0.020	het	0.83	18	15
	M3	39	−0.034+0.463 X				0.72	26	22
	M4	41	0.145+ −0.872 X				0.74	24	20
DRP	M2	35	0.0170+0.677 X	0.013	NS	het	0.69	8	7
	M3	39	0.0424+0.452 X				0.16	13	11
	M4	41	0.0271+0.558 X				0.20	19	15
Total Kjekdahl N (TKN)	M2	35	2.57+0.688 X	NS	<0.001	het	0.94	21	18
	M3	39	1.89+0.326 X				0.45	27	23
	M4	41	1.80+0.713 X				0.54	28	23
NO_3-N	M2	35	1.24+0.862 X	NS	<0.001	het	0.85	16	13
	M3	39	3.32+0.261 X				0.18	39	33
	M4	41	0.88+0.638 X				0.81	18	15
Total N (TKN+NO_3-N)	M2	35	7.26+0.622 X	NS	0.032	het	0.39	13	11
	M3	39	5.61+0.283 X				0.12	23	19
	M4	41	1.39+0.739 X				0.40	19	16
			Load (kg ha^{-1})						
Suspended sediment	M2	35	34.7+0.640 X	NS	<0.001	het	0.99	10	9
	M3	39	39.9+0.093 X				0.58	55	46
	M4	41	−43.9+1.078 X				0.94	42	35
Total P	M2	35	0.0397+0.602 X	NS	<0.001	het	0.80	28	23
	M3	39	0.0240+0.292 X				0.71	34	28
	M4	41	−0.0144+0.993 X				0.87	31	26
DRP	M2	35	0.00025+0.877 X	NS	NS	het	0.88	24	20
	M3	39	0.00125+1.013 X				0.60	42	35
	M4	41	0.00036+1.189 X				0.63	51	43
Total Kjekdahl N (TKN)	M2	35	0.210+0.497 X	NS	<0.001	het	0.64	34	29
	M3	39	0.060+0.356 X				0.89	21	17
	M4	41	0.164+0.593 X				0.80	27	22
NO_3-N	M2	35	0.044+0.875 X	NS	<0.001	het	0.92	26	22
	M3	39	0.123+0.352 X				0.74	38	31
	M4	41	0.116+0.860 X				0.86	34	28
Total N (TKN+NO_3-N)	M2	35	0.162+0.714 X	NS	<0.001	het	0.80	25	21
	M3	39	0.169+0.364 X				0.77	24	20
	M4	41	0.073+0.853 X				0.85	24	20

[z]P values for homogeneity tests of intercept (Int.) and slope among fields M2, M3, and M4 (Y). NS = non-significant ($P>0.05$). Variance homogeneity was determined by Akaike's Information Criterion: $AIC_{hom} < AIC_{het}$.

Cumulative runoff and cumulative SS, TP, and TKN loads showed the same general pattern over time during the calibration and early treatment (transition) time period (Fig. 4a, b). Runoff was not greatly different by field, although M4 increased more than other fields in a few events in April 2008. There were greater differences in SS, TP, and TKN cumulative loads, most notably lower loads in M3, reflecting the lower concentrations from that field (Fig. 2). Average annual loads of SS and total and dissolved N and P constituents of runoff for the calibration period confirm these differences and show similar trends among fields (with the exception of DRP) (Table 4). This emphasizes value of the paired-watershed design and the need for a calibration period to assess inherent differences. The paired watershed design does not require that all watersheds be identical, only that they respond in a similar way as determined by analyzing calibration period data.

Another paired-watershed study monitored stream flow from two larger watersheds (370 and 460 ha) with dairy-based corn, alfalfa, and pasture production in Pennsylvania, USA (Galeone 1999). Annual loads of SS averaged just over half (56%), TP loads were slightly less, and NO_3-N and DRP loads were much higher than those in our study. The lower SS and TP loads might be expected because of the mix of agricultural land uses (vs.

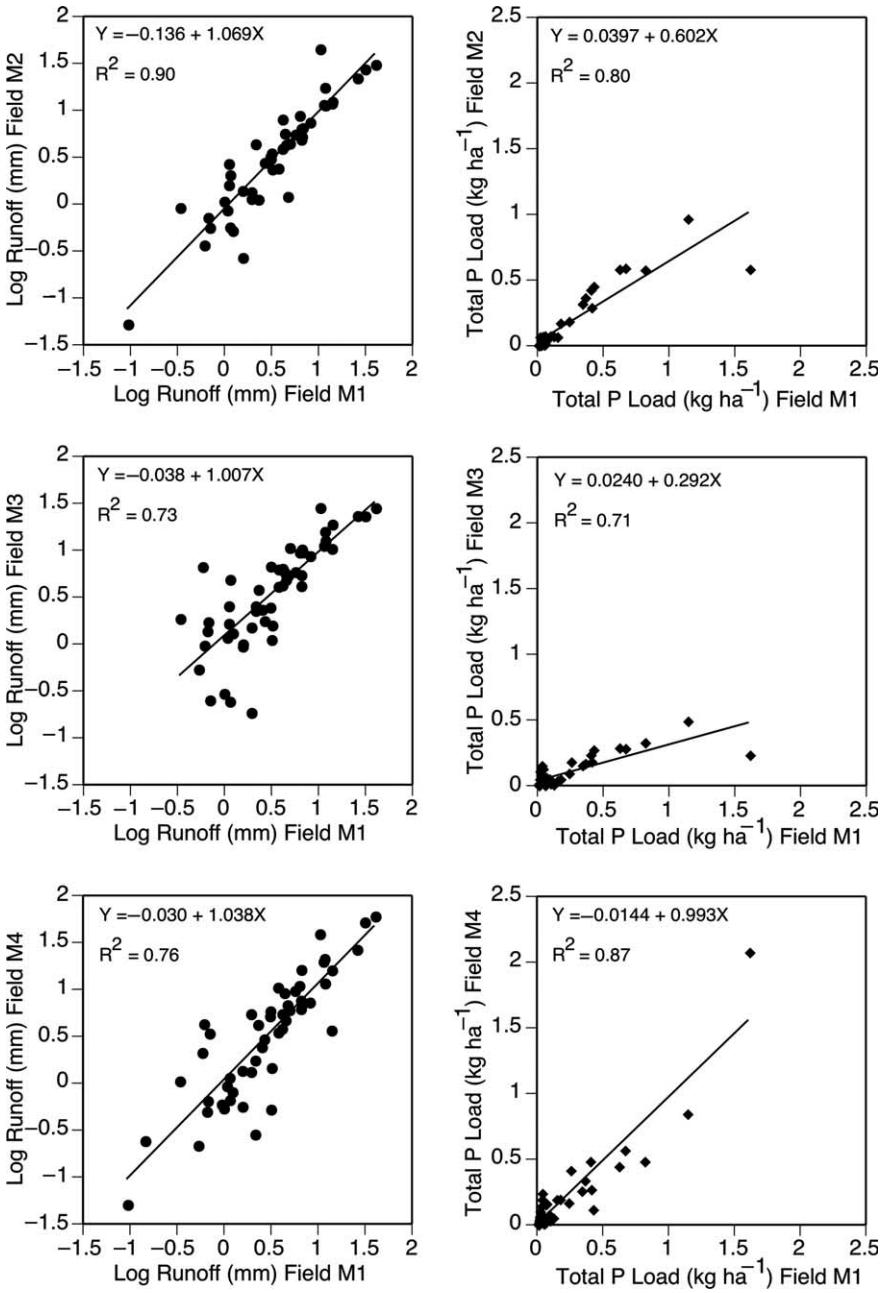

Fig. 7. Regression plots of runoff (log-transformed) and total P load for M2, M3, and M4 vs. M1 (control) during calibration period.

silage corn only) and the field-to-stream deposition of sediment that is likely to occur. Higher dissolved N and P may have resulted from release from perennial vegetation during freeze-thaw periods and surface application or deposition of manure on cropland and in pastures.

A large portion of the runoff and total loads of all measured and derived constituents were from snowmelt events, over 50% for runoff and dissolved N and P forms (Table 4). This is consistent with results reported in a paired-watershed study in Manitoba (Tiessen et al., 2010). Total P and TKN loads in snowmelt runoff were lower, reflecting their association with sediment, which was lower in snowmelt events (mean SS concentration of 1468 mg L^{-1} compared with 4844 in rain runoff events, data not shown). Dissolved P (DRP) load was a very small portion (2%) of TP load, but it can still be important environmentally because it is the most biologically active portion. Dissolved N forms (NO_3-N + NH_4-N) represented about half of the total N load. The dissolved forms of P and N were present in

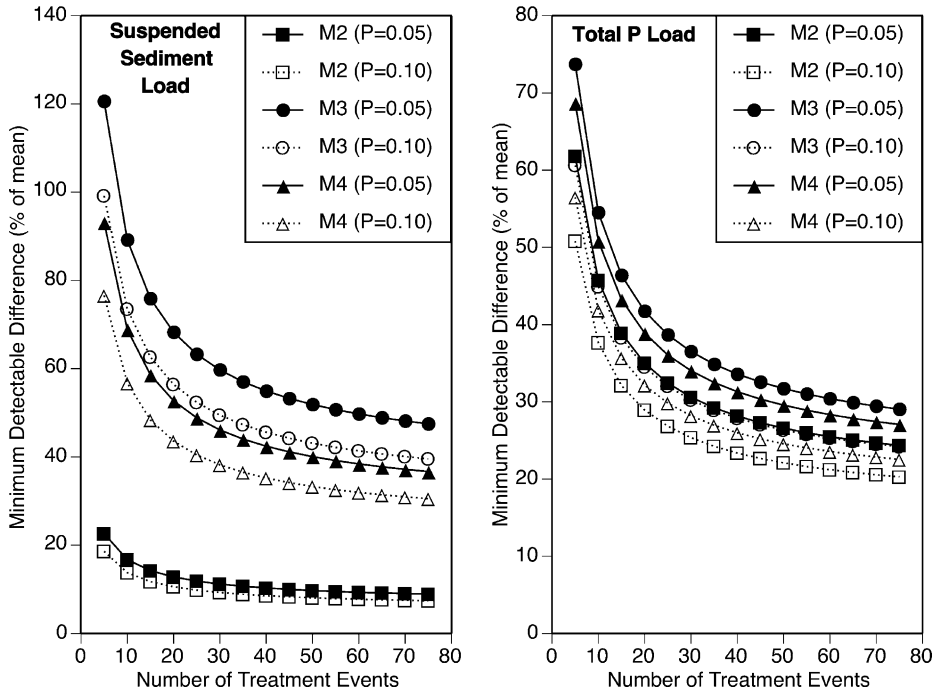

Fig. 8. Minimum detectable difference (or change) of suspended sediment (left) and total P load (right) as a function of number of treatment period events.

much higher proportions in snowmelt runoff (6 and 78% for P and N, respectively) than in rainfall-derived runoff (1 and 21% for P and N; data not shown). Larger portions of these more biologically available nutrient forms suggest a potentially greater impact of snowmelt runoff on eutrophication of surface waters.

Total P load would typically be closely related to SS load if runoff is dominated by sediment-bound P. Runoff data from all events in our study showed a moderate relationship (R^2 of 0.62; data not shown). However, if the first two large runoff events after establishment of the field site (one snowmelt, one rain) are separated from the others, both populations show an excellent relationship between TP load and SS load (Fig. 5). Analysis of variance showed highly significant differences in the slopes of these two regressions ($P<0.0001$).

Comparison of TP and total N loads for all runoff events also showed only a moderate relationship ($R^2=0.32$). But separating them into rain-derived (excluding Event 6) and snowmelt runoff events resulted in a very good relationship for rain runoff events ($R^2=0.88$; Fig. 6). Analysis of variance showed highly significant differences in the slopes of these two regressions ($P<0.0001$). Different slopes indicate that TP load was 25% of total N load in rain runoff, but only about 2% of total N load in snowmelt events.

All regressions of treatment fields (M2, M3, and M4) against the control field (M1) were highly significant for runoff and concentration and load of all constituents (data not shown). There was significant heterogeneity among linear slopes across the three fields for most variables, pointing out the importance of the internal calibration period for each field as the basis of comparing future treatment effects across fields (Table 5).

Most R^2 values were fairly high (0.7–0.9), e.g., runoff and TP load (Fig. 7 and Table 5), but some were lower, in particular for the concentrations of DRP and some N forms (Table 5). Values of MDC (difference between means), assuming 40 treatment-period runoff events (approximately equal to the number of calibration period events), were 10 to 30% of the mean for most concentration and load parameters (Table 5). However, a few MDC values were higher, especially some of the load parameters (31 to 55%). Calculation of MDC values for a range of treatment-period sample sizes showed a dramatic decrease as number of treatment events increased to about 30, as illustrated for suspended sediment load and total P load (Fig. 8). Increasing treatment sample size beyond the calibration sample size (35 to 41) resulted in only slightly lower MDC values.

Runoff water quality results from this paired-watershed silage corn site have shown relatively high runoff SS and P and N concentrations (with the exception of DRP), but values within the range of those in other comparable studies. Concentrations varied seasonably, primarily a function of rainfall vs. snowmelt runoff. Cumulative SS and P and N loads followed similar patterns over time, but average annual loads varied by field. Runoff from snowmelt was important,

contributing over 50% of the runoff and dissolved P and N load and 20 to 50% of SS, TP, and TKN load. Total P load showed a linear relationship with SS load, confirming the dominance of sediment-associated P from this low-residue site. Total P and total N loads were also closely related, but with different relationships for rain-derived and snowmelt runoff. Despite differences among the four fields, regressions of the three treatment fields against the control for runoff concentrations and loads were all highly significant with relatively high R^2 values (0.7 to 0.9) for most. Calculation of MDC values indicate that treatment differences of 10 to 30% between calibration and treatment period means would be statistically significant for most concentration and load parameters, suggesting a reasonable probability of success in detecting treatment effects with this paired watershed design.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the contributions of Craig Simson, former research technician with USDA-ARS, in managing the field site, sample collection, and water quality data and David Owens, USGS hydrologist for help establishing the runoff collection stations and consulting about data management.

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