Precision feeding and forage management effects on phosphorus loss modeled at a watershed scale

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Abstract: Delaware County and the Cornell Cooperative Extension of Delaware County of New York State have initiated a farm-scale precision feed management (PFM) program to reduce soil-phosphorus build-up and phosphorus (P) losses to the Cannonsville Reservoir, a major supply source of New York City drinking water. The PFM program includes strategies that more precisely balance dairy cattle dietary P requirements with actual P intake and that improve on-farm forage production and utilization in the animal diet. The goal of the PFM program is to reduce manure P concentration, feed nutrients importation, P imbalance problems, and soil-P build-up while maintaining farm profitability. In this study, several PFM strategies were evaluated with respect to controlling P losses and soil-P build-up at both field and watershed scales using the Soil and Water Assessment Tool (SWAT) model. Using the SWAT model, manure with reduced P concentration was applied to cropland while grass-forage crop productivity was increased through N fertilizer application. The SWAT model simulation revealed decreased particulate phosphorus and soluble phosphorus losses by 22% and 13%, respectively. Predicted reductions of average particulate phosphorus and soluble phosphorus losses at the watershed outlet were 16% and 13% respectively, over a three-year period, compared to the baseline (conditions before changes were implemented). Model results also demonstrated an appreciable decrease in field-level soil-P during the growing season, indicating increased soil-P uptake by the improved grass-forage. For the growing season, reductions for predicted active and labile P pools were 11 and 5 mg kg^{-1} (0.02 and 0.01 lb tn^{-1}), respectively, compared to the baseline. The corresponding reductions in field-level soil P were equivalent to 8% and 7% for labile and active P pools, respectively. Overall, the PFM strategies were found to have a potential for reducing soil-P build-up and P losses both at field and watershed levels. Performing a model-based environmental evaluation of farm management strategies at a watershed level helps to integrate farm management planning (the smallest management unit) into watershed level planning. Also, evaluating farm management strategies at a watershed scale provides valuable and comprehensive information for assessing the potential for long-term, cost-effective, and permanent reduction of P loss from dairy agriculture to the Cannonsville Reservoir.

Key words: phosphorus loss—precision feed management—simulation—soil phosphorus—Soil and Water Assessment Tool (SWAT)

Major concerns remain regarding continuing phosphorus (P) inputs to the Cannonsville reservoir, a major water supply source for New York City. Historically, the reservoir has experienced eutrophication problems caused by excess P loading from agriculture, mainly dairy farming, within the Cannonsville Reservoir Watershed (CRW) (Delaware County Watershed Affairs 2002). The impairment of the reservoir is also believed to be exacerbated by continuous soil-P build-up (Tolson and Shoemaker 2003) which, in turn, is caused by the imbalance between farm P imports and P exports (Wang et al. 1999). An increasing number of New York farm fields have tested high and very high in soil P over the past 20 years, with currently almost 50% of agricultural fields testing medium high or high in soil P (Ketterings et al. 2005).

Many dairy herds in the study area are still fed dietary P levels that are 25% larger than the published National Research Council recommendations (National Research Council 2001; Dou et al. 2003). Moreover, grassland in northeastern US is underutilized, in that it is not managed intensively and does not produce high yields. Average grass yield for New York from 2002 to 2005 was 5.8 t dry matter (DM) ha^{-1} (2.6 tn DM ac^{-1}) (USDA National Agricultural Statistics Service 2005) and grass yield for southeastern New York, including Delaware County, was 6 t DM ha^{-1} (2.7 tn DM ac^{-1}) (Knoblauch et al. 2005). When forage production of a farm is low, more purchased feed supplement is required to satisfy animal feed needs. Northeastern US farming operations often import feed grain and supplements from the midwestern US. This one-way transfer of nutrients and excess feeding of dietary P increases P imbalance, as P imports in purchased feed and fertilizers quickly exceed P exports in milk, meat, or off-farm sales of harvested crops. For typical New York dairy farms, purchased animal feeds account for 65% to 85% of P imported annually (Tylutki and Fox 1997; Cerosaletti et al. 1998). Additionally, studies by Rotz et al. (2002) and Cerosaletti et al. (2004) reported 42% to 63% excess of imported over exported P on CRW farms. These P excesses likely increase the accumulation of soil-P in the CRW.

Management strategies, collectively called best management practices (BMPs), for reducing P losses from agricultural land to water bodies focus mainly on managing the source and transport of P (Novotny and Olem 1994). The source management strategies attempt to minimize accumulation of P at the soil surface by controlling the amount of P in manure and fertilizers applied to the agricultural land. The transport management strategies are efforts that interfere with P movement from soil to water bodies through runoff, leaching, and erosion. Runoff, leach-

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ing, and erosion control practices include conservation tillage, crop rotation, crop residue management, terraces, buffer strips, filter strips, riparian buffers, cover crops, and others. Recent studies (Sharpley et al. 2007; George et al. 2008) have emphasized the importance of implementing comprehensive P management strategies that primarily begins with precisely balancing dietary P in animal production, which eventually translates to less manure P to manage.

Currently, the Watershed Agricultural Program of the New York City watersheds implements BMPs through a 100% cost share program to address the P-related impairment of the Cannonsville Reservoir (Walter and Walter 1999; Delaware County Watershed Affairs 2002). The BMP strategies, mainly structural or management based, while expected to be effective in controlling off-field P losses, do not address long-term, on-farm P imbalances. Over time, the effectiveness of such BMPs may also be limited as soil-P build-up continues.

Efforts to address the problem of P imbalance led to development of the Precision Feed Management (PFM) program by the Cornell Cooperative Extension of Delaware County. The PFM program is a whole-farm-scale set of BMPs that directly addresses the farm P imbalance problem by reducing excess dietary P to match the National Research Council (2001) recommendations and by improving on-farm forage production and utilization in the animal diet. These farm-scale BMPs work together to reduce purchased feed and P imports to a farm, reduce manure P, and ultimately reduce P loss in runoff. In addition, the PFM program involves forage land use management to control potential generation of erosion and associated P losses and tries to enhance farm economic returns to improve farm viability. Implementation of one PFM component, precision feeding of dietary P, on two pilot CRW farms resulted in reduced P imbalance (Cerosaletti et al. 2004).

Testing of various PFM strategies on actual farms may be impractical, taking years or enormous quantities of resources. Hence, the importance of using models comes in to play. Ghebremichael et al. (2007) used a whole-farm, model-based method, including the Integrated Farm System Model (IFSM) (Rotz and Coiner 2006), to quantitatively assess farm-level profitability and P imbalance and loss changes as a result of implementing various PFM strategies on the two pilot farms. However, IFSM-predicted P losses only represent total potential off-farm P losses. When fields of a farm are located in different hydrologic drainage units, predicted off-farm P losses provided by IFSM do not drain to the same stream or outlet. In such cases, the effects of different fields can only be seen by evaluating hydrological subbasins separately. Hence, IFSM-predicted water quality related effects, such as P losses, from implementing farm plan strategies are hard to interpret on an actual landscape basis and on specific stream segments. That is, from IFSM-predicted data it is hard to know how much of the off-farm pollutant losses will actually affect the water quality of a certain stream or stream segment. As part of the comprehensive assessment of PFM strategies to support the ongoing PFM project, watershed-level quantification of P loss impacts of these farm-level PFM strategies on water quality is required.

Moreover, farm-level modeling studies are important for evaluating farm planning strategies for their economic and environmental impacts for a farm enterprise. There are, however, limited studies available that have assessed impacts of such farm-level planning within a watershed context. Quantification of environmental impacts of various BMP strategies is also important for watershed-based water quality assessment studies, such as those required under the total maximum daily load program. Additionally, there is growing interest through the national Conservation Effects Assessment Project to quantitatively establish BMP impacts at the watershed scale. Therefore, the objectives of this study were to assess benefits of farm-level PFM strategies at a watershed scale by evaluating field- and watershed-level effects of these farm-level BMPs on water quality using a watershed-scale model. Three PFM-based farm scenarios were represented in the Soil and Water Assessment Tool (SWAT) (Neitsch et al. 2002a), and the model was used to quantitatively assess the relative effectiveness of the PFM-based farm plans with regard to controlling P, both at field and watershed scales.

Materials and Methods

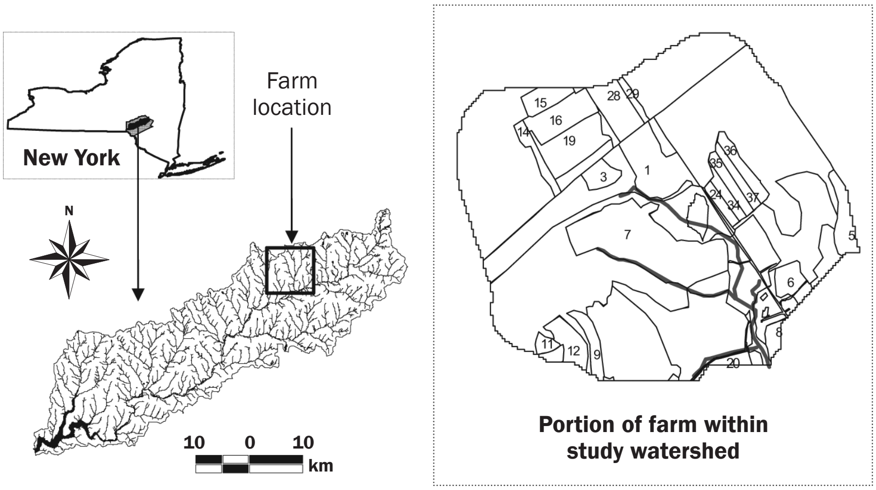
Soil and Water Assessment Tool Description. The SWAT model is a hydrologic and pollutant model developed by the USDA Agricultural Research Service (Neitsch et al. 2002a). The SWAT is a process-based, distributed, and continuous daily time-step watershed model that simulates the transport of sediment, runoff, nutrients, and pesticides as a function of land use at subwatershed and watershed scales. It has a long history of use in hydrologic watershed response and in the study of land management impacts on water quantity and quality. Summaries of over 250 peer-reviewed SWAT publications are presented in Borah and Bera (2004) and Gassman et al. (2007). The SWAT is one of the two models of choice within the USDA Agricultural Research Service for evaluating the effects of land use and climate on water resources. The SWAT model and its associated geographic information system interface have been integrated into the US Environmental Protection Agency's modeling framework of Better Assessment Science Integrating Point and Non-Point Sources, which is being used in several states for total maximum daily load analysis (Di Luzio et al. 2002).

The SWAT model allows a watershed to be divided into subbasins based on topographic criteria, with further subdivision of subbasins into hydrologic response units (HRUs) based on land use and soil type. In order to simplify SWAT runs, areas of a particular land use and soil type within a subbasin are normally combined together to form one HRU without consideration to individual fields and their spatial locations. However, with some modification to typical SWAT model input data, individual fields can be distinctly represented in the SWAT modeling process. The distinct representation of fields is useful during the process of HRU formation to avoid lumping of similar land use and soil combinations of different fields within a subbasin into one HRU. Runoff quantities and associated sediment and nutrient loadings that are distinct to each field can then be extracted from the outputs of HRUs. This allows better investigation and assessment of field-specific management practices.

Phosphorus may be added to the soil by fertilizer, manure, or residue application. The SWAT model represents P dynamics using six pools: three organic P pools (fresh [associated with crop residue], active, and stable [the latter two are associated with humus]) and three inorganic P pools (labile [solution], active, and stable). Neitsch et al. (2002a) details the various soil-P pools and interac-

Figure 1

General location of single-farm study watershed within the Cannonsville Reservoir Watershed, New York.



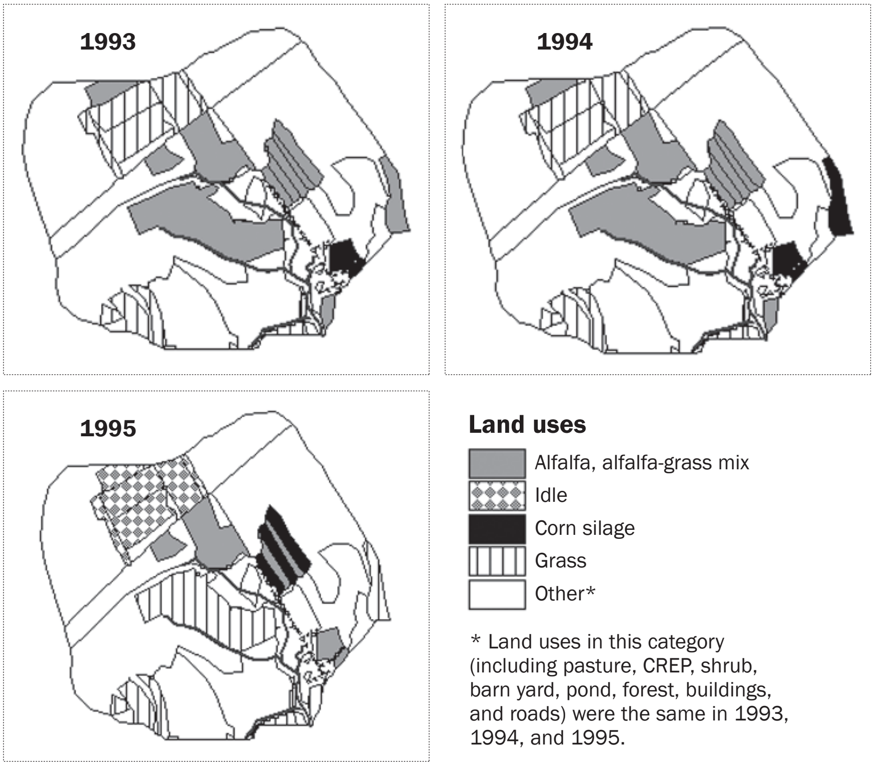
tions represented in SWAT. The organic P forms transform into inorganic P forms through the process of mineralization. Most of the mineral and organic P occurs in its adsorbed form. The inorganic P in the labile pool is in rapid equilibrium (several days or weeks) with the active pool. The active pool is in slow equilibrium with the stable pool. Phosphorus removed from the soil by plant uptake and runoff losses is taken from the labile P pool. The model estimates plant use of P using the supply and demand approach (Williams et al. 1984). Daily plant demand is estimated as a function of plant biomass and biomass P concentration. Depending on total plant biomass grown, or yield rate, the mass of P stored in plant biomass for each growth stage and the necessary plant uptake of P are determined. The SWAT model simulates crop growth and crop uptake of P for specified management, soil, and weather conditions. It also simulates soluble P (SolP) removed from the soil via runoff and particulate P (PP) removed with erosion. Using the SWAT model, the effects of varying concentrations of manure P on the amount of P loss and water quality can be evaluated.

Study Watershed and Data. The study watershed (~163 ha [403 ac]) is located in the headwaters of the CRW, Delaware County, New York (figure 1). Elevations of the farm watershed range from 601 to 735 m (1,972 to 2,411 ft) above mean sea level. The climate of the area is characterized as humid continental with an average annual temperature of about 8°C (46.4° F) and precipitation of approximately 107 cm y^{-1} (42 in yr^{-1}) (20-year average). The watershed encompasses a single 102-cow dairy farm. Seventy-one hectares of the total 120 ha (297 ac) agricultural land of the farm is located within the study watershed, and the remaining 49 ha (121 ac) agricultural land of the farm is located outside of the study watershed. The farm produces grass and alfalfa forages and corn silage and imports feed concentrate supplements to support dairy production.

The study farm watershed has been the site of considerable water quality related research. In 1993, a sampling station was established at the outlet of the watershed as part of a paired watershed experiment (Bishop et al. 2005) designed to evaluate the effect of BMPs implemented in the farm by the Watershed Agricultural Program. The BMPs implemented in the farm included strip cropping, crop rotations, filter strips, and barnyard paving. In 2005, Gitau and Gburek (2005) applied SWAT to the farm watershed to assess the applicability of SWAT in modeling impacts of BMPs at a watershed scale. In doing so, Gitau and Gburek calibrated the SWAT model to this watershed with respect to stream flow, sediment, and P losses for the period before the BMPs were installed (1993 to 1995).

Figure 2

Study watershed baseline land uses and crops for 1993, 1994, and 1995.



* Land uses in this category (including pasture, CREP, shrub, barn yard, pond, forest, buildings, and roads) were the same in 1993, 1994, and 1995.

One measure of prediction strength commonly used when calibrating watershed-level hydrologic and water quality models is the Nash-Sutcliffe statistic (NS) (Martinez and Rango 1989). Nash-Sutcliffe statistic values range from negative infinity to one, with values of NS close to 1 indicating improved model performance and a value of zero indicating that the simulated values provide no better prediction than the mean of observed values. The NS can be calculated on a daily, monthly, or yearly scale. A review of the watershed-level, water quality modeling literature by Morasai et al. (2007) found values of NS > 0.50 were generally considered satisfactory with median monthly NS values across the reviewed calibration literature of 0.79, 0.76, and 0.51 for stream flow, sediment load, and total P, respectively. In the study by Gitau and Gburek (2005) the pre-BMP period (June 1993 to June 1995) monthly NS values for stream flow, sediment load, dissolved P, and total P were 0.86, 0.40, 0.60, and 0.62, respectively. The calibrated model by Gitau and Gburek (2005) was used in the current study as a baseline from which to predict the effect of changes in farm management on hydrologic, sediment, and nutrient responses.

For representing the baseline conditions in the SWAT model, 10-m (32.8-ft) topographic and land use data of the farm watershed were used. Precipitation and temperature data were taken from the Delhi, New York meteorological station (Delhi 2 SE COOP-WBAN ID: 302036-99999). Hydrologic response units were defined by considering individual fields as distinct units. This entailed assigning field-distinct land use names to each field to avoid lumping of fields that have the same land use (Gitau and Gburek 2005). As a result of such a representation, detailed field-level management data including crop rotations (figure 2), planting, harvesting, tillage, and manure application were represented distinctively for each field. Such detailed representation of field boundaries in the process of HRU development also enabled the amount of runoff and associated sediment and nutrient loadings of a particular field to be distinctively derived from the outputs of HRUs that directly represent the individual fields.

Other baseline SWAT input data related to manure application, crop land use types and rotations, harvesting, and grazing information were based on field-by-field data obtained from farm management plans. Crop rotations in 1993 and 1994 (table 1; figure 2) were identical except one alfalfa field (2 ha [5 ac]) in 1993 was planted with corn in 1994. However, several fields rotated crops from 1994 to 1995. For example, some fields that were in alfalfa and alfalfa-grass mix in 1994 were planted with grass in 1995. Two fields planted with corn in 1994 rotated to grass and alfalfa-grass in 1995. Three alfalfa and alfalfa-grass mix fields (totaling 3.4 ha [8.4 ac]) in 1994 were planted with corn in 1995. Some grass, alfalfa and alfalfa-grass mix fields in 1994 were left idle in 1995.

In addition, manure was applied to all agricultural crops, with manure application rates based on field-specific nitrogen (N) requirements determined from the nutrient management plans. Planting or initial growth dates were May 1 for alfalfa, May 15 for corn, May 10 for grass, and May 1 for pasture. The harvest date for corn was October 1. For alfalfa and grass multiple harvests per year were used. Harvest dates for alfalfa were June 1, July 15, and August 25 (for first, second, and third cutting, respectively); harvest dates for grass were May 20, July 1, and August 15 (for first, second, and third cutting, respectively).

Table 1
Land uses within the study farm watershed for three study years.

	Land use area (ha)		
	1993	**1994**	**1995**
Alfalfa and alfalfa-grass mix	27.3	25.3	9.5
Land under CREP	6.0	6.0	6.0
Corn silage	1.6	3.6	3.4
Idle land	0.0	0.0	13.0
Barn yard	0.1	0.1	0.1
Forest	80.8	80.8	80.8
Grass	15.9	15.9	18.9
Pasture	26.2	26.2	26.2
Pond	1.0	1.0	1.0
Shrub	1.1	1.1	1.1
Building/roads	2.7	2.7	2.7
Total watershed area	162.7	162.7	162.7

Table 2
Alternative precision feed management scenarios evaluated.

Scenario	Description
Baseline	1993 to 1995 conditions before any precision feed management changes
Scenario 1	Reduced manure P concentrations, as a result of dietary P reductions
Scenario 2	Scenario 1 + increased grass productivity
Scenario 3	Scenario 2 + 100% corn land converted to high yielding grass

Baseline. SWAT representation of the study watershed and predictions of hydrology and nutrient losses for the period of 1993 to 1995 were previously performed by Gitau and Gburek (2005). Their calibrated model representation of the watershed was used in this study to represent the baseline condition and was assumed to be adequate as a baseline to assess relative effects of management changes on the water quality response of the watershed.

Scenario 1. Scenario 1 involved adoption of reduced dietary P to match the National Research Council (2001) diet P recommendations. When dietary P contents of cows are changed, both total and water-soluble P contents of manure are expected to change (Satter and Wu 1999; Dou et al. 2002; Ebeling et al. 2002; Cerosaletti et al. 2004). Manure application to the agricultural land containing less P subsequently reduces runoff P concentration (Ebeling et al. 2002).

Manure P concentrations used in the SWAT scenario 1 representation were reduced from the baseline to reflect dietary P intake reductions, which translated into reduced P concentration in manure. To use the SWAT model to evaluate changes of dietary P on P runoff losses in a given watershed, information was required on the concentrations of different P forms in the manure produced within the watershed for the prescribed dietary P levels. For this study farm under the existing farm management scenario, the average dietary P content was found to be 22% above the levels recommended by the National Research Council. Because the study watershed encompasses a single dairy farm, data were obtained from a previous study (Ghebremichael et al. 2007) that employed IFSM on this dairy farm to determine the change in the manure P content as a result of feeding cows a reduced dietary P. Based on the IFSM simulation study, a 22% reduction of excess dietary P resulted in a 25% reduction of P content in the manure produced. Hence, a 25% reduction of baseline manure P for both mineral and organic forms was used for this scenario 1. The mineral P to organic P ratio in manure was, however, kept the same as the baseline condition.

Scenario 2. Scenario 2 increased forage productivity in addition to adjustment of dietary feed P to the prescribed National Research Council level (scenario 1). The increased forage production and utilization component of the PFM strategy involved increasing the yield of forage produced on farm for utilization in animal diets. The objective for increasing forage productivity was to decrease the farm's dependence on purchased feeds in dairy production. Reducing farm P imports over the long-term could decrease subsequent soil-P build-up on the agricultural fields.

For proper SWAT representation of this scenario, firstly, the manure P concentrations were adjusted to reflect the balanced P diet and, secondly, the simulated grass crop yield was increased. According to P.E. Cerosaletti, a local farm planner, an average grass yield increase of 2 t ha^{-1} (0.9 tn ac^{-1}) was considered an attainable goal for this farm (personal communication, September 2006). Fields with grass land use type were selected for increasing yields. The total grass areas increased in yield within the study watershed were 15.9 ha (39.3 ac), 15.9 ha (39.3 ac), and 18.9 ha (46.7 ac) for the respective crop years of 1993, 1994, and 1995 (table 1; figure 2).

Assuming that there are no constraints (such as rain, soil-P, and others) in increasing grass productivity, grass yield can typically be increased by adding additional N fertilizer. New York farm fields have high soil-P (Ketterings et al. 2005), hence availability of soil-P is not presumed to be a limiting factor for increasing grass productivity. In the SWAT modeling of scenario 2, an additional 150 kg ha^{-1} (134 lb ac^{-1}) of elemental N fertilizer was applied to the baseline grass fields to attain increased prescribed forage production. The 150 kg N ha^{-1} was split and applied equally before plant emergence and after first forage harvesting. The increased 150 kg ha^{-1} N application rate was found by performing iterative SWAT runs with different application rates of N fertilizer until the prescribed average yield goal was achieved.

Depending on the length of growing season, New York farmers usually make two to four harvests each year. In this study, baseline harvest dates for grass were May 20, July 1, and August 15 (for first, second, and third cuttings, respectively). To plan harvest times that are practical for most dairy farms, the three harvests per year used in SWAT baseline representations were not altered.

Scenario 3. Scenario 3 retained the practices used in scenario 2 and added the management strategy of converting areas in corn production to grass production. Corn silage land use in the CRW has been identified as high risk for erosion and associated P losses. A modeling study of CRW by Tolson and Shoemaker (2004) reported that 58% of the watershed P loss results from corn production land that, in turn, represents only 1.2% of the total watershed. Hence, studying effects of this corn-to-grass-production strategy on reducing sediment and P losses was of interest.

Representation of this third scenario in the SWAT model required conversion of corn fields to grass production in addition to the practices included in scenario 2. Changes in parameters such as tillage, planting, fertilizer application dates, and harvesting dates in the management file in the SWAT model were made to reflect land use conversion of corn to grass. For the years of 1993, 1994, and 1995, 1.6 ha (4 ac), 3.6 ha (9 ac), and 3.4 ha (8.4 ac), respectively, were converted from corn to grass with intensive management (table 1; figure 2). This change required the elimination of tillage in the SWAT management files for these fields since grass crops do not require tillage once established and, as evidenced by Mann and Tolbert (2000), tillage operations used during grass or alfalfa establishment can result in more soil disturbance hence higher sediment losses.

Impacts of Precision Feed Management Strategies. Results for simulated sediment and P loss from HRUs were summarized by individual fields. Hence, it is possible to see field-specific effects on streamflow, baseflow, crop yield, plant P uptake, and sediment along with P losses as a result of field-specific management changes (table 3). SWAT-predicted baseline soil-P levels, including labile and active soil-P pools, from grass fields were compared to the reported soil-P test catagories of fields in the study area (figure 3). In addition, predicted soil-P movement between the mineral pools for different land uses across all scenarios was compared (figure 4). Utilization of active and labile P pools by high- and low-yielding grasses were compared (figure 5).

In addition, to simplify data presentation, sediment and P losses were aggregated based on land use type for the three-year analysis period (table 4). Predicted sediment and P losses were also aggregated for various crop land uses (corn, grass, alfalfa, and alfalfa-grass mix), pasture, and the entire watershed (including crop land uses and pasture) (table 5). Percentage changes of sediment and P losses for the simulated scenarios were compared to those of the baseline to evaluate watershed-level reductions of P attributable to PFM strategies (table 5).

Moreover, SWAT-predicted P loss effects of PFM-based strategies were compared to results from the IFSM study (table 6). Percent reductions of sediment and P losses were calculated by considering all agricultural land uses (alfalfa, corn, grass, and pasture). SWAT predictions represent the 71 ha (175 ac) of agricultural land located within the study watershed (e.g., in 1994, alfalfa and alfalfa-grass mix = 25 ha [62 ac]), corn = 3.6 ha [9 ac], grass = 16 ha [39.4 ac], and pasture = 26 ha [64.3 ac]. Integrated Farm System Model predictions represent agricultural land use of the entire farm of 120 ha (alfalfa = 9 ha [22 ac], corn = 12 ha [30 ac], grass = 63 ha [156 ac], and pasture = 36 ha [89 ac]). Thus, for comparison, IFSM-predicted percent changes of farm P imbalance and net-return as a result of implementing of the PFM-based strategies were included (table 6).

Results and Discussion

The SWAT simulations analyzed in this study were for the 1993 to 1995 period. These years represent a period of time before BMPs were installed in the watershed. This

Table 3
Soil and Water Assessment Tool–simulated effects from selected fields for the baseline condition and for differences between 1994 alternative scenario results and baseline scenario results.

Field ID Land use type Area (ha)	5 Corn 2.0	6 Corn 1.6	9 Grass 1.3	11 Grass 0.5	12 Grass 1.8	14 Grass 1.1	16 Grass 3.1	19 Grass 3.9	20 Grass 0.7	28 Grass 0.1	29 Grass 1.9
Surface runoff/baseflow (mm)											
Baseline	261/397	337/252	352/289	354/276	375/268	283/355	355/298	265/365	161/469	155/453	609/62
Scenario 1 – baseline	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
Scenario 2 – baseline	–/–	–/–	2/-1	4/0	4/-1	3/-5	3/-2	1/-2	0/0	0/-1	-24/4
Scenario 3 – baseline	1/-5*	-6/-1*	–/–	–/–	–/–	–/–	–/–	–/–	–/–	–/–	–/–
Crop yield (t ha^{-1})											
Baseline	6.5	6.1	0.7	0.5	2.1	0.3	1.2	1.1	2.6	0.9	0.1
Scenario 1 – baseline	0	0	0	0	0	0	0	0	0	0	0
Scenario 2 – baseline	–	–	2.8	2.9	2.2	2.6	2.7	2.4	0.0	0.1	3.4
Scenario 3 – baseline	-1.5*	-1.8*	–	–	–	–	–	–	–	–	–
Plant P uptake (kg ha^{-1})											
Baseline	20	18.5	6.612	5.313	25.92	3.12	11.85	10.74	6.5603	9.394	19.5
Scenario 1 – baseline	0	0	0	0	0	0	0	0	0	0	0
Scenario 2 – baseline	–	–	26.69	28.25	16.00	25.2	27.48	23.77	0.00015	0.992	14.9
Scenario 3 – baseline	20*	39.5*	–	–	–	–	–	–	–	–	–
Sediment loss (t ha^{-1})											
Baseline	5.44	4.66	3.67	2.11	0.47	2.95	0.38	0.46	0.11	0.60	0.06
Scenario 1 – baseline	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Scenario 2 – baseline	0.00	0.00	-3.03	-1.83	-0.24	-2.67	-0.29	-0.33	0.00	-0.12	-0.22
Scenario 3 – baseline	-5.15*	-4.34*	–	–	–	–	–	–	–	–	–
Particulate P loss (kg ha^{-1})											
Baseline	5.67	6.32	1.39	1.18	0.60	2.04	0.49	0.71	0.94	1.70	0.07
Scenario 1 – baseline	-0.57	-1.28	-0.04	-0.13	-0.09	0.00	-0.04	-0.05	-0.21	-0.05	0.00
Scenario 2 – baseline	-0.58	-1.28	-1.02	-0.95	-0.31	-1.63	-0.35	-0.47	-0.21	-0.31	-0.13
Scenario 3 – baseline	-4.93*	-5.50*	–	–	–	–	–	–	–	–	–
Soluble P loss (kg ha^{-1})											
Baseline	1.23	1.57	0.42	0.59	0.81	0.18	0.93	0.50	2.86	0.41	1.01
Scenario 1 – baseline	-0.19	-0.34	-0.01	-0.06	-0.12	0.00	-0.08	-0.04	-0.64	-0.02	-0.08
Scenario 2 – baseline	-0.19	-0.34	-0.09	-0.10	-0.26	-0.08	-0.08	-0.05	-0.64	0.02	-0.42
Scenario 3 – baseline	0.02*	0.18*	–	–	–	–	–	–	–	–	–

Notes: Scenario 1 = reduced manure phosphorus (P) concentrations as a result of dietary P reductions. Scenario 2 = scenario 1 + increased grass productivity. Scenario 3 = scenario 2 + 100% corn land converted to high yielding grass.

* (values of grass – values of corn).

also represents a period for which calibrated model baseline conditions were available against which to compare results of the management changes.

Crop Yield and Plant P Uptake. In scenario 1, yields of agricultural crops and plant P uptake were not affected as a result of reduced-P manure application. Crop yields were not affected because of initial levels of soil-P on the farm fields were nonlimiting. Dicussions on soil-P status of the fields are presented in the next section.

For scenario 2, applying 150 kg N ha^{-1} (134 lb N ac^{-1}) fertilizer increased grass yield by an average of 2.1 t DM ha^{-1} (1 tn DM ac^{-1}) over the three-year period. The predicted yield increments ranged from 4.5 to 1.2 t DM ha^{-1} (2 to 0.5 tn DM ac^{-1}) with a few fields having minimal increase in yield. Increments in grass yield varied annually across the three years analyzed due to different weather conditions. In addition, increments achieved in grass yield varied among fields due to differences in suitablity (e.g., soil type, soil depth, and slope) to grow high productivity grasses (table 3). The average grass yield response to N fertilization was 14 kg DM (kg N)$^{-1}$ (14 lb DM [lb N]$^{-1}$), with a range from 8 to 30 kg DM (kg N)$^{-1}$ (excluding few fields with low yield response). A field trial study in New York farms by Cherney et al. (2003) found a 20 kg DM (kg N)$^{-1}$ grass yield response to N fertilization when N application rate was increased from 112 kg N ha^{-1} to 224 kg N ha^{-1} (100 to 200 lb N ac^{-1}). Hence, the SWAT-predicted average yield responses seemed reasonable for the study area. Increasing grass yield from average values of 1.9 t DM ha^{-1} (0.85 tn DM ac^{-1}) in the baseline scenario to 4.0 t DM ha^{-1} (1.8 tn DM ac^{-1}) in scenario 2 increased average annual crop-P uptake by 20.7 kg P ha^{-1} (18.5 lb P ac^{-1}) for high-yielding grasses.

For scenario 3, the highest grass yield was predicted on converted fields (table 3). For example, in 1994 fields 5 and 6 yielded 4.5 and 4.3 t DM ha^{-1} (2 and 1.9 tn DM ac^{-1}), respectively, after conversion to grass. These fields were likely favored by high grass yields because they were located on land suitable for corn production and hence were somewhat more fertile than the non-converted grass fields. Consequently, an increase in crop soil-P uptake was also predicted compared to the replaced corn crops.

Impacts of Precision Feed Management on Soil-P. Though field-by-field based soil-P test data was not available to validate SWAT-predicted baseline soil-P status, predicted amounts of both labile and active soil-P pools from grass fields were similar to reported soil-P tests of fields in the study area (Ketterings et al. 2005) (figure 3). In New York, the Morgan solution extraction method is used to estimate soil-P availability for crops. The Morgan solution extraction soil-P test measures the amount of soil-P both in solution and that can be expected to become soluble from the mineral and organic P sources (Morgan 1941). The SWAT model predicts different soil-P pools: labile (solution), active, and stable. Though not exactly the same, the Morgan soil-P tests may be related to the SWAT-predicted total amount of soil-P in labile and active pools. SWAT-predicted baseline amounts of soil-P of both labile and active pools for grass fields have been shown to be in the high SolP range as classified by Ketterings et al. 2003 (with soil-P test values of 9 to 22 kg ha^{-1} [8 to 20 lb ac^{-1}] [based on Morgan solution extraction method] classifed as having high soil-P; figure 3).

Figure 3

Soil and Water Assessment Tool–predicted phosphorus in labile (solution) and active pools for 1993 baseline grass fields as line graph using left-hand y-axis; soil test P (Morgan solution) classifications developed for New York field crops by Ketterings et al. (2003) as shaded regions using right-hand y-axis.

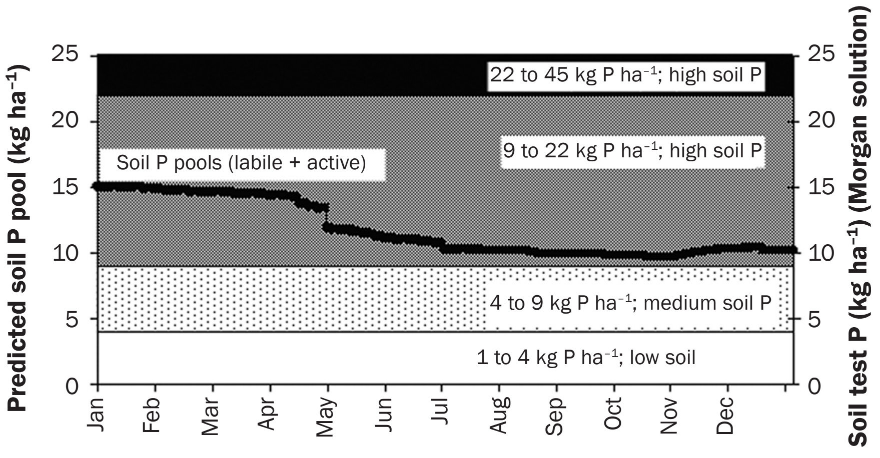
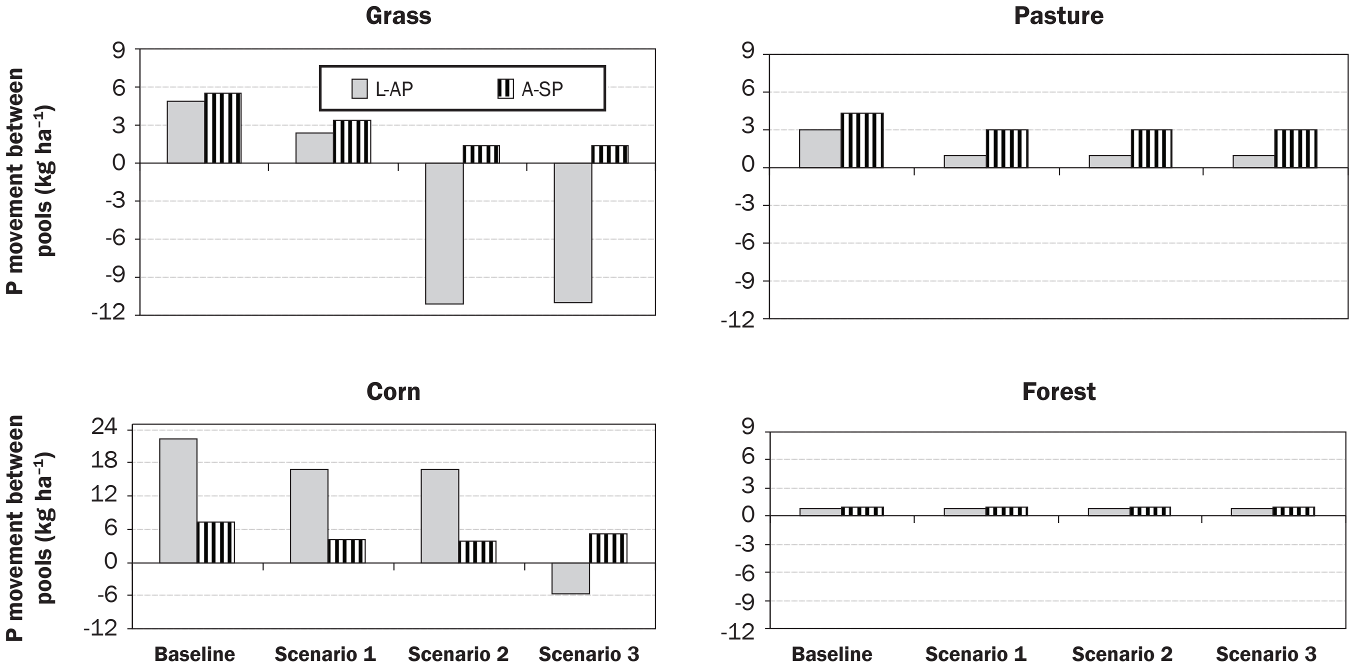


Figure 4

Soil and Water Assessment Tool–predicted movement of mineral phosphorus from the labile (solution) to active pool (indicated by "L-AP") and the active to stable pool (indicated by "A-SP") averaged over three years (1993 to 1995).



Note: Corn land use was converted to grass in scenario 3.

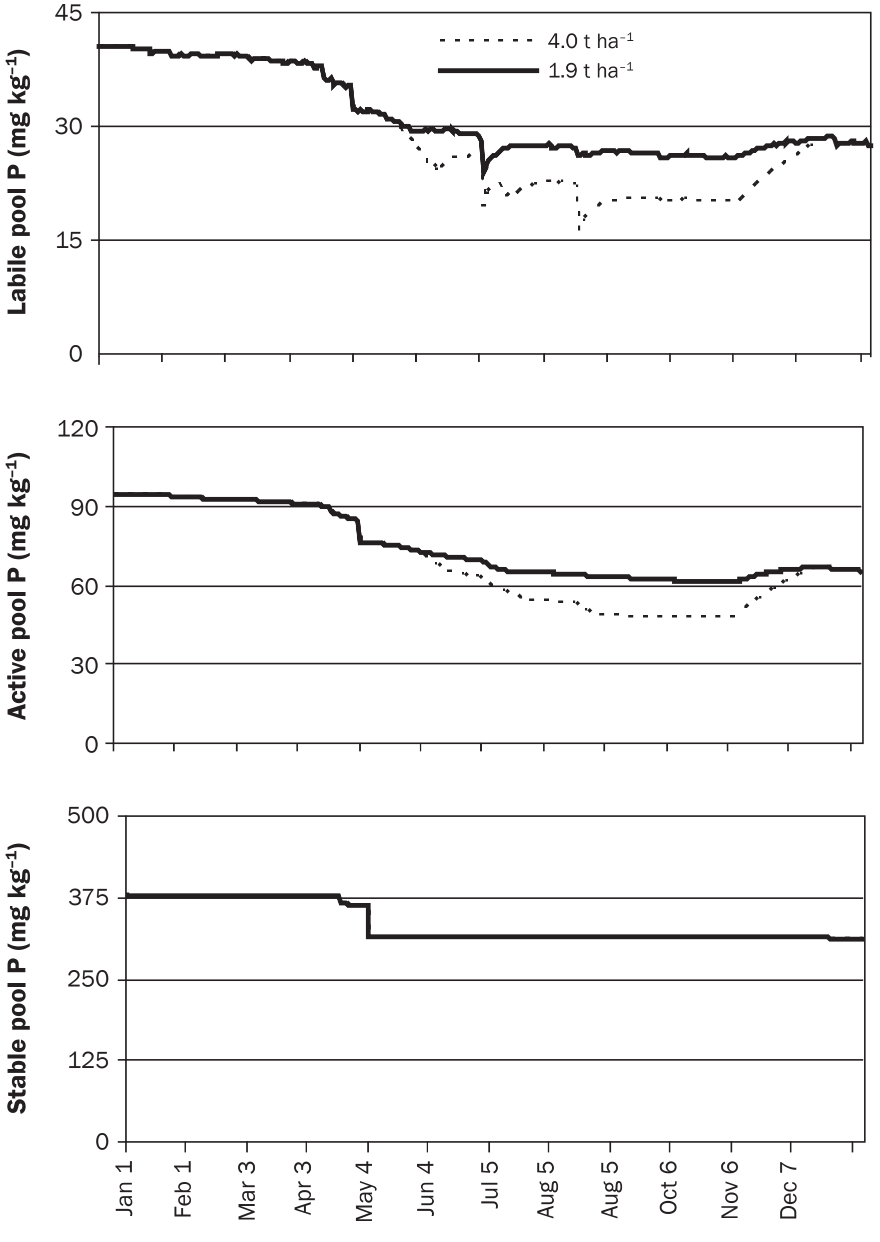
Figure 4 shows predicted P movement between the mineral pools for different land uses (grass, corn, pasture, and forest) for all scenarios, averaged over the three-year period (1993 to 1995). For the baseline condition, the magnitudes of movement from labile (solution) to active (L-AP) and from active to stable pools for grass and corn land uses were larger than those of pasture and forest land uses. This was deemed reasonable since most of the P application (manure or fertilizer) occurs in corn and grass land uses. Baseline values for forested land use were small, implying slower transformation and transfer of P between pools (figure 4).

Decreasing the concentration of P in the manure (scenario 1) reduced the amounts of P available in the soil. For scenario 1, compared to the baseline scenario, the L-AP and active to stable pools decreased across all agricultural land uses to which manure was applied (e.g., grass, corn, and pasture) (figure 4). This was expected because the amount of P in the manure applied was lower in scenario 1 than in the baseline scenario.

As compared to scenario 1, the movement of soil P for scenario 2 was affected only for grass fields with increased productivity. Due to the increased P uptake by the higher-yielding grass, the L-AP value became negative. This negative value indicates movement of P from the active pool to the labile pool to replenish the increased demand by higher yielding grasses for the labile P. The quantity of active to stable pools conversion was also reduced. This could be interpreted as an indication of the smaller extent of soil-P accumulation over a period of time. For scenario 3, a further decrease in quantity of conversion from L-AP pools was observed for fields originally in corn production (figure 3). This was due to the replacement of the corn crop with higher-yielding grass, which required greater P uptake compared to the replaced corn plants.

Figure 5

Soil and Water Assessment Tool–predicted phosphorus concentrations in stable, active, and labile (solution) mineral pools for 1993 grass fields with two yield levels: 1.9 t and 4.0 t DM ha^{-1}.



The short-term effect of crop-P uptake by increased grass production results in an increased depletion of active and labile P pools for higher-yielding grasses (4.0 t DM ha^{-1} [(1.8 tn ac^{-1})]) in scenario 2 as compared to the lower-yielding grasses (1.9 t DM ha^{-1} [0.8 tn ac^{-1}]) in the baseline scenario (figure 5). Because the active pool is in slow equilibrium (several years) (Neitsch et al. 2002a) with the stable pool, the stable pool did not change over the time period presented. Over the entire simulation year, average percent reductions from low and high yield were 7% and 8% for active and labile P pools, respectively. As predicted by SWAT, growing season reductions for active and labile P pools from low to high yields were 11 mg kg^{-1} and 5 mg kg^{-1}, respectively. These seasonal decreases in field-level soil-P pools indicate increased soil-P removal by the grass-forage due to its increased productivity. Thus, as stressed by Lanyon (1992), increasing productivity of on-farm forage can promote recycling and re-use of P on the farm. This strategy of enhancing crop yields to increase crop-P harvest has been widely practiced on dairy farms with higher levels of soil-P throughout Europe (Sibbesen and Runge-Metzger 1995). Moreover, increasing on-farm forage production can reduce reliance on the importation of animal feed supplements and, over the long-term, can reduce accumulation of excess P in the soil profile.

Table 4

Soil and Water Assessment Tool–simulated total sediment, particulate phosphorus, and soluble phosphorus losses for each agricultural land use for the baseline condition and all alternative scenarios.

Year	1993					1994					1995				
Land use	Grass	Corn	Alfalfa*	Pasture	Idle	Grass	Corn	Alfalfa*	Pasture	Idle	Grass	Corn	Alfalfa*	Pasture	Idle
Area (ha)	15.9	1.6	27.3	26.2	0	15.9	3.6	25.3	26.2	0	18.9	3.4	9.5	26.2	13
	Total sediment loss (t ha^{-1})					Total sediment loss (t ha^{-1})					Total sediment loss (t ha^{-1})				
Baseline	0.85	2.02	0.11	0.15	–	2.59	12.35	0.09	0.05	–	2.19	7.17	1.01	0.06	5.61
Scenario 1	0.85	2.02	0.11	0.15	–	2.59	12.35	0.09	0.05	–	2.19	7.17	1.01	0.06	5.61
Scenario 2	0.32	2.02	0.11	0.15	–	0.57	12.35	0.09	0.05	–	1.13	7.17	1.01	0.06	3.37
Scenario 3	0.32	0.37†	0.11	0.15	–	0.57	0.90†	0.09	0.05	–	0.41	0.45†	0.30	0.06	3.37
	Particulate P loss (kg ha^{-1})					Particulate P loss (kg ha^{-1})					Particulate P loss (kg ha^{-1})				
Baseline	0.32	1.31	0.18	0.25	–	0.79	5.95	0.14	0.18	–	0.99	2.21	0.81	0.2	1.62
Scenario 1	0.30	1.12	0.16	0.23	–	0.74	5.07	0.13	0.16	–	0.88	1.91	0.65	0.18	1.54
Scenario 2	0.18	1.12	0.16	0.23	–	0.31	5.07	0.13	0.16	–	0.58	1.91	0.65	0.18	1.32
Scenario 3	0.18	0.27†	0.17	0.23	–	0.31	0.77†	0.13	0.16	–	0.39	0.28†	0.29	0.18	1.32
	Soluble P loss (kg ha^{-1})					Soluble P loss (kg ha^{-1})					Soluble P loss (kg ha^{-1})				
Baseline	0.92	0.68	0.72	0.47	–	0.73	1.38	0.62	0.62	–	0.53	0.62	0.93	0.67	0.51
Scenario 1	0.80	0.55	0.62	0.40	–	0.65	1.12	0.53	0.54	–	0.43	0.51	0.75	0.58	0.47
Scenario 2	0.78	0.55	0.62	0.40	–	0.58	1.12	0.53	0.54	–	0.38	0.51	0.75	0.58	0.46
Scenario 3	0.78	0.65†	0.62	0.40	–	0.58	1.47†	0.53	0.54	–	0.44	0.67†	0.83	0.58	0.46

Notes: Scenario 1 = reduced manure phosphorus (P) concentrations, as a result of dietary P reductions. Scenario 2 = scenario 1 + increased grass productivity. Scenario 3 = scenario 2 + 100% corn land converted to high yielding grass.

* Land use is alfalfa or alfalfa-grass mix, depending on field.

† Losses from fields orginally in corn production. Note that fields in corn were converted to grass production in scenario 3.

Impacts of Precision Feed Management on Surface Runoff and Stream Flow. SWAT-simulated responses of stream flow to the various scenarios were examined, and negligible differences compared to the baseline scenario were observed (table 3). For example, surface runoff depth slightly decreased (by an average of 3 mm [0.12 in]) when corn land uses were converted to grass production (scenario 3). Field-by-field examinations of scenario 2 surface runoff and baseflow components of stream flow from grass showed opposite trends compared to the baseline, with surface runoff increasing and baseflow decreasing. Field 29 was exceptional, as the stream flow decreased by 24 mm (0.95 in), and the baseflow increased by 4 mm (0.16 in) compared to baseline (table 3). This grass field had very low yield in the baseline scenario of 0.1 t ha^{-1} (0.05 tn ac^{-1}), and the yield improved dramatically to 3.4 t ha^{-1} (1.5 tn ac^{-1}) as a result of management change in scenario 2. Overall, the change in the total stream flow was negligible as the increase in surface flow depth was canceled by the decrease in the baseflow depth predictions. However, in reality, additional variation in the predicted surface runoff and stream flow for scenario 2 compared to the baseline would be expected as a result of increasing grass productivity. The change from low- to high-yielding grasses was expected to increase rainfall interception, water storage capacity, and infiltration, which should ultimately reduce runoff generation. In SWAT, curve numbers of each HRU in the management file can be adjusted to reflect the management changes of increasing grass yield. However, there is no specific guideline as to how much a curve number should change relative to increases in crop yield. Hence, to avoid biases, no adjustment was made to the curve number of grass crops when an increase in yield was intended. This was also presumed reasonable because it avoids subjectivity of the results, relative to effects of PFM management change, on predicted losses of sediment and P with surface runoff because predictions of sediment and P losses are derived by the predictions of these hydrologic variables. In this study, it is recognized that increasing grass yield should have some effect in reducing surface runoff and its subsequent P loss (which was not predicted).

Effects on Sediment Losses. For all simulation years, scenario 1 had no effect on the amount of sediment loss prediction from all land use types. This was as expected because scenario 1 involved changing only the concentration of P in manure applied to the agricultural land uses.

For scenario 2, an increase in grass yield resulted in a reduced amount of sediment loss (tables 3 and 4) for the grass land for which yield was increased. Reduction in sediment loss varied among fields (table 3). Based on these spatially explicit field-by-field results, planning can be focused on those fields that are closer to water bodies and have higher gradients of change in losses.

The three-year average sediment loss reduction compared to the baseline scenario for grass fields was 63% (62%, 78%, and 48% for 1993, 1994, and 1995, respectively) (calculated from table 3). For 1995, the predicted sediment losses from fields denoted as idle were reduced in scenario 2 compared to the baseline scenario, even though yields were increased only for grass fields (table 4). These idle fields, however, were in grass prior to 1995, when they became idle. Hence, the reduction in predicted sediment loss from idle fields in scenario 2 was mainly due to the increased crop residue on the soil surface remaining from yield increase of the previous year. The reduction in predicted sediment loss is likely due to increased interception of rainfall energy by the increased land cover and residue, thus decreasing erosion. In SWAT, the crop management factor used to estimate sediment loss is updated every day as a function of above-ground biomass, residue on the soil surface, and the plant cover (C) factor (Neitsch et al. 2002a).

Three-year average sediment loss reductions in scenario 2 compared to the baseline scenario was 34% for all crop land uses (table 4). Because management was not altered for pasture fields, there was no change in the percent reduction of sediment loss from pasture land use. Overall, the three-year average sediment loss was reduced by 25% (table 5) when aggregated over the entire watershed.

For scenario 3, when corn land was switched to grass production, SWAT-predicted sediment loss was reduced substantially for fields originally planted with corn. For example, in 1994 the reductions in sediment loss from fields 5 and 6 were 95% and 93%, respectively. Field 6 is located closer to the stream compared to field 5 (figure 1). This is an example of how knowing the specific location of the fields can help prioritize land use management change and plan amendment practices.

The three-year average sediment loss reduction compared to the baseline scenario for fields originally planted with corn was 89% (82%, 93%, and 94% for 1993, 1994, and 1995, respectively) (calculated from table 4). The reduction in predicted sediment loss due to conversion of corn land use to grass was likely due to greater crop vegetative soil cover by grasses. The annual cover and management C factor of corn (default annual C factor of corn ~0.2; Neitsch et al. 2002b) is larger than that of the grass crops (default annual C factor of grass ~0.003; Neitsch et al. 2002b), implying lower residue cover, increased soil surface roughness due to tillage, and lower interception ability of corn crops compared to grasses. In addition, grass crops cover the ground for greater part of the year.

As noted in figure 2, for the baseline scenario, fields 5 and 6 (figure 1) that were in corn in 1994 rotated to grass and alfalfa-grass in 1995. When scenario 3 replaced the 1994 corn with grass, 1995 spring tillage was not needed. Hence, scenario 3 predicted lower sediment losses in 1995 from these fields than did scenario 2 (table 4).

When sediment losses for scenario 3 were aggregated for all crop land uses, the three-year average sediment loss reduction compared to the baseline scenario was 68% (table 5). Over the entire watershed, the three-year average sediment loss reduction in scenario 3 compared to the baseline was 49% (table 5).

Table 5

Soil and Water Assessment Tool–simulated average annual sediment and phosphorus losses and percent reductions from baseline for precision feed management–based scenarios for croplands, pasture, and the entire watershed.

	Cropland*	Pasture land	Entire watershed
Area (ha)	**44.8**	**26.2**	**163**
Sediment loss (t [% reduction from baseline]$^{-1}$)			
Baseline	85.32/—	2.27/—	120.10/—
Scenario 1	85.65/(0)	2.27/(0)	120.10/(0)
Scenario 2	56.09/(34)	2.27/(0)	90.20/(25)
Scenario 3	27.40/(68)	2.27/(0)	61.13/(49)
Particulate P loss (kg [% reduction from baseline]$^{-1}$)			
Baseline	36.20/—	5.50/—	61.87/—
Scenario 1	33.19/(8)	4.98/(10)	57.57/(7)
Scenario 2	28.09/(22)	4.98/(10)	51.80/(16)
Scenario 3	18.72/(48)	4.98/(10)	42.00/(32)
Soluble P loss (kg [%reduction from baseline]$^{-1}$)			
Baseline	33.41/—	15.37/—	58.00/—
Scenario 1	29.47/(12)	13.27/(14)	51.37/(11)
Scenario 2	29.30/(12)	13.27/(14)	50.53/(13)
Scenario 3	30.58/(8)	13.27/(14)	51.83/(11)

Notes: Scenario 1 = reduced manure phosphorus (P) concentrations as a result of dietary P reductions. Scenario 2 = scenario 1 + increased grass productivity. Scenario 3 = scenario 2 + 100% corn land converted to high yielding grass.

* Cropland areas include areas under corn, grass, and alfalfa/alfalfa-grass mix.

Table 6

Soil and Water Assessment Tool (SWAT)–predicted and Integrated Farm System Model (IFSM)–predicted effects of precision feed management-based strategies relative to the baseline scenario on sediment and phosphorus losses, farm phosphorus imbalance, and farm net returns.

	Scenario 1		Scenario 2		Scenario 3	
	SWAT predicted	IFSM predicted	SWAT predicted	IFSM predicted	SWAT predicted	IFSM* predicted
Sediment loss	0%	0%	−35%	−2%	−63%	−55%
Particulate P loss†	−10%	−2%	−24%	−5%	−45%	−44%
Soluble P loss	−14%	−13%	−13%	−17%	−10%	−23%
P imbalance	NA	−60%	NA	−100%	NA	−100%
Farm net return	NA	+5%	NA	+54%	NA	+89%

Notes: Scenario 1 = reduced manure phosphorus (P) concentrations as a result of dietary P reductions. Scenario 2 = scenario 1 + increased grass productivity. Scenario 3 = scenario 2 + 100% corn land converted to high yielding grass. All IFSM-simulated data taken from Ghebremichael et al. (2007). NA = not applicable, as SWAT does not simulate P imbalance or farm economics.

* Denoted as scenario 4 in Ghebremichael et al. (2007); represents 100% corn land use conversion to grass in addition to scenario 2.

† A positive (+) value represents an increase and a negative (−) value represents a reduction in predicted values relative to the baseline scenario.

Effects on P Losses. For scenario 1, a 25% reduction in manure P content, relative to the SWAT baseline data, resulted in lower PP and SolP losses for fields that received manure application (table 4). Aggregated reduction of PP from crop land uses was 8% for the three years; reduction of SolP was 12% for the three years (table 5). Similarly, average reductions of PP and SolP losses from pasture land uses were 10% and 14%, respectively. These results are comparable to a 12% reduction in SolP losses predicted by Santhi et al. (2001), who used SWAT with a 29% reduction in manure P concentration. When all agricultural land use areas were considered, SWAT-predicted reductions of P loss, particularly SolP, were comparable to the IFSM-predicted loss reductions reported in Ghebremichael et al. (2007) (table 6).

Depending on the size of agricultural land use relative to the encompassing watershed, application of manure with reduced P content can result in reduced PP and SolP losses at the outlet of the watershed. In this study, 71 ha of the total 163 ha watershed area was comprised of agricultural land uses; PP and SolP reductions at the watershed outlet were 7% and 11%, respectively. Due to the dilution effects from land uses other than those in which management alteration was imposed, effects at the watershed level were smaller than the effects calculated from altered agricultural land uses alone.

Generally, the practice of reducing dietary P requires minimal strategic change to the farm management. When dietary P is properly balanced to the cow's requirement no negative effects related to milk production and animal production performance are expected (Wu and Satter 2000; Wu et al. 2001). In fact, as reported in Ghebremichael et al. (2007) the farm can save money from reduced purchases of dietary mineral P. Hence, in addition to the environmental benefits of reduced soil P and off-field P losses discussed previously, this strategy reduces farm P importation, which in turn reduces farm P surplus problems and dairy feed costs for the farmer (table 6).

Application of scenario 2 resulted in a minimal effect on P loss compared to scenario 1. Exceptions were observed for PP loss reduction from grass fields that were intensified and idle (fallow) fields that followed high-yielding grass (tables 3 and 4). Similar to sediment loss reductions discussed previously, PP loss reductions varied by field. These field-specific PP loss predictions provide important information for focusing management resources on areas with greater PP loss reductions.

For scenario 2 grass fields, average PP and SolP loss reductions over the three years were 44% and 15%, respectively, compared to the baseline scenario and 40% and 3%, respectively, compared to scenario 1. When aggregated over all crop land uses, three-year average predicted PP and SolP loss reductions were 22% and 12%, respectively, compared to the baseline (table 5). The decrease in the predicted PP loss was due to lower sediment losses, discussed previously, to which PP could be attached.

For scenario 2, average predicted PP and SolP losses reductions were 16% and 13%, respectively, compared to the baseline when losses were aggregated over the entire watershed land uses (table 5). Unlike for the PP loss, predicted SolP loss as a result of increased grass production was only slightly reduced compared to scenario 1. Note also that the area in grass constituted 38% of the management-altered agricultural area, but only 10% of the entire study watershed area, causing dilution effects of P loss reductions at the watershed level.

For scenario 3, when corn land was converted to grass production, SWAT-predicted PP loss was reduced substantially for fields originally growing corn (table 3) (fields under corn land use column in table 4). However, predicted SolP was increased for those fields. For example, PP loss for corn fields in 1993 was reduced from 1.12 kg ha^{-1} (1.0 lb ac^{-1}) (scenario 2) to 0.27 kg ha^{-1} (0.24 lb ac^{-1}) in scenario 3; SolP loss for corn fields in 1993 was increased from 0.55 kg ha^{-1} (0.5 lb ac^{-1}) (scenario 2) to 0.65 kg ha^{-1} (0.58 lb ac^{-1}) in scenario 3 (table 4). Also, PP losses were reduced for grass and alfalfa/alfalfa-grass mix land uses (1995) due to exclusion of tillage operations and subsequent lowering in sediment losses (table 4).

With regard to reduction of erosion and associated P loss, the strategy of corn land conversion to grass was determined effective. This was supported by the findings of modeling results from SWAT (tables 3, 4, and 5). Overall, compared to the baseline scenario, the predicted average PP loss from crop land uses in scenario 3 declined by 48% while average SolP decreased by 8% (table 5). Scenario 3 incrementally reduced PP loss by 26% and slightly increased SolP loss by 4% when all crop land uses were considered (table 5). Average reductions for crop land uses in scenario 2 were 22% and 12% for PP and SolP, respectively, compared to the baseline scenario. When the entire watershed was considered, scenario 3 incrementally reduced PP by 16% and slightly increased SolP by 2% compared to scenario 2. The average corn area converted to grass was only 6% of the management-altered agricultural land and 2% of the total watershed area.

Since additional N fertilizer was used to increase grass yield for scenarios 2 and 3, simulated off-field N-loss changes were investigated. Simulated average total dissolved and organic N losses from grass fields for the three years analyzed were 23 kg ha^{-1} (4.3 mg L^{-1}) and 1.3 kg ha^{-1} (0.2 mg L^{-1}) for scenarios 2 and 3, respectively, compared to the baseline losses of 15.1 kg ha^{-1} (2.8 mg L^{-1}) of dissolved N and 2.2 kg ha^{-1} (0.4 mg L^{-1}) of organic N losses. The reduced organic N losses for scenarios 2 and 3 were likely due to reduced sediment losses, which transport organic N. Because the additional N fertilizer applied to boost grass-forage productivity was split into two treatments of 75 kg N ha^{-1} (67 lb ac^{-1}), only a slight increase in dissolved N loss was observed. Predicted N concentrations from grass fields were below the 10 mg L^{-1} maximum contaminant level for drinking water. However, continuous losses of these magnitudes to water bodies may potentially pose a concern to water quality degradation and aquatic life. Therefore, the need for BMPs that control P losses while simultaneously matching N availability to crop needs in order to control N losses and increase N use efficiency for forage production is recognized.

Summary and Conclusions

This study evaluated the effectiveness of alternative PFM-based farm management scenarios with regard to achieving P loss reductions at both field and watershed scales. The PFM farm management strategies were simulated in SWAT on a single-farm watershed, which allowed straightforward representation of the farm-level planning strategies at the watershed level.

SWAT simulation of reduced manure P concentration due to feeding cows less dietary P resulted in decreased P losses (both SolP and PP) at field and watershed scales. The strategy of increasing grass yield demonstrated appreciable decrease in field-level soil P during the growing season, indicating increased soil-P removal by the improved grass forage. The strategy of improving crop productivity to reduce a farm's feed importation can be practical in areas where plant soil-P availability is not of concern and when excess soil-P depletion is desired. In addition, PP loss was reduced due to more ground cover and less erosion when crop productivity was increased. When corn land uses were converted to grass production, a decrease in

PP loss was revealed at both field and watershed scales despite the smallness of the corn area converted to grass. In summary, these PFM-based strategies collectively were able to reduce PP losses from crop land uses by 8% to 48% and SolP by 8% to 12%.

Such model-based representation and evaluation of farm plans at a watershed level helps integrate the smallest management unit (farm management plan) into a watershed plan. Also, it is a helpful tool in assessing comprehensive and economically viable solutions for permanent reduction of P losses from dairy agriculture to the Cannonsville Reservoir.

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References

Bishop, P.L., W.D. Hively, J.R. Stedinger, M.R. Rafferty, J.L. Lojpersberger, and J.A. Bloomfield. 2005. Multivariate analysis of paired watershed data to evaluate agricultural best management practice effects on stream water phosphorus. Journal of Environmental Quality 34(3):1087-1101.

Borah, D.K., and M. Bera. 2004. Watershed_scale hydrologic and nonpoint_source pollution models: Review of applications. Transactions of the ASAE 47(3):789-803.

Cerosaletti, P.E., D.G. Fox, L.E. Chase, A.N. Pell, and W.A. Knoblauch. 1998. Application of the Cornell Net Carbohydrate and Protein System on a pasture based dairy farm. *In* Proceedings of Cornell Nutrition Conference for Feed Manufacturers, Rochester, New York, October 1998, 197- 211. Ithaca, NY: Cornell University.

Cerosaletti, P.E., D.G. Fox, and L.E. Chase. 2004. Phosphorus reduction through precision feeding of dairy cattle. Journal of Dairy Science 87(7):2314-2323.

Cherney, J.H., D.J.R. Cherney, and M.D. Casler. 2003. Low intensity harvest management of reed canarygrass. Agronomy Journal 95(3):627-634.

Delaware County Watershed Affairs. 2002. Delaware County Action Plan DCAP II for Watershed Protection and Economic Vitality. Delaware County Department of Watershed Affairs, Delhi, NY.

Di Luzio, M., R. Srinivasan, and J.G. Arnold. 2002. Integration of watershed tools and SWAT model into BASINS. Journal of American Water Resources Association 38(4):1127-1141.

Dou, Z., F.K. Knowlton, R.A. Kohn, Z. Wu, L.D. Satter, G. Zhang, J.D. Toth, and J.D. Ferguson. 2002. Phosphorus characteristics of dairy feces affected by diets. Journal of Environmental Quality 31(6):2058-2065.

Dou, Z., J.D. Ferguson, J. Fiorini, J.D. Toth, S.M. Alexander, L.E. Chase, C.M. Ryan, K.F. Knowlton, R.A. Kohn, A.B. Peterson, J.T. Sims, and Z. Wu. 2003. Phosphorus feeding levels and critical control points on dairy farms. Journal of Dairy Science 86(11):3787-3795.

Ebeling, A.M., L.G. Bundy, T.W. Andraski, and J.M. Powell. 2002. Dairy diet phosphorus effects on phosphorus losses in runoff from land-applied manure. Soil Science Society of American Journal 66(1):284-291.

Gassman, P.W., M.R. Reyes, C.H. Green, and J.G. Arnold. 2007. The Soil and Water Assessment Tool: Historical development, applications, and future research directions. Transactions of the ASABE 50(4):1211-1250.

George, M.R., N.K. McDougald, W.A. Jensen, R.E. Larsen, D.C. Cao, and N.R. Harris. 2008. Effectiveness of nutrient supplement placement for changing beef cow distribution. Journal of Soil and Water Conservation 63(1):11-17.

Ghebremichael, L.T., P.E. Cerosaletti, T.L. Veith, C.A. Rotz, J.M. Hamlett, and W.J. Gburek. 2007. Economic and phosphorus-related effects of precision feeding and forage management at a farm-scale. Journal of Dairy Science 90(8):3700-3715.

Gitau, M.W., and W.J. Gburek. 2005. Best management practice effects for phosphorus control on a dairy farm: The Cannonsville Reservoir Watershed, New York. Paper presented at the American Society of Agricultural and Biological Engineers Annual International Meeting, Tampa, FL, July 17-20, 2005. ASABE paper no. 052046. St. Joseph, MI: ASABE.

Ketterings, Q.M., K.J. Czymmek, and S.D. Klausner. 2003. Phosphorus guidelines for field crops in New York. Second Release. Department of Crop and Soil Sciences Extension Series E03-15. Ithaca, NY: Cornell University.

Ketterings, Q.M., J. Kahabka, and W.S. Reid. 2005. Trends in phosphorus fertility of New York agricultural land. Journal of Soil and Water Conservation 59(1):10-20.

Knoblauch, W.A., L.D. Putnam, M. Kiraly, J.J. Walsh, S.E. Hadcock, and L. Hulle. 2005. Dairy farm business summary: Southeastern New York region 2004. Ithaca, NY: Department of Applied Economics and Management, College of Agriculture and Life Sciences, Cornell University, Ithaca, NY.

Lanyon, L.E. 1992. Implication of dairy herd size for farm material transport, plant nutrient management, and water quality. Journal of Dairy Science 75(1):334-344.

Mann, L., and V. Tolbert. 2000. Soil sustainability in renewable biomass plantings. Ambio 29(8):492-496.

Martinez, J., and A. Rango. 1989. Merits of statistical criteria for the performance of hydrological models. Water Resources Bulletin 25(2):421-432.

Morgan, M.F. 1941. Chemical soil diagnosis by the universal soil testing system. Connecticut. Agricultural Experimental Station. Bulletin No. 450. University of Connecticut, Storrs Mansfield, CT.

National Research Council. 2001. Nutrient requirements of dairy cattle, 7th edition. Washington, DC: National Academic Press.

Neitsch, S.L., J.G. Arnold, T.R. Kiniry, J.R. Williams, and K.W. King. 2002a. Soil and Water Assessment Tool: Theoretical Documentation Version 2000. Report number TR-191, College Station, TX: Texas Water Resources Institute. http://www.brc.tamus.edu/swat/downloads/doc/swat2000theory.pdf.

Neitsch, S.L., J.G. Arnold, T.R. Kiniry, and J.R. Williams. 2002b. Soil and Water Assessment Tool: Users Manual Version 2000. Report number TR-192. College Station, TX: Texas Water Resources Institute. http://www.brc.tamus.edu/swat/downloads/doc/swatuserman.pdf.

Novotny, V., and H. Olem. 1994. Water Quality: Prevention, Identification, and Management of Diffuse Pollution. New York, NY: Van Nostrand Reinhold.

Rotz, C.A., A.N. Sharpley, L.D. Shatter, W.J. Gburek, and M.A. Sanderson. 2002. Production and feeding strategies for phosphorus management on dairy farms. Journal of Dairy Science 85(11):3142-3153.

Rotz, C.A., and C.U. Coiner. 2006. Integrated Farm System Model (IFSM): Reference Manual Version 2.0. Agricultural Research Service, USDA. http://www.ars.usda.gov/SP2UserFiles/Place/19020000/ifsmreference.pdf.

Santhi, C., J.G. Arnold, J.R. Williams, L.M. Hauck, and W.A. Dugas. 2001. Application of a watershed model to evaluate management effects on point and nonpoint source pollution. Transactions of the ASAE 44(6):1559-1570.

Satter, L.D., and Z. Wu. 1999. Reducing manure phosphorus by dairy diet manipulation. *In* Proceedings of Cornell Nutrition Conference for Feed Manufacturers, Rochester, New York, October 1999, 183-192. Ithaca, NY: Cornell University.

Sibbesen, R.D., and A. Runge-Metzger. 1995. Phosphorus balance in European agriculture - status and policy options. *In* Phosphorus in the Global Environment, ed. H. Tiessen, 43-57. New York, NY: John Wiley & Sons.

Sharpley, A.N., S. Herron, and T. Daniel. 2007. Overcoming the challenges of phosphorus-based management in poultry farming. Journal of Soil and Water Conservation 62(6):375-387.

Tolson, B.A., and C.A. Shoemaker. 2003. Future phosphorus loading to the Cannonsville Reservoir. *In* Proceedings of 2003 World Water and Environmental Resources Congress, Philadelphia, Pennsylvania, June 2003. Reston, VA: American Society of Civil Engineers.

Tolson, B.A., and C.A. Shoemaker. 2004. Watershed Modeling of the Cannonsville Basin Using SWAT2000 for the Cannonsville Reservoir: Version 1.0 Technical Report. Ithaca, NY: School of Civil and Environmental Engineering at Cornell University.

Tylutki, T.P., and D.G. Fox. 1997. Application of the Cornell Nutrient Management Planning System: Optimizing herd nutrition. *In* Proceedings of Cornell Nutrition Conference for Feed Manufacturers, Rochester, New York, October 1997, 54-65. Ithaca, NY: Cornell University.

USDA National Agricultural Statistics Service. 2005. US Department of Agriculture National Agricultural Statistics Database: New York crop data 2002-2005. Washington, DC: USDA National Agricultural Statistics Service. http://www.nass.usda.gov/Statistics_by_State/New_York/index.asp.

Walter, M.T., and M.F. Walter. 1999. The New York Watershed Agricultural Program: A model for comprehensive planning for water quality and agricultural economic viability. Water Resource Impact 1(5):5-8.

Wang, S.J., D.G. Fox, D.J.R. Cherney, S.D. Klausner, and D.R. Bouldin. 1999. Impact of dairy farming on well water nitrate level and soil content of phosphorus and potassium. Journal of Dairy Science 82(10):2164-2169.

Williams, J.R., C.A. Jones, and P.A. Dyke. 1984. A modeling approach to determine the relationship between erosion and soil productivity. Transactions of the ASAE 27(1):129-144.

Wu, Z., and L.D. Satter. 2000. Milk production and reproductive performance of dairy cows fed two concentrations of phosphorus for two years. Journal of Dairy Science 83(5):1052-1063.

Wu, Z., L.D. Satter, A.J. Blohowiak, R.H. Stauffacher, and J.H. Wilson. 2001. Milk production, estimated phosphorus excretion, and bone characteristics of dairy cows fed different amounts of phosphorus for two or three years. Journal of Dairy Science 84(7):1738-1748.