Effect of cover crops established at time of corn planting on phosphorus runoff from soils before and after dairy manure application

P.J.A. Kleinman, P. Salon, A.N. Sharpley and L.S. Saporito

ABSTRACT: Phosphorus (P) runoff from agricultural soils is a concern due to eutrophication. The simultaneous corn and cover crop system was developed by U.S. Department of Agriculture's Natural Resources Conservation Service (USDA-NRCS) for dairy farms in the northeastern United States, where short growing seasons have limited fall seeding of cover crops. The simultaneous corn and cover crop system uses post-emergence imidazolinone herbicides to allow for simultaneous seeding of cover crops with silage corn. Trials were established at two locations in the Cannonsville Reservoir watershed, New York, part of New York City's drinking water supply system, to assess the effects of this cover cropping system on water quality. Rain simulations (60 mm hr^{-1}) were conducted to evaluate the initial 30 minutes of runoff from small (1 x 2 m; 3 ft x 7 ft) plots before and after surface application of dairy manure (50 or 100 kg total P ha^{-1} ; 45 or 89 lb P ac^{-1}). Corn yields from plots interseeded with red clover compared most favorably with the conventionally cropped controls, with no significant differences in yields noted between the two treatments at either location. Prior to dairy manure application, losses of P in runoff were primarily a function of erosion. Because all cover crops increased ground cover (up to 81 percent greater than the control), total P loads in runoff were significantly lower from cover cropped plots (averaging 10 mg per plot) than from conventionally cropped controls (averaging 39 mg per plot). At the same time, suspended solids loads averaged 25.3 g (1 oz) from the control plots and 5.9 g (0.2 oz) from the cover crop plots. Despite concern that release of soluble P from the cover crops could enrich dissolved reactive P in runoff, dissolved reactive P losses from the simultaneous corn and cover crop system were generally not different from conventionally-cropped silage corn losses. Application of manure obscured cover crop/conventional silage corn treatment differences with regard to P runoff, with dissolved reactive P becoming the dominant form of P in runoff due to contributions of readily soluble P in manure. Because runoff P losses were already high from unmanured conventional silage corn plots, application of manure did not significantly increase P losses from some of the conventional silage corn treatments. Results highlight the agronomic and water quality benefits of the simultaneous corn and cover crop system, particularly when implemented with red clover.

Keywords: Corn, cover crops, erosion, manure, phosphorus, runoff

Accelerated eutrophication, the biological enrichment of surface waters due to anthropogenic inputs of nutrients, is widespread in the United States (U.S. Environmental Protection Agency, 1996). Due to the role of phosphorus (P)-laden runoff in accelerated eutrophication of many agricultural watersheds (USGS, 1999), the U.S. Department of Agriculture (USDA) and U.S. Environmental Protection Agency signed a joint accord to promote management practices that minimize P losses from agricultural lands (USDA and USEPA, 1999). A growing number of field management practices have been identified as "best management practices" to minimize P transport in agricultural runoff (Sims and Kleinman, 2005).

Minimizing P in runoff requires an understanding of the mechanisms of P transport. Due to the high affinity of P to soil solids, there has been an historical emphasis on reducing P loss by controlling erosion. Erosion remains the primary mechanism of P loss from most agricultural soils (Sharpley et al., 1996). More recently, dissolved P in runoff has surfaced as a key concern from soils with a high degree of P sorption saturation due to repeated P application in fertilizer or manure (Sibbeson and Sharpley, 1997). In addition, when manure is broadcast during times of high runoff potential, soils are particularly vulnerable to dissolved P loss (Eghball and Gilley, 1999). Given the ubiquitous nature of P loss, nearly all U.S. states have developed site assessment indices that weigh various management and site-specific factors to identify fields prone to P runoff (Sharpley et al., 2003).

The beneficial effects of cover crops on erosion control, soil tilth, and fertility have been well documented (Sharpley and Smith, 1991). By protecting the soil surface, cover crops can prevent direct impact of raindrops on soil, reducing surface sealing, improving infiltration and lowering erosion in comparison with bare soils. Also, leguminous cover crops can provide nitrogen (N) to subsequent crops in the rotation cycle. When N from leguminous crops is adequately credited in nutrient management planning, lower rates of manure application are generally recommended, resulting in less manure P available to runoff (Beegle, 1999).

Cover crops can have mixed effects on nutrient runoff, benefiting from the standpoint of particulate P reductions but increasing dissolved P losses. Sharpley and Smith (1991) reported long-term results of research in Oklahoma that compared runoff from small watersheds cropped with alfalfa (*Medicago sativa*), cotton (*Gossypium hirsutum*) or wheat (*Triticum aestivum*). Annual erosion

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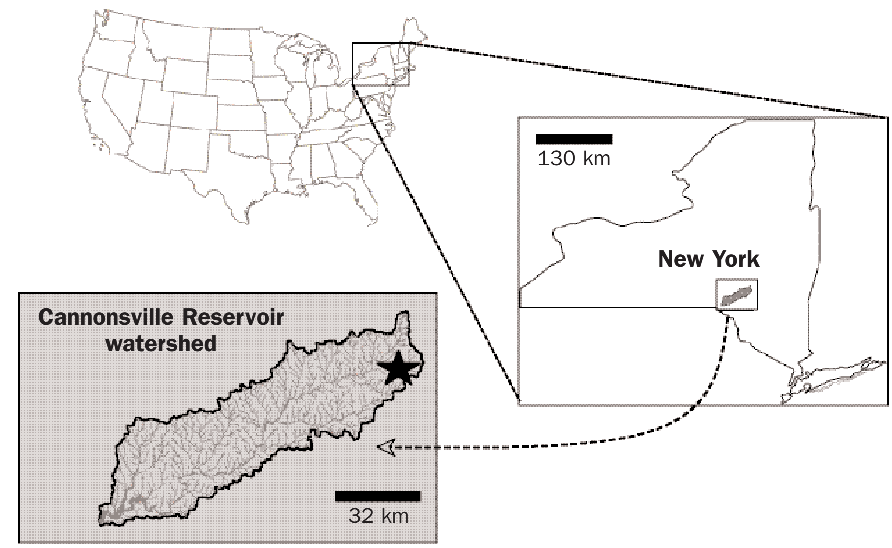
rates from the alfalfa watershed (300 kg ha^{-1}; 268 lb ac^{-1}) were more than ten times lower than from the cotton watershed (3800 kg ha^{-1}; 3,393 lb ac^{-1}) and approximately six times lower than from the wheat watershed (1900 kg ha^{-1}; 1,697 lb ac^{-1}). However, mean annual dissolved P concentrations in runoff were two to three times greater from the alfalfa watershed (0.81 mg L^{-1}) than from the cotton (0.36 mg L^{-1}) and wheat watersheds (0.26 mg L^{-1}). They attributed the elevated concentrations of dissolved P from the alfalfa watershed to two major processes: leaching of P from clipped and decaying alfalfa; and sorption of dissolved P by high concentrations of suspended sediment in runoff from the cotton and wheat watersheds. Thus, the use of cover crops to reduce P runoff is most effective when targeted to fields where erosion and particulate losses of P are of primary concern.

The establishment of cover crops following silage corn (*Zea mays*) is a problem in the northern United States due to late harvest and short growing seasons (Hively and Cox, 2001). As a result, the practice of planting a cover crop following harvest of a row crop has not been widely adopted (Johnson et al., 1998). An alternative method for establishing cover crops in the spring has been under investigation by the U.S. Department of Agriculture's Natural Resources Conservation Service (USDA-NRCS) Plant Materials Center (Big Flats, New York). Until recently, seeding cover crops at corn planting has not been feasible due to limitations of commonly used residual pre-emergence herbicides. Now, with the use of post-emergence imidazolinone herbicides and corn hybrids resistant to these herbicides, the option of seeding cover crops at corn planting is possible (Salon and van der Grinten, 1999; Squire, 1997). This system, referred to here as the simultaneous corn and cover crop system, has shown promise with perennial rye grass (*Lolium perenne*), white clover (*Trifolium repens*), red clover (*Trifolium pratense*) and even alfalfa (NRCS, 2000). Judicious application of post-emergence herbicides is required to minimize competition between the cover crop and silage corn during early corn development. A major perceived advantage of the simultaneous corn and cover crop system, compared with fall seeding of a cover crop, is that the cover crop is already established at the time of corn harvest, normally a period of high vulnerability of soil to direct impact of rain drops.

Figure 1

General location of field sites (☆) within the Cannonsville Reservoir watershed, part of the New York City water supply system.



This study examines the benefits of the simultaneous corn and cover crop system in controlling P runoff from silage corn grown on two agricultural soils in New York. Differences in runoff properties are compared between conventionally managed silage corn, and silage corn intercropped with either alfalfa, perennial rye grass, or red clover. As manure management plays an important role in P runoff from dairy farms, runoff properties before and after manure application are also compared.

Methods and Materials

Site description. The study was conducted in the Cannonsville Reservoir Watershed, New York (42°21'N, 74°52'W), part of the New York City drinking water supply system (Figure 1). The watershed falls within the Glaciated Allegheny Plateau and Catskill Mountain Region (Major Land Resource Area 140), a sub-region of the Northeastern Forage and Forest Region (SCS, 1981). The climate is humid, with annual precipitation of approximately 105 cm (41.3 in) (Slack et al., 1993). Due to accelerated eutrophication of the Cannonsville Reservoir, the watershed is subject to P-based total maximum daily load regulation under the Clean Water Act (NYDEC, 2000). Consequently, broad efforts are underway in the watershed to develop innovative solutions to controlling P runoff (Walter and Walter, 1999).

Agriculture accounts for 28 percent of the land area in the Cannonsville Reservoir watershed, with forests constituting 70 percent of the total area (Schneiderman et al., 2002). Farms in the watershed are predominantly dairy operations, averaging roughly 90 ha (222 ac) in area with approximately 75 milking cows. Typical crop rotation involves three years of silage corn followed by five years of alfalfa and/or mixed grasses. Many soils in the watershed possess fragipans that seasonally perch shallow water tables resulting in variable source area hydrology. Surface runoff occurs most frequently in the spring and fall (Walter et al., 2003).

Two fields were selected from adjacent farms in the watershed for trials of the simultaneous corn and cover crop system. Both fields had been in silage corn production for at least one year prior to the trails and both had long histories of receiving dairy manure as a source of nutrients. Dairy manure in the area is typically broadcast year round, and incorporated into the soil by moldboard and chisel plow during spring site preparation. At one site, trials were established on a moderately well drained Willowemoc soil (coarse-loamy, mixed, semiactive, frigid Typic Fragiudept) in May 2000. At the other site, trials were established on a somewhat-poorly drained Onteora soil (coarse-loamy, mixed, semiactive, frigid Aquic Fragiudept) in May 2001. Agronomic trials were conducted with four replicate, 12 x 18 m (39 x 59 ft) plots for treatment in a completely randomized design. Slope gradients within the trial

Table 1. Management, yield, and canopy cover at Willowemoc and Onteora sites.

Site/treatment	Crop variety	N	Silage corn: Planting date	Silage corn: Harvest date	Silage yield*	Cover crop seeding: Date	Cover crop seeding: Rate	Ground cover: Fall†	Ground cover: Spring‡
					(Mg ha^{-1})		(kg ha^{-1})	(%)	(%)
Willowemoc site (2000-2001)									
Control (corn only)	Pioneer 37J99, 97 day	4	5/18/00	9/26/00	41.1 (2.7)	N/A	0	43 (5)	33
Perennial rye grass	Citadel	4	5/18/00	9/26/00	34.0 (5.2)	5/20/00	19.0	93 (2)	80 (7)
Red clover	Arlington	4	5/18/00	9/26/00	40.0 (3.8)	5/20/00	9.3	66 (6)	61 (5)
Onteora site (2001-2002)									
Control (corn only)	Garst, 87 day	4	5/4/01	9/18/01	31.2 (5.9)	N/A	0	10	36 (11)
Alfalfa	Preferred Blend	4	5/4/01	9/18/01	19.7 (5.4)	5/13/01	14.0	85 (4)	68 (18)
Perennial rye grass	Amazon	4	5/4/01	9/18/01	23.7 (8.2)	5/13/01	16.8	91 (3)	88 (6)
Red clover	Arlington	4	5/4/01	9/18/01	34.6 (12.8)	5/13/01	11.2	81 (8)	59 (13)

* Standard deviations given in parentheses.

† Fall ground cover observation dates: 11/14/2000 and 9/18/2001.

‡ Spring ground cover observation dates: 5/2/2001 and 4/16/2002.

N/A = not applicable.

plots averaged 6 percent at the Willowemoc site and 11 percent at the Onteora site. Perennial rye grass and red clover were grown as cover crop treatments at both sites. In addition, at the Onteora site, alfalfa was included. Adjacent areas under conventional corn silage production served as references to the cover crop treatments.

At both sites, imidazoline resistant corn varieties were planted in 30-inch rows prior to cover crop seeding, with varieties and planting/harvest dates presented in Table 1. All Willowemoc plots were fertilized with 91 kg (200 lbs) of 20-5-20 (N-P_2O_5-K_2O) and the Onteora plots were fertilized with 91 kg of 24-6-20 starter blend at corn planting. There were no additional manure or fertilizer applications during the crop establishment and growth phase of the study. Cover crops were planted with a Brillion seeder, with dates and rates given in Table 1. For both sites, herbicides were applied post emergence before weeds and cover crops reached 8-cm height to minimize competitive interactions with the growing corn: Pursuit (imazethapyr) at 0.11 kg ha^{-1} (1.44 oz ac^{-1}) and Buctril (bromoxynil) at 1.16 L ha^{-1} (1.5 pts ac^{-1}).

Silage yield was determined by hand harvesting and weighing whole plants from 0.6 to 4.6 m (2 to 15 ft) rows within the center of each plot. Three representative plants were harvested from each 4.6 m (15 ft) of row to determine dry matter content. Ground cover was determined on 11/14/2000 and 5/2/2001 at the Willowemoc site, and on 9/18/2001 and 4/16/2002 at the Onteora site. Ground cover was quantified within a 0.36 m^2 (4 ft^2) frame placed randomly at three locations within each plot, and an average of these observations used to represent the entire plot.

Rainfall-runoff experiments. Runoff plots were established at both sites within the larger cover crop plots developed for the cover crop trials. For each treatment, two pairs of 1 x 2 m (2m^2) runoff plots were installed with the long axis orientated down the slope. Runoff plots were isolated on the upper three sides by painted, steel frames driven 5 cm (2 in) into the soil and extending 5 cm (2 in) above the soil. At the lower end of each runoff plot, a collection gutter was installed, inserted 5 cm (2 in) into the soil with the upper edge level with the soil surface. The collection gutter was equipped with a canopy to exclude direct input of rainfall.

Rainfall-runoff experiments were conducted once at the Willowemoc soil site in spring 2001 (beginning 5/7/2001)), and twice at the Onteora soil site, in fall 2001 (beginning 10/9/2001) and spring 2002 (beginning 4/23/2002). Spring experiments were timed to occur shortly before annual cultivation so that they represented the maximum development of a cover crop stand. The fall experiment, occurring at the Onteora site only, was conducted shortly after corn harvest. This experiment was added to the study to elucidate differences that might be expected between the simultaneous corn and cover crop system where cover crops have already been established and a traditional cover crop scenario with no established cover crop prior to the fall seeding. Temperature and precipitation conditions around the time of each of the three rain simulation experiments are summarized in Table 2.

For the experiment at the Willowemoc site (spring 2001), a total of six rainfall-runoff events were conducted. The first events occurred over three consecutive days, with four replicates for each treatment. Immediately following the third rainfall-runoff event, manure was broadcast at two rates to each pair of abutting plots: 50 or 100 kg total P ha^{-1} (45 or 89 lb ac^{-1}). Five days later, the second set of events was initiated, also over three consecutive days, with two replicates for each cover crop/manure treatment combination. For the experiments at the Onteora site (fall 2001 and spring 2002), four rainfall-runoff events occurred per experiment rather than six events, as at the Willowemoc site. The first events occurred over two consecutive days prior to manure application, while the second two events occurred on the fifth and

Table 2. Climatic conditions surrounding the rain simulation experiments at the Willowemoc and Onteora sites.

Experiment	Dates	Temperature: maximum	Temperature: minimum	Temperature: mean	Precipitation
		°C	°C	°C	(mm)
Willowemoc, spring 2001	April 30 to May 22	21.9	4.0	13.2	4.6
Onteora, fall 2001	October 2 to 24	17.8	2.4	10.2	41.9
Onteora, spring 2002	April 16 to May 14	16.1	2.6	9.5	130.8

sixth day after application. Data from the Willowemoc site and other studies conducted by the authors indicated that hydrology and water quality over the second and third days of consecutive rainfall-runoff events were sufficiently similar to warrant parsimonious removal of the third consecutive event from the Onteora experiments. It is important to note that the spring 2002 experiments at the Onteora site were carried out on runoff plots established near to, but not overlapping, the locations of the fall 2001 runoff plots. As a result, manure applied as part of the fall 2001 experiments at the Onteora site did not influence runoff plot conditions in the spring 2002 experiments. Also, during the fall 2001 and spring 2002 Onteora experiments, approximately 20-mm and 45-mm, respectively, of natural precipitation occurred after manure was applied to the plots. Consequently, all plots were covered with tarpaulins to minimize the influence of this additional precipitation on plot chemistry and hydrology. Finally, an equipment malfunction resulted in no rainfall simulation being conducted on alfalfa plots (hence no runoff data) on the second day of the spring 2002 experiment at the Onteora site.

Rain simulations were conducted using a modified protocol of the National Phosphorus Research Project (2001). Portable rain simulators (Humphry et al., 2002) equipped with TeeJet™ 1/2 HH SS 30 WSQ nozzles[1] (Spraying Systems Co., Wheaton, Illinois) were placed approximately 3 m (10 ft) above the soil surface. At this height, simulated rainfall achieves approximately 90 percent terminal velocity and has a coefficient of uniformity greater than 0.80 within the 2 x 2 m (4 m^2) area of the abutting runoff plots situated directly below the nozzle. The simulator is enclosed on all four sides by tight fitting canvas walls that prevent wind from influencing the distribution of simulated rainfall. Rainfall was delivered at approximately 60 mm h^{-1} until 30 min of runoff was collected. A maximum rainfall duration of 150 minutes was prescribed, so that, if no runoff occurred within that time period, the rain simulation was terminated. Rainfall events of this intensity and maximum duration exceed a 100-year return period in the region (Aaron et al., 1986). For each event, antecedent soil moisture was measured at six locations within each plot by capacitance sensor (Theta Probe, Delta-T Devices, Ltd., Cambridge, UK).

Table 3. Properties of dairy manures used in study.

Experiment	Dry matter	Total N	Total P	Water extractable P
	(%)	g kg^{-1} (dry weight basis)		
Willowemoc, May 2001	17	30	6.5	4.7
Onteora, October 2001	14	25	4.4	2.6
Onteora, May 2002	15	32	6.3	4.2

Runoff from the plots was continuously collected and volumes determined every five minutes to develop plot-specific hydrographs. Runoff from the entire 30 minute period was combined into a single composite sample, thoroughly stirred to resuspend settled particles and sampled immediately for laboratory analysis. Filtered (0.45 μm) and unfiltered sub-samples were stored at 4°C (39.2°F) (prior to laboratory analysis. Ten soil samples were collected from a 0 to 5 cm (0 to 2 in) depth adjacent to each plot and combined into a single, composite sample for each plot.

Laboratory analyses: All soils were air dried, sieved (2-mm) and analyzed for Mehlich-3 P by shaking 2.5 g (0.1 oz) of soil with 25 mL of Mehlich-3 solution (0.2 M CH_3COOH + 0.25 M NH_4NO_3 + 0.015 M NH_4F + 0.013 M HNO_3 + 0.001 M EDTA) for 5 min (Mehlich, 1984). Water-extractable soil P was measured by shaking 0.5 g of soil in 5-mL of distilled water for one hour, filtering the supernatant through a Whatman No. 1 paper filter. Phosphorus in the Mehlich-3 and water extracts was measured colorimetrically by a modified method of Murphy and Riley (1962), with λ = 712 nm.

Manure was analyzed for total P and total N by modified semimicro-Kjeldahl procedure (Bremner, 1996) (Table 3). Water extractable P was analyzed by the method of Kleinman et al. (2002a), where one gram dry-weight equivalent fresh manure was shaken with 200 mL of distilled water on an end-over-end shaker for 60 minutes (Table 3). The mixture was then centrifuged (about 2900 g for 20 minutes to facilitate filtration) and filtered through a Whatman No. 1 filter paper. Filtrate P was determined colorimetrically as described above. Dry matter content of all manures was determined gravimetrically after oven-drying manures at 70° C (158° F) for 48 hours (Table 3).

Dissolved reactive P was determined on 0.45-μm filtered runoff water by the colorimetric method described for soil and manure extracts. Total P was measured on unfiltered runoff water by modified semimicro-Kjeldahl procedure of Bremner (1996). Runoff water was also analyzed for total suspended solids by evaporating 200 mL of unfiltered runoff water in an oven at 70° C (158° F) and weighing the remaining material.

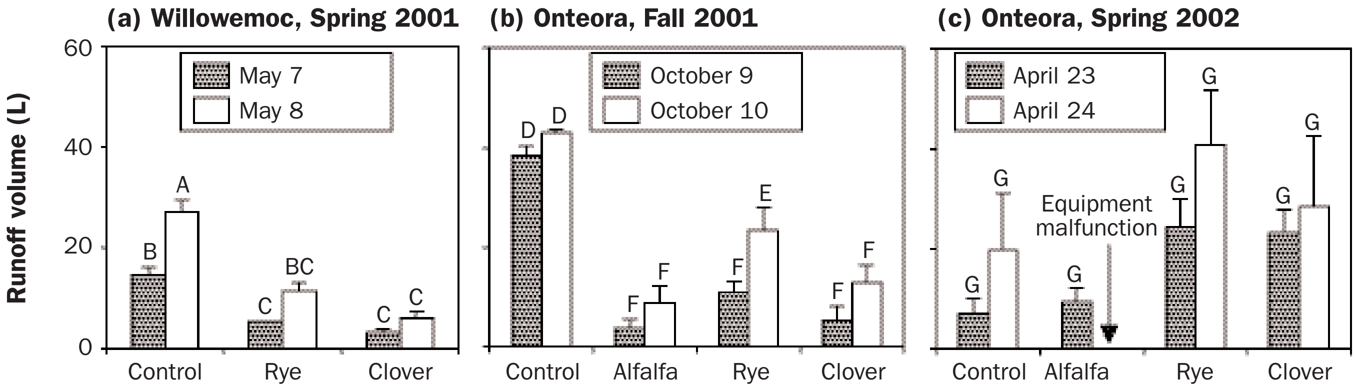
Data presentation and statistical analyses. Due to the above-mentioned similarities in hydrology and runoff water quality between second and third consecutive events at the Willowemoc site, only results from the first and second consecutive days are presented, facilitating direct comparison of Willowemoc and Onteora results, where only two consecutive events were conducted. Treatment effects were evaluated by general linear model using Tukey's test to compare individual means. Relationships between soil and runoff variables were quantified by least squares regression. Differences in regression parameters were assessed by a homogeneity of variance test (Gomez and Gomez, 1976). Treatment differences discussed in the text were significant at ≤ 0.05. All analyses, except for the homogeneity of variance test, were performed using Minitab's statistical software, Release 13 (Minitab Inc., 2001).

Results and Discussion

Yield and crop canopy trends. Corn silage yields from the conventionally cropped controls compared favorably with the ten-year average of 34.4 Mg ha^{-1} (15.3 t ac^{-1}) in New York (NYASS, 2004), although yields were slightly lower for the Onteora site (Table 1). The higher yields from the Willowemoc site reflect different growing conditions during the two seasons (local growing conditions were poor in 2001), compounded by differences in fertility of the two soils [e.g., mean Mehlich-3 P was 78 Mg kg^{-1} (34.8 t ac^{-1}) for the Willowemoc and 26 Mg kg^{-1} (11.6 t ac^{-1}) for the Onteora], differences in silage corn yield potential [31.3 Mg ha^{-1} (14.0 t ac^{-1}) for Onteora, 22.3 Mg ha^{-1} (10.0 t ac^{-1}) for Willowemoc; NRCS, 2004] and differences in corn varieties (87 vs. 97 day corn).

Corn silage yields from the three simultaneous corn and cover crop treatments (perennial rye grass, red clover and alfalfa) varied relative to the conventional silage corn (control) treatment (Table 1). At both sites, there was no significant difference in silage yield between conventional corn and red clover treatments. At the Onteora site, yields from

Figure 2
Average runoff volume and standard errors as a function of cover crop treatment and day of runoff event for three rainfall-runoff experiments prior to manure application. Letters above columns represent Tukey's mean categories for individual experiments.



the control and perennial rye grass treatments did not differ significantly. However, significantly depressed yields were observed for perennial rye grass at the Willowemoc site and for alfalfa at the Onteora site, suggesting competitive interactions between these cover crops and the growing corn crop. As such, from an agronomic standpoint, red clover, and, to a lesser extent, perennial rye grass, exhibited the greatest potential for adoption. It is likely that reducing the seeding rates of perennial rye grass and alfalfa would reduce competition between these cover crops and the corn, resulting in improved corn yields. Clearly, more research is necessary to determine appropriate seeding rates.

The simultaneous corn and cover crop treatments possessed greater ground cover in both fall and spring sampling periods than did the conventionally cropped corn, even though a substantial weed presence was observed in the control plots of both sites (Table 1). Although winterkill did affect the perennial rye grass and red clover at the both sites, and substantial frost heaving was evident with deep-rooted alfalfa at the Onteora site, all cover crops rapidly re-established themselves in the spring. Some variability in the extent of ground cover was observed between cover crop species. It is well established that legume leaves tend to senesce to a greater extent than grasses as a result of freezing temperatures (Sustainable Agriculture Network, 1998; Hively and Cox, 2001). Not surprisingly, perennial rye grass consistently produced the most extensive cover, while alfalfa produced a comparable ground cover at the Onteora site and red clover consistently produced the least ground cover, particularly in the fall.

Runoff properties prior to manure application. *Runoff volume.* The effect of cover crops on runoff volume varied between sites and with the timing of the rainfall-runoff event. Significantly more runoff was observed from the control than from cover crop treatments in the spring 2001 experiments on the Willowemoc soil and in the fall 2001 experiments on the Onteora soil (Figure 2a and 2b)[2]. Greater runoff volumes from the control than from cover crop treatments likely reflect the effect of surface cover on sealing and infiltration (e.g., Ruan et al., 2001); cover crop canopies afforded increased protection of the soil surface from raindrop impact (Table 1). Differences in runoff observed in spring 2001 and fall 2001 were not apparent in the spring 2002 experiments on the Onteora soil (Figure 2c), due to large deviations in runoff volume within individual treatments as well as elevated antecedent soil moisture (θ = 0.36 m^3 m^{-3}). Although alfalfa plots appeared to generate the least amount of runoff of all cover crop treatments in the Onteora experiments (Figure 2b and 2c), no statistically significant differences in runoff volumes were observed between individual cover crop species for any of the three experiments.

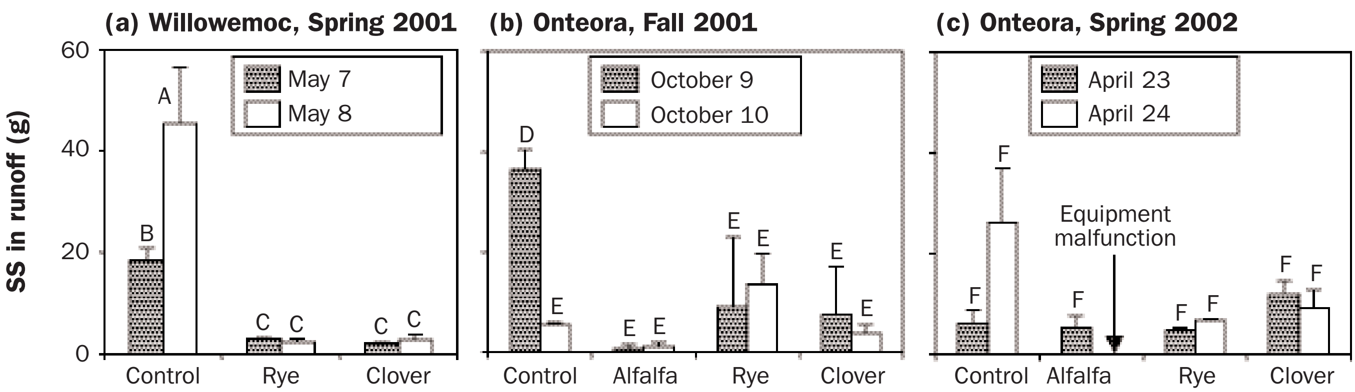
Antecedent soil moisture undoubtedly played a role in differences (or lack thereof) in runoff volume (e.g., Bargar et al., 1999; Needelman et al., 2004). Antecedent moisture increased in both soils and across all treatments from the first to the second day of rain simulations. At the same time, significantly more runoff was generated on the second day of rain simulations than on the first day. Antecedent soil moisture was well below field capacity ($\theta \sim 0.30$ m^3 m^{-3}) at the start of the spring 2001 experiments on the Willowemoc soil (θ = 0.14 m^3 m^{-3}) and the fall 2001 experiments on the Onteora soil (θ = 0.24 m^3 m^{-3}). However, at the beginning of the spring 2002 experiments, the Onteora soil was nearly saturated (θ = 0.36 m^3 m^{-3}). The Onteora soil was located in a foot-slope position where upslope contributions of lateral, subsurface flow likely contributed to a perched water table above the fragipan. In contrast, the moderately well drained Willowemoc soil was located near a summit position, such that lateral flow to the site was not expected to be a substantial contributor to soil moisture. Surface soil saturation due to the accumulation of sub-surface lateral flow at lower landscape positions has been documented in similar soils with prominent fragipans, and is thought to be a key landscape process determining runoff potential in the region (Needelman et al., 2004).

Differences in antecedent soil moisture between the fall 2001 and spring 2002 Onteora experiments also reflect climatic variability. A total of 19 mm (0.75 in) rainfall occurred in the two weeks prior to the fall 2001 experiments whereas 58 mm (2.28 in) of rainfall occurred in the two weeks prior to the spring 2002 experiments. Thus, in spring 2002, infiltration of rainfall into the Onteora soil was largely controlled by climatic and landscape processes affecting soil moisture. As a result, differences in runoff volume between treatments were obscured.

Suspended solids. As expected, cover crops generally reduced suspended solids relative to the conventionally cropped control treatments (Figure 3). Averaged across all experiments (spring 2001, fall 2001, spring 2002), suspended solid loads were significantly greater from control than cover crop plots. However, within individual experiments, some variability was observed. Differences in suspended solid loads between control and cover crop plots were not observed for the

Figure 3

Average suspended solids load in runoff and standard errors as a function of cover crop treatment and time of runoff event prior to manure application. Letters above columns represent Tukey's mean categories for individual experiments.



Onteora soil on the second day of the fall 2001 experiments or for either day of the spring 2002 experiments (Figure 3b and 3c). It is likely that the considerable variability in spring 2002 runoff volumes (Figure 2c) helped to obscure differences in suspended solid loads (Figure 3c). No significant differences in suspended solid load were observed between any of the cover crop treatments. Nor were consistent differences in suspended solid loads observed between the first and second day of rain simulation.

Total P. Total P in runoff was largely a function of erosion, as illustrated by generally strong relationships between total P and suspended solid concentration prior to manure application (Table 4). These relationships indicate that, especially for the Willowemoc experiment and the fall 2001 Onteora experiment, particulate sources of P were the primary source of total P in runoff. The poor regressions derived for the spring 2002 Onteora experiment likely reflect the confounding role of elevated antecedent soil moisture on treatment differences in runoff volume and suspended solid, as described above. As with suspended solid loads, total P loads were generally greater from control plots than from cover cropped plots, although not always so (Figure 4). Average total P loads from Onteora control plots were not greater than from cover crop plots on the second day of the fall 2001 experiments and the first day of the spring 2002 experiments. Even so, differential total P loads from cover crop and control plots in fall 2001 highlight a key benefit of the simultaneous corn and cover crop system: erosion and associated total P losses are already lowered at time of corn harvest due to presence of an established cover crop. Such an immediate benefit would not be expected from traditional, fall-seeded cover cropping systems. Finally, no significant differences in total P loads were observed between cover crop treatments.

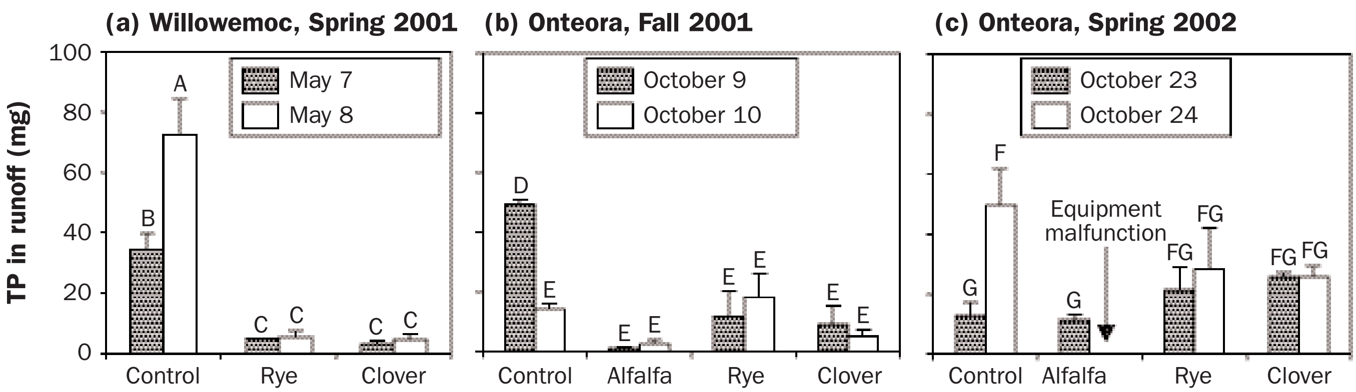
Dissolved reactive P. With the exception of the second day of runoff in fall 2001, loads of dissolved reactive P in runoff generally did not differ significantly between control and cover crop treatments (Figure 5). The similarity in dissolved reactive P loads and concentrations (data not shown) from control and cover crop treatments points to factors other than erosion determining dissolved reactive P concentrations in runoff. For instance, soil P levels (e.g., Mehlich-3 P) have been shown to be strongly related to dissolved reactive P in runoff (Pote et al., 1999). Erosion did significantly affect the relative contribution of dissolved reactive P to total P in runoff. As exhibited in Figure 6, the contribution of dissolved reactive P to total P diminished exponentially as suspended

Table 4. Linear regressions relating total phosphorus and suspended solids concentrations in runoff before and after manure application.

		Regression parameters*			
Site	**Date**	**a**	**b**	**r^2**	**p†**
Before manure application					
Control plots					
Willowemoc	Spring 2001	1.0	1.0	0.66	0.001
Onteora	Fall 2001	1.2	0.2	0.98	< 0.001
Onteora	Spring 2002	0.1	2.1	0.02	0.737
Cover crop plots					
Willowemoc	Spring 2001	1.3	0.3	0.72	< 0.001
Onteora	Fall 2001	1.1	0.1	0.96	< 0.001
Onteora	Spring 2002	1.1	0.6	0.38	0.011
After manure application					
Control plots					
Willowemoc	Spring 2001	7.3	0.5	0.47	0.014
Onteora	Fall 2001	3.5	0.2	0.48	0.057
Onteora	Spring 2002	4.9	3.1	0.17	0.308
Cover crop plots					
Willowemoc	Spring 2001	8.6	2.4	0.64	< 0.001
Onteora	Fall 2001	7.0	0.1	0.94	< 0.001
Onteora	Spring 2002	11.1	4.4	0.16	0.054

* TP = aSS + b.
† ANOVA p-value.

Figure 4
Average total phosphorus load in runoff from plots as a function of cover crop treatment and time of runoff event prior to manure application. Letters above columns represent Tukey's mean categories for individual experiments.



solid concentration increased. Here, concentration data (mg L^{-1} or g L^{-1}) are used rather than loads (mg or g) as P sorption/desorption mechanisms are largely a function of concentrations in solution. Sharpley et al. (1981) reported similar findings, reasoning that the decline in dissolved P fractions resulted from sorption of dissolved P by sediments during runoff. It is likely that the trend observed in our study also reflects a greater contribution of P-enriched soil particles to total P in runoff with greater suspended solid concentrations (e.g., runoff from bare soils in control plots). The generally higher relative contribution of dissolved reactive P to total P from cover crop soils can be seen to the left of each graph, corresponding to lower suspended solid concentrations.

The poor relationship between dissolved reactive P total P^{-1} and suspended solid for the spring 2002 experiments on the Onteora soil (Figure 6c) is associated with elevated levels of dissolved reactive P in runoff at this time when compared with runoff concentrations from the same site the previous fall. In spring 2002, runoff dissolved reactive P concentrations from many Onteora plots exceeded those expected from soils with similar Mehlich-3 P (11 to 40 mg kg^{-1}). In a recent literature review of 16 rain simulation studies that related Mehlich-3 P to dissolved P in runoff, Vadas et al. (2005) found that runoff dissolved reactive P from soils with Mehlich-3 P less than 50 mg kg^{-1} did not exceed 0.8 mg L^{-1}. In spring 2002, runoff dissolved reactive P concentrations from some of the Onteora plots approached 2.0 mg L^{-1}. In contrast, dissolved reactive P concentrations in fall 2001 fell within the range of those reviewed by Vadas et al. (2005) with similar Mehlich-3 P concentrations.

Two potential sources of the elevated dissolved reactive P concentrations and associated loads in the spring 2002 runoff are vegetation and soil oxidation-reduction fluctuations. Vegetation can release significant quantities of dissolved reactive P to water, particularly when cells are lysed by senescence or freezing and thawing (Sharpley, 1981). Indeed, there is concern in several Scandinavian countries that over-wintered cover crops (locally referred to as catch crops) create an additional source of P to runoff. Uhlen (1989) in Norway and Ulén (1997) in Sweden have shown that the concentration of P in runoff from areas with cover crops may increase significantly when the crop is frozen. Recent research by Bechmann et al. (2005) showed that the concentration of dissolved reactive P in runoff from rye grass cover was appreciably greater after repeated freezing and thawing (9.72 mg L^{-1}) than before (0.06 mg L^{-1}), and greater than that from bare frozen soil (0.10 mg L^{-1}). In these countries recommendations are being established for catch or cover crop use so that P loss, as well as erosion, is

Figure 5
Average dissolved reactive phosphorus load in runoff from plots as a function of cover crop treatment, location and time of runoff event prior to manure application. Letters above columns represent Tukey's mean categories for invidiual experiments.

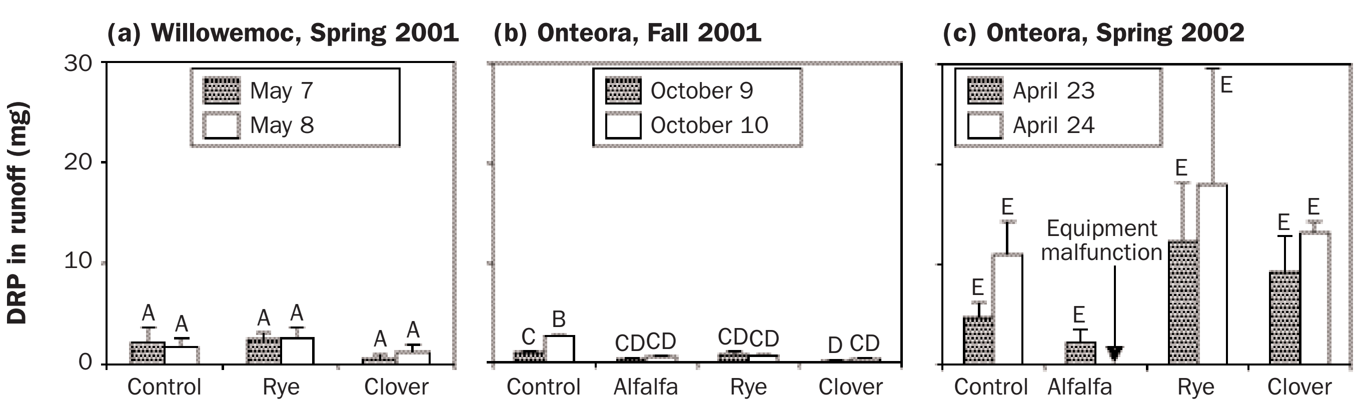
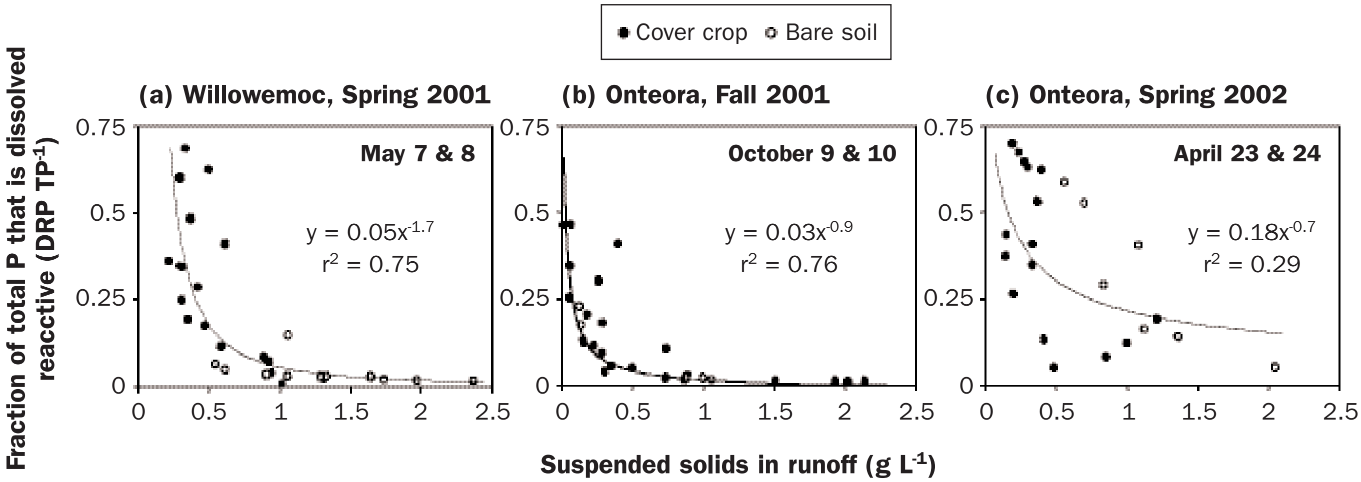


Figure 6

Relationship of fraction of total phosphorus that is dissolved reactive (DRP TP^{-1}) with suspended solids in runoff from bare soil and cover crop plots prior to manure application.



minimized. This involves the ultimate management of the cover crop; either left in place, plowed in the soil, or harvested (to "catch" and remove P from high P testing soils).

In the present study, it is unlikely that the cover crops were a significant contributor because the highest concentrations of dissolved reactive P were observed in runoff from the control plots. A more likely explanation is that the near-saturated moisture conditions were associated with the reduction of soils in spring 2002. Onteora soils possess prominent color mottles within 25 cm (9.8 in) of the soil surface—an indicator of seasonal reduction at shallow depths. Greater mobilization of P under reducing conditions following soil moisture saturation has been widely reported (e.g., Jensen et al., 1998). Reduction of iron (Fe) from the ferric (Fe^{3+}) to ferrous (Fe^{2+}) state causes dissolution of Fe-phosphates. Kleinman et al. (2000) identified Fe as a key control of P solubility in these soils. Thus, it is likely that reduction of the soils exacerbated runoff dissolved reactive P concentrations in spring 2002, influencing the relatively high contribution of dissolved reactive P to total P in runoff.

Runoff properties following manure application. *Increasing role of dissolved reactive P in runoff losses.* Broadcasting dairy manure to soils over-rode differences in runoff P between control and cover crop treatments observed in the initial rainfall simulation experiments prior to manure application (Figures 7 and 8). Relative trends in runoff P properties after manure was applied were consistent across sites (Willowemoc vs. Onteora) and over time (Onteora fall vs. Onteora spring). Significant increases in runoff P (dissolved reactive P and total P) loads were observed for most cropping treatments when compared to before manure application, with no discernable differences between treatments after manure was applied. Notably, runoff total P loads after manure application did not differ significantly from before manure application for the conventional silage corn treatment for the Willowemoc (Figure 8a) and spring 2000 Onteora (Figure 8c) experiments. This highlights the large losses of P from conventional silage corn prior to the application manure, as described above (see also, Figure 4).

Much of the increase in runoff P observed

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Figure 7

Average dissolved reactive phosphorus load in runoff from plots as a function of cover crop treatment and location before and after manure application. Letters above columns represent Tukey's mean categories for individual experiments.

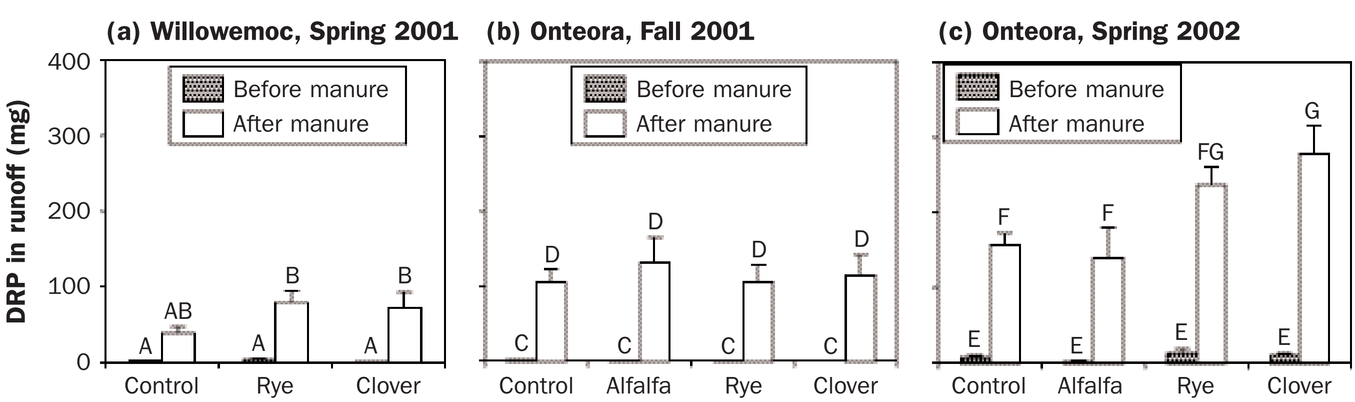
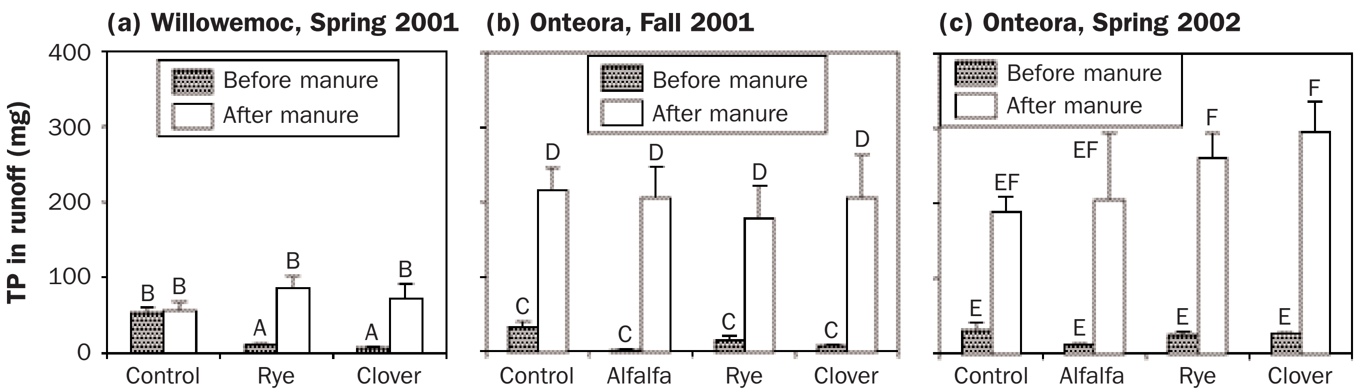


Figure 8

Average total phosphorus load in runoff from plots as a function of cover crop treatment and location before and after manure application. Letters above columns represent Tukey's mean categories for individual experiments.



after manure was applied was related to augmented dissolved reactive P, with dissolved reactive P accounting for an average of 91, 59, and 83 percent of total P in the spring 2001, fall 2001, and spring 2002 experiments. Across all experiments, the proportion of total P that was dissolved reactive P increased from 28 percent before manure application to 78 percent after manure application. The elevated concentration of dissolved reactive P in runoff can be attributed to high concentrations of water extractable P in the applied manures. Water extractable P in manure is well established as an indicator of potential dissolved P loss in runoff from soils broadcast with manure (Moore et al., 2000; Kleinman et al., 2002b). As summarized in Table 3, the majority of P applied in manure was water extractable, equivalent to 73, 59, and 66 percent of total manure P in the spring 2001, fall 2001, and spring 2002 experiments, respectively.

Erosion of manure solids. Manure solids can be associated with large amounts of water extractable and particulate P (Hill and Baier, 2000; Vadas et al., 2004). Consequently, erosion of manure solids was moderately to strongly correlated with total P in runoff from the Willowemoc experiment in spring 2001 and from the Onteora experiment in fall 2001 (Table 4). Notably, coefficients of determination for these two experiments were not as strong after manure was applied as

Table 5. Average runoff volume and suspended solids loads in runoff from plots following dairy manure application.

			Willowemoc		Onteora			
		Manure Applic. rate	May 2001		October 2001		May 2002	
Treatment	N	kg TP ha^{-1}	Day 1*	Day 2	Day 1	Day 2	Day 1	Day 2
Runoff (L)								
Control	2	50	9.8 (9.0)†	22.2 (12.2)	29.6 (8.0)	37 (1.0)	38.8 (6.2)	39.6 (2.6)
Control	2	100	2.4 (0.6)	4.4 (1.0)	25.8 (1.2)	29.8 (3.4)	15.8 (4.6)	15.8 (2.0)
Alfalfa	2	50	NA	NA	16.6 (2.8)	23.6 (15.2)	24.4 (5.8)	17.8 (3.6)
Alfalfa	2	100	NA	NA	21.0 (4.4)	27.2 (12.2)	14.4 (5.0)	21.2 (14.0)
Rye	2	50	5.8	13.8	12.2 (6.0)	21.8 (20.0)	38.4 (4.0)	37.6 (7.4)
Rye	2	100	5.0	11.6	19.2 (4.2)	22.2 (3.2)	22.6 (6.6)	24.8 (12.4)
Clover	2	50	4.6 (1.0)	16.2 (16.2)	15.8 (1.0)	12.2 (2.4)	29.4 (4.0)	38.6 (3.2)
Clover	2	100	2.8 (2.4)	6.6 (9.4)	21.8 (7.0)	22.6 (12.8)	18.2 (4.6)	26.8 (11.6)
Suspended solids (g)								
Control	2	50	12.0 (10.9)	18.5 (12.1)	60.0 (4.9)	48.5 (10.0)	34.3 (4.1)	32.9 (4.9)
Control	2	100	3.1 (1.3)	4.0 (0.5)	78.7 (5.3)	49.8 (6.3)	14.6 (0.5)	14.9 (0.1)
Alfalfa	2	50	NA	NA	19.7 (16.1)	15.9 (6.3)	13.5 (1.9)	9.1 (0.9)
Alfalfa	2	100	NA	NA	48.1 (0.6)	41.7 (14.0)	10.3 (3.9)	12.3 (9.9)
Rye	2	50	3.6	3.3	12.1 (5.5)	11.3 (9.4)	9.4 (4.0)	10.1 (0.9)
Rye	2	100	1.2	8.0	42.4 (20.4)	23.2 (6.3)	14.2 (3.7)	14.9 (3.2)
Clover	2	50	3.1 (0.6)	9.5 (10.0)	18.9 (4.7)	5.9 (1.1)	7.5 (3.0)	11.2 (0.7)
Clover	2	100	3.2 (4.3)	3.9	55.6 (21.5)	39.6 (22.7)	12.0 (8.4)	11.4 (5.4)

* **Day number refers to sequence of rain simulation events in each of the three experiments.**
† **Standard deviations are presented in parentheses.**
NA = data not available.

Table 6. Average dissolved reactive phosphorus concentrations and loads in runoff from plots following dairy manure application.

			Willowemoc		Onteora			
		Manure Applic. rate	May 2001		October 2001		May 2002	
Treatment	N	kg TP ha^{-1}	Day 1†	Day 2	Day 1	Day 2	Day 1	Day 2
Dissolved reactive P concentration (mg L^{-1})								
Control	2	50	4.8 (1.2)‡	2.7 (1.1)	1.6 (0.5)	1.8 (0.2)	5.5 (0.5)	4.2 (0.5)
Control	2	100	9.9 (1.9)	8.5 (2.2)	6.3 (0.5)	4.7 (0.4)	8.1 (0.8)	7.6 (1.0)
Alfalfa	2	50	—¥	—	4.4 (2.8)	2.5 (0.9)	5.2 (2.9)	4.0 (2.2)
Alfalfa	2	100	—	—	11.2 (3.1)	5.6 (0.1)	8.5 (4.1)	8.3 (5.2)
Rye	2	50	4.8	5.5	4.8 (1.3)	2.7 (0.5)	6.4 (1.4)	5.2 (1.3)
Rye	2	100	6.7	8.2	8.8 (1.6)	5.9 (0.6)	11.6 (0.1)	9.4 (0.5)
Clover	2	50	6.9 (2.7)	6.2 (2.3)	5.0 (1.2)	2.4 (0.2)	7.7 (0.7)	6.4 (0.2)
Clover	2	100	8.4 (5.3)	11.3	9.5 (0.4)	6.1 (0.2)	15.5 (4.7)	12.7 (1.6)
Dissolved reactive P load (mg)								
Control	2	50	41 (30)	67 (58)	49 (28)	68 (9)	211 (16)	168 (33)
Control	2	100	24 (9)	36 (0)	162 (4)	138 (4)	126 (50)	121 (32)
Alfalfa	2	50	—	—	78 (60)	51 (16)	135 (102)	75 (54)
Alfalfa	2	100	—	—	241 (115)	152 (66)	133 (104)	212 (226)
Rye	2	50	28	76	54 (13)	63 (64)	245 (34)	200 (89)
Rye	2	100	33	95	172 (69)	132 (33)	264 (77)	235 (128)
Clover	2	50	31 (6)	119 (139)	78 (24)	29 (4)	225 (11)	246 (30)
Clover	2	100	30 (35)	150	208 (77)	137 (75)	293 (156)	348 (192)

† Day number refers to sequence of rain simulation events in each of the three experiments.

‡ Standard deviations are presented in parentheses.

¥ No data due to equipment malfunction.

before application, reflecting the changing role of erosion in P transport and the fact that substantial amounts of water extractable P are not associated with manure solids. Poor relationships were observed between total P and suspended solid for the Onteora experiment in spring 2002 when soil moisture was at or near saturation, consistent with the poor relationships observed between these variable prior to manure application.

Application of manure changed the relationship of runoff total P and suspended solid concentrations relative to runoff from unmanured plots (Table 4). This represents a shift from erosion of soil particles to erosion of manure solids. Following manure application, regression slopes increased significantly, indicating that eroded materials (i.e., manure) were associated with greater concentrations of total P than prior to manure application, when eroded solids consisted primarily of soil. Regression slopes appeared to be greater for cover crop plots than for control plots after manure was applied, but were found to be statistically similar when analyzed by homogeneity of variance test. The lack of significant differences in regression slopes between treatments, as well as the absence of statistically significant differences in total P losses from conventional and cover cropped treatments after manure application (Figure 8) support the conclusion that individual cover crops had little effect on the nature of manure P loss in runoff.

Manure application rate effects. Runoff P losses were greatly influenced by manure application rate, although different effects of rate on runoff volume (Table 5) and dissolved reactive P concentrations produced variable trends in dissolved reactive P concentrations and loads (Table 6). Broadcasting dairy manure at a rate of 100 kg total P ha^{-1} resulted in significantly higher concentrations of runoff dissolved reactive P than did application of 50 kg total P ha^{-1} (45 lb ac^{-1}). These results are consistent with those of previous studies that have described quantitative associations between manure application rate and P in runoff (e.g., Edwards and Daniel, 1993a; 1993b). However, dissolved reactive P loads from plots spread with dairy manure at 100 kg total P ha^{-1} (89 lb P ac^{-1}) were sometimes equivalent, or even lower, than those from plots spread at 50 kg total P ha^{-1} (45 lb P ac^{-1}). This was associated with a general trend in declining runoff volumes with increasing application rate (Table 5). In fact, runoff volumes were significantly greater from the 50 kg total P ha^{-1} (45 lb P ac^{-1}) plots, than from the 100 kg total P ha^{-1} (89 lb P ac^{-1}) plots in the Willowemoc experiment and the Onteora spring 2002 experiment. Elsewhere, McDowell and Sharpley (2003) reported similar findings where dairy manure applications of less than 50 kg total P ha^{-1} (45 lb P ac^{-1}) imparted physical benefits to the soil, which decreased particulate P and total P loss potential compared to unmanured soil. This benefit was attributed to the addition of labile organic carbohydrates in manure that cause soil particles to bind together and reduce runoff and erosion (McDowell and Sharpley, 2003).

Summary and Conclusion

This study evaluated the benefits of a novel cover cropping system in controlling P loss from two soils under silage corn production. Agronomically, the simultaneous corn and cover crop system produced corn silage yields that were comparable to those obtained under conventional management when red clover, and, to a lesser extent, perennial rye grass were inter-seeded with corn. This study clearly highlights the potential water quality benefits of the simultaneous corn and cover crop system, even in the fall immediately after corn harvest when traditional, relay-cropped cover crops would not yet be established. Prior to manure application, cover crops functioned to decrease surface runoff and soil erosion. At that time, differences in runoff and erosion resulted in lower total P losses from cover cropped soils than from conventionally cropped (control) soils. Although greater concentrations of eroded sediments were associated with lower dissolved reactive P concentrations in runoff, and some studies had found cover crop vegetation to contribute to dissolved P in runoff, no significant influence of cover crops on runoff dissolved reactive P losses was detected prior to manure application.

Broadcasting manure to conventional and cover crop treatments resulted in large increases in runoff dissolved reactive P losses, which, for the cover crops, corresponded with large increases in total P losses. Application of manure had less of an effect on total P losses from the conventional silage corn treatment, as losses were already great prior to manure application due to high rates of erosion. Because manure application rate was positively related to runoff P losses, results support the widely-held conclusion that managing manure application rate is important to controlling losses of P in runoff. In as much as the simultaneous corn and cover crop system provides an opportunity to establish leguminous cover crops (especially red clover, which performed the most favorably in terms of combined agronomic and water quality benefits), it is possible that this system could reduce the agronomic recommendation for manure N over time, justifying lower manure application rates than for conventional silage corn or non-leguminous cover crops. Thus, the simultaneous corn and cover crop system, combined with prudent manure management, shows great potential in limiting non-point source P pollution from corn silage fields in the northeastern United States.

Endnotes

[1]Mention of trade names does not imply endorsement by the U.S. Department of Agriculture.

[2]Note that Tukey's mean categories presented in figures are not intended for comparison between Willowemoc and Onteora fall and spring experiments.

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