

Reducing Phosphorus Runoff from Dairy Farms

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ABSTRACT

Phosphorus (P) runoff from manure can lead to eutrophication of surface water and algae growth. This study evaluates the impacts of alternative P reduction practices on dairy farm net returns and on potential P runoff. The P control practices include dairy herd nutrient management, crop nutrient management, and runoff and erosion control. Four farms representative of dairies in the Virginia Shenandoah Valley are simulated including dairies with and without supplementary broiler enterprises and with average and below average land area. A mathematical programming model was developed to predict farm production and net returns and the GLEAMS model was used to predict potential P runoff. The farms are evaluated under four scenarios: Scenario 1, no constraint on P runoff with access to crop nutrient, runoff and erosion control strategies but no access to dairy herd nutrient control strategies; Scenario 2, no constraint on P runoff with access to all crop and dairy herd nutrient control strategies; Scenario 3, constraint on P runoff with access to crop nutrient, runoff and erosion control strategies but no access to dairy herd nutrient control strategies; and Scenario 4, constraint on P runoff with access to all crop and dairy herd nutrient control strategies. Under Scenario 2, the herd nutrient control strategies increase milk output per cow and net returns on both farms and reduce P content of manure and P runoff. Under Scenario 3, limiting P runoff reduces farm returns by 1 and 3% on the average and small farms, respectively. Under Scenario 4, the P runoff constraint is less costly, reducing returns by less than 1% on both farms. Animal nutrient control strategies should be an important part of pollution control policies and programs for livestock intensive watersheds.

NITROGEN (N) and phosphorus (P) runoff pose a threat to many waterbodies because accumulation of these nutrients can result in rapid algae growth, oxygen depletion when algae decompose, and accelerated eutrophication in saline and fresh waters (Fisher and Butt, 1994). Numerous federal and state policies reflect increasing public concern about nutrient runoff and necessary nonpoint-source pollution control. The National Pollutant Discharge Elimination System (NPDES), which resulted from the Clean Water Act of 1972, sets limits on discharges from point sources including large confined animal operations (over 1000 animal units) (Ribaud et al., 1999). The Coastal Zone Management Act Reauthorization Amendments require states with approved coastal zone management programs to develop nonpoint-source pollution control plans for coastal zone areas including agriculture (Ribaud et al., 1999).

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States are now required to develop Total Maximum Daily Loads (TMDLs) for waters where the applicable water quality standard has not been achieved (USEPA, 1991). The Chesapeake Bay Agreement signed in 2000 contains numerous protection and enhancement goals for the Chesapeake Bay including a reaffirmed commitment to achieve and maintain a 40% reduction in controllable nutrient loads to the Bay (Chesapeake Bay Program, 2000).

Agriculture has been affected because it is a major contributor to nonpoint-source pollution (USEPA, 1994). In some watersheds, dairy nutrient runoff is an important contributor to total nutrient loadings. Many dairies import some or most of their feeds, particularly concentrates. Some feed nutrients are excreted with manure. Manure spreading on adjacent cropland, the typical method of manure disposal, can result in increased risk of nutrient runoff. As a result, farms are being encouraged to develop nutrient management plans to adapt the timing, amount, and method of manure spreading to minimize risk of nutrient runoff.

A key change in water quality regulations in the past five years is the shift from a primary focus on N to an increasing focus on P contamination of surface water. Limiting manure application to the P needs of the crop is one way to avoid continued accumulation of P in soil and to minimize potential P runoff and contamination of surface water. Regulations limiting manure application to the P needs of the crop are in place for all farms in Maryland (Water Quality Improvement Act of 1998; State of Maryland, 1998) and for poultry farms in Virginia (Virginia Poultry Waste Management Program; State of Virginia, 1999). The recently finalized Federal Concentrated Animal Feeding Operation regulations to address water pollution call for site-specific decisions on whether N- or P-based manure application limits are needed to protect water quality (USEPA, 2003).

Reducing P runoff to acceptable levels may be more costly than controlling N because manures usually have more P relative to crop nutrient requirements than N. When manures are applied according to crop N requirements (as has been typical), the P applied in manure is often two- to fivefold greater than crop requirements. This imbalance results in a high soil P loading when manure applications are made to meet the N needs of agronomic crops. Research has shown that the high loading of P in excess of plant needs directly influences the amount of P in surface runoff (Sharpley, 1995; Sharpley et al., 1977, 1978, 1994, 1996; Daniel et al., 1994; Pote et al., 1996, 1999). While soil P is less mobile than N, high levels of soil P may result in dissolved P and sediment-adsorbed P transported with runoff and

Abbreviations: bST, bovine somatotropin; LDPP, long-day photoperiod; 3×, three times per day.

eroded sediment (National Research Council, 1993). Reducing P losses in runoff to acceptable levels for water quality may require dairy farms to reduce P content of manure, reduce manure application rates, or reduce potential for manure and sediment runoff with practices such as stream buffers, conservation tillage, and cover crops. Farmers and other watershed stakeholders have an interest in finding the most cost-effective methods for reducing P runoff and delivery to surface water. Cost-effective control methods reduce risks to the economic viability of dairy production in affected watersheds.

The purpose of this study is to evaluate the impacts of alternative P reduction practices on farm net returns and on potential P runoff and delivery to surface water. The P control practices are divided into three types: (i) dairy herd nutrient management; (ii) crop nutrient management; and (iii) runoff and erosion control. Dairy herd nutrient management refers to practices to reduce P excretion per unit of milk production. Crop nutrient management refers to changes in the quantity, method, and/or timing of nutrient applications including manure to reduce potential for P runoff. Runoff and erosion control includes practices to reduce the potential for runoff and sediment losses from the site where manure is applied and practices that reduce potential for nutrient delivery to surface water. The analysis is applied to simulated farms that are representative of farms in Muddy Creek watershed located in the Virginia Shenandoah Valley.

MATERIALS AND METHODS

Scenarios

Scenarios examined in the study include:

- Scenario 1: baseline with no constraint on P runoff with access to crop nutrient, runoff and erosion control strategies but no access to dairy herd nutrient control strategies.
- Scenario 2: no constraint on P runoff with access to all crop and herd nutrient control strategies.
- Scenario 3: constraint on P runoff with access to crop nutrient, runoff and erosion control strategies but no access to dairy herd nutrient control strategies.
- Scenario 4: constraint on P runoff with access to all crop and dairy herd nutrient control strategies.

Under Scenario 1, the baseline, farms attempt to maximize profits given the set of resources and practices that typify dairy farms in the region. There are no constraints on nutrient applications or nutrient losses except for the requirement that crop N, P, and potassium (K) requirements be met. Farms have access to crop nutrient management and runoff and erosion control strategies but not herd nutrient management strategies. Herd nutrient management strategies are less well known in the study area compared to crop nutrient management and runoff and erosion control methods. The farms are assigned six months of manure storage for dairy and/or broiler operations, which is typical of farms in the area (G. Spitler, USDA Farm Service Agency, Harrisonburg, VA, personal communication, 2000). Both no-till and conventional-till cultivation are available to the farm. Under Scenario 2, farms have full access to all herd and crop nutrient control strategies including runoff and erosion control.

Under Scenario 3, farmers face a constraint on P runoff from their farms. Runoff is constrained to be lowered by 40% relative to the baseline. A 40% reduction is selected because it is consistent with the nutrient reduction goal of the Chesapeake Bay Agreement, which includes the study area (Chesapeake Bay Program, 2000). Access to nutrient reduction technologies is the same as under Scenario 1. Scenario 4 includes full access to all nutrient control strategies similar to Scenario 2 and the constrained 40% reduction in P runoff similar to Scenario 3.

Study Area and Representative Farms

The representative farms were based on dairy farms in the Muddy Creek watershed located in the Upper Shenandoah Valley of Virginia. Farms were characterized based on digital soils and land use data from the Virginia Department of Conservation and Recreation; personal interviews with a panel of dairy farmers in the area (Parsons, 1995); and personal interviews with extension and natural resource conservation specialists familiar with the watershed. The Muddy Creek watershed contains approximately 120 farms with a combined area of about 5260 ha, of which half contain dairy operations. Herd sizes in this area range from small (about 60 cows) to medium (100 cows) to large (150 cows) (Parsons, 1995). Half of the dairy farms have a supplementary broiler or turkey feeding operation.

Four case farms are specified: (i) an average dairy farm with 100 cows and average amount of cropland (Parsons, 1995) (average dairy); (ii) an average size, 100-cow dairy farm with a supplemental poultry (broiler) operation (average dairy-poultry); (iii) a 100-cow dairy with lower than average amount of cropland (small dairy); and (iv) a 100-cow dairy with below average cropland and a supplemental broiler operation (small dairy-poultry). The average dairy reflecting average conditions in the watershed was created by selecting a set of contiguous fields in Muddy Creek watershed with land area totaling 67.7 ha or 0.67 ha per cow (Table 1). The small dairy was created by selecting a subset of fields with total area of 40.9 ha. The dairy-poultry farms are assigned two broiler houses, with each house producing 160 000 birds/yr.

The farm models are constructed as linear programming models written in General Algebraic Modeling System (GAMS) (Brooke et al., 1998). The farms' objective function is to maximize returns above variable costs subject to physical resource constraints and technical requirements for dairy, poultry, and crop production. Gross revenues per cow include milk sales (\$0.36/kg), sales of cull cows, bull calf sales, and patronage dividends. Broiler contract payments are \$26 625 per year per house plus revenue from sales of broiler litter. Variable costs of crop and livestock production including feed and nutrient purchases are subtracted. All costs and revenues are expressed in 2001 dollars.

Crop Production

The sum of crop production plus purchases is required to equal crop sales plus crops fed on the farm. Yields and minimum nutrient requirements (N, P, and K) of crops and pasture by soil type and slope are based on the Virginia Agronomic Land Use Evaluation System (VALUES) (Donohue et al., 1994; Moore and White, 1980). Slopes and soil types assigned to each field are based on the SSURGO digital database provided by the Natural Resources Conservation Service (2004). Farm land is about equally divided into 0 to 7.49 and 7.5 to 15% slopes, and the major soil type is Frederick (Table 1).

Table 1. Labor, land, and livestock facilities of representative dairy and dairy-poultry farms.

	Average dairy	Average dairy-poultry	Small dairy	Small dairy-poultry
Milking capacity, number of cows	100	100	100	100
Annual broiler production capacity, 1000 birds	0	320	0	320
Full-time labor available, h				
Winter (December-February)	1518	1847	1474	1802
Spring (March-May)	1856	2257	1801	2203
Summer (June-August)	1518	1847	1474	1802
Fall (September-November)	1856	2257	1801	2203
Total annual	6748	8208	6550	8010
Total crop and pasture land, ha	67.7	67.7	40.9	40.9
Land by slope class, ha				
0-7.49%	36.9	36.9	22.4	22.4
7.50-15%	30.8	30.8	18.5	18.5
Land by soil type, ha				
Frederick (clayey, mixed, mesic Typic Paleudults)	50.0	50.0	26.5	26.5
Buckton (fine loamy, mixed, mesic Typic Udifluvents)	7.9	7.9	7.9	7.9
Chilhowie (very fine, mixed, mesic Typic Hapludalfs)	6.5	6.5	3.4	3.4
Shenval (fine, mixed, mesic Typic Paleudalfs)	3.1	3.1	3.1	3.1
Endcav (very fine, mixed, mesic Typic Hapludalfs)	0.1	0.1	0.0	0.0

Livestock Production

Dairy production is limited to no more than 100 cows, the facility limit of each farm. Three alternative dairy rations with roughage provided primarily by rye (*Secale cereale* L.) silage, corn (*Zea mays* L.) silage, and alfalfa (*Medicago sativa* L.) are included.

Manure Production

All manure production has to be spread or sold within the year. Sale prices per Mg for broiler litter are \$8.81, \$4.41, \$6.62, and \$4.41 in spring, summer, fall, and winter, respectively (James Pease, Department of Agricultural and Applied Economics, Virginia Tech, personal communication). Because liquid dairy manure is bulky relative to its nutrient content, dairy farmers who export manure are assumed to give the manure away and pay the transportation charge for a haul of 96 km or less resulting in a negative dairy manure export price of -\$6.97/1000 L. Manure spreading costs on cropland are \$1.95/1000 L of dairy manure (VanDyke, 1997) and \$5.78/Mg of poultry litter (Bosch and Napit, 1991).

Labor

Full-time labor available on the farm (operator, family, and permanent hired labor) is equal to 7.4 h times the number of hectares of crop and pasture land plus the labor requirement of livestock enterprises (Table 1). Part-time seasonal labor can be hired at \$7.50/h (Virginia Cooperative Extension, 2001), but seasonal hiring cannot exceed one-third of full-time labor.

Potential Phosphorus Runoff

Potential P runoff (dissolved and sediment-bound P) for each combination of field, crop, tillage, and P application rate was estimated for each field using the GLEAMS model (Leonard et al., 1987). The field-scale GLEAMS model simulates edge-of-field and bottom-of-root-zone loadings of water, sediment, pesticides, and plant nutrients. Phosphorus mineralization, immobilization, and plant uptake processes, as well as dissolved and sediment P losses through surface runoff and dissolved P leaching through the soil profile are simulated in GLEAMS. While GLEAMS is not an absolute predictor, numerous evaluations indicate that it is useful for evaluating relative effects of management on nutrient and chemical loadings (Leonard et al., 1987; Knisel et al., 1991; Diebel et al., 1995; Hopkins et al., 1996; Shirmohammadi et al., 1998; Bakhsh et al., 2000; Knisel and Turtola, 2000).

Average annual P loss in runoff (dissolved and absorbed to sediment) was estimated based on a 10-yr GLEAMS simulation with weather inputs simulated using the CLIGEN (Nicks et al., 1995) weather generator. For each field, various combinations of crops, tillage practices, and P application rates were simulated. Input data were based on characteristics of crops, tillage practices, and P application in the study area. Resulting P runoff estimates are entered into the farm model for each combination of field, crop, tillage, and P application rate. Total P runoff for the farm is the sum of P runoff from each crop and nutrient application activity on the farm.

Herd Nutrient Management Strategies

Nine nutrient management strategies for lactating cows are compared (Table 2): (i) no P overfeeding, (ii) P overfeeding, (iii) administration of bovine somatotropin (bST) to lactating cows with no overfeeding of P, (iv) three-times-per-day milking (3× milking) with no P overfeeding, (v) long-day photoperiod (LDPP) with no P overfeeding, (vi) bST and 3× milking with no P overfeeding, (vii) bST and LDPP with no P overfeeding, (viii) LDPP and 3× milking with no P overfeeding, and (ix) bST, LDPP, and 3× milking with no P overfeeding. The third through ninth strategies rely on increasing milk production per cow to reduce P excretion per unit of milk. The maintenance requirements of a cow, which are the nutrients required just to maintain the cow's body, must be met before any production (growth, milk, pregnancy) can occur. Because maintenance requirements are the same regardless of milk yield, and because these requirements are met first, increasing milk yield to dilute the "fixed cost" of maintenance increases the efficiency of nutrient utilization by the animal and decreases manure nutrient excretion per unit of product (i.e., fecal P/milk P) (Table 2) (Dunlap et al., 2000).

Administration of Bovine Somatotropin

Injecting lactating cows with exogenous bST triggers a series of coordinated changes in metabolism that increases feed efficiency and milk production (Thomas et al., 1991; Bauman, 1992). The use of bST typically increases milk yield by 4.9 kg/cow/d, although significant variation is observed among herds and cows (Thomas et al., 1991). Approximately one third of the cows in the United States (3 million cows) are in herds supplemented with bST. Typically, 50% of mature cows within herds using bST are receiving the hormone at any one time.

Exogenous bST is implemented in the farm model with 16 biweekly injections of 500 mg of bST in a liquid, prolonged-

Table 2. Total milk yield and P excretion, added variable costs, and added labor per cow lactation by dairy herd nutrient management strategy.[†]

Herd nutrient management strategy	Milk yield	Added variable costs (excluding feed and labor) [‡]	Added labor	P excreted	P excreted
	kg	\$	h	kg	g/kg milk
Control, no overfeeding	9 693	–	0.00	17.68	1.82
Control, with overfeeding	9 693	–	0.00	28.57	2.95
Bovine somatotropin (bST) [§]	10 844	119.71	0.80	18.68	1.72
Three-times-per-day (3×) milking	10 760	24.94	10.68	18.60	1.73
Long-day photoperiod (LDPP) [#]	10 455	48.92	0.00	18.34	1.75
bST + 3× milking	11 912	144.65	11.48	19.79	1.66
bST + LDPP	11 607	168.62	0.80	19.52	1.68
LDPP + 3× milking	11 523	73.86	10.68	19.26	1.67
bST + LDPP + 3× milking	12 674	193.57	11.48	20.43	1.61

[†] All figures are values per cow per 305-d lactation period.

[‡] Additional variable costs included for each treatment are the following: bST, injections and syringes; LDPP, utilities and light fixtures; 3× milking, utilities and milking supplies. An additional \$0.023/kg was charged for milk hauling and assessment for production that exceeded the conventional production level. Feed costs are endogenous to the model because some feed is raised on the farm.

[§] Administration of bovine somatotropin from Day 70 to Day 305 of lactation.

^{||} Three-times-per-day milking throughout the lactation.

[#] Adoption of long-day photoperiod technology throughout the lactation.

release form beginning at Day 70 of lactation for all cows. The cost of product is \$5.80 per dose with no additional capital expense for this practice. Additional labor to administer bST is 3 min per cow per dose, or 0.8 h/cow/lactation. Injection of bST increases milk yield by 1151 kg/cow/lactation (Thomas et al., 1991). Feed intake increases by 1.65 kg/d during administration of bST (National Research Council, 2001).

Long-Day Photoperiod

Extending the daily photoperiod to 16 h light and 8 h dark by using artificial lighting increases milk yield by 2.5 kg/d compared to cows exposed to 12 h/d or less of light (Dahl et al., 2000). Feed intake increases in response to the increased milk yield. In a survey conducted in 2001, 32.4% of respondents indicated that they were using supplemental photoperiod lighting to extend daylength for the milking herd (Geoff Dahl, personal communication).

A LDPP is simulated in the farm model based on artificial lighting. Installation of 29, 250-W metal halide lamps produces about 69 cd/m² for 16 h a day in a 13.72- by 67.07-m, open-sided, free-stall barn. Installation costs (including labor) are \$285 per lamp, and one timer is installed (\$145) to control the light-dark cycle. The lamps and timer are amortized over the 20-yr life of the facility. Increasing the length of the daily photoperiod increases milk yield by 763 kg/cow/lactation (Dahl et al., 2000). Feed intake increases by 0.83 kg/d (National Research Council, 2001).

Three-Times-per-Day Milking

While most dairy cows are milked twice daily, increasing milking frequency increases milk yield. The proportion of cows milked three times a day was 23.5% in 2001 (Dairy Herd Improvement Association, 2002). The technology increases milk yield by 1068 kg/lactation (Erdman and Varner, 1995), increases dry matter intake (DMI) by 1.17 kg/d (National Research Council, 2001), and increases labor for the 100-cow herd by 3.5 h/d. No additional capital investment is required.

Phosphorus Overfeeding

Reduced overfeeding of dietary P reduces P content of manure and purchased feed costs. Knowlton and Kohn (1999) found that 32 of 33 Virginia dairies sampled were overfeeding P by an average of 45% with average dietary P content of 0.49% compared to a requirement of 0.34% (National Research Council, 2001). Severe P deficiencies may impair repro-

ductive performance of cows, but there is no evidence that feeding P in excess of P requirements will enhance performance (Brodison et al., 1989; Brintrup et al., 1993; Wu et al., 2000, 2001).

Phosphorus requirements are formulated for milk production levels. For cows without bST, LDPP, or 3× milking, production is set at 31.7 kg/d milk (9693 kg/305 d lactation), which was the average milk production of Holstein herds on a Dairy Herd Improvement Association test in Rockingham County (Virginia) in April 2002. Rations are formulated using lead factors (Stallings and McGilliard, 1984), with the target milk yield set at one standard deviation (6.5 kg/d) above herd average milk yield, ensuring that 83% of the cows in the group will receive adequate or more than adequate nutrients. Dry matter intake is predicted for the baseline herd and for each management strategy based on target milk yield, a body weight of 600 kg, and 150 d in milk (National Research Council, 2001).

Corn silage, alfalfa hay, or rye silage rations are formulated to meet the energy and protein requirements of cows based on their milk production (National Research Council, 2001). With overfeeding of P, diets are formulated to contain 0.49% P to reflect current industry practice of overfeeding P. With no overfeeding, dietary P in the baseline rations meets requirements.

Combinations of Bovine Somatotropin, Three-Times-per-Day Milking, and Long-Day Photoperiod

The effects of bST, long-day photoperiod, and three-times-per-day milking on milk yield and feed intake are additive (Dunlap et al., 2000). The effects of these technologies on P excretion are also additive.

Manure Excretion

Baseline Excretion

Nutrient excretion by livestock can be predicted as the difference between nutrient intake and nutrient retained in body weight gain, fetal development, and milk, meat, or eggs (Van Horn et al., 1996). Evaluation of this mass balance model indicates that it predicts manure nutrient excretion as accurately as more complicated multivariate equations (Van Horn et al., 1994; Tomlinson et al., 1996).

In this study, excretion of N, P, and K by lactating cows equals the difference between nutrient intake and nutrient secretion in milk. Milk P content is 0.9 g/kg, milk N content is 4.7 g/kg, and milk K content is 1.5 g/kg (National Research Council, 2001). Intakes of N, P, and K equal the product of

predicted dry matter intake and the concentration of each nutrient in the diet. Dry matter intake is predicted based on fat-corrected milk yield, body weight, and week of lactation (National Research Council, 2001). Nutrient excretion by heifers equals the difference between nutrient intake and nutrient retention in body weight gain. Nutrient excretion by dry cows equals the difference between nutrient intake and weight gain during late pregnancy associated with fetal tissues. Dietary nutrient intake is based on meeting dry cow dietary requirements for maintenance, growth, and pregnancy (National Research Council, 2001). Manure excretion (kg dry matter per day) is calculated based on 90% digestibility of consumed dry matter for calves 0 to 2 mo of age and 65% digestibility of consumed dry matter for all others.

Broiler litter production on a wet basis (including manure plus bedding and feed waste) is 1.13 Mg per 1000 birds (Virginia Department of Conservation and Recreation, 1995). Nutrient content is 3.58% N, 2.91% P₂O₅, and 2.17% K₂O (wet basis) (Pease and Mullins, 2001).

Crop Nutrient Management

Nutrient management adjusts plant nutrient applications (N, P, and K) for expected crop production and water quality protection (Bosch and Wolfe, 1998). While nutrient management based on crop N requirements may increase farm net returns (Van Dyke et al., 1999), P-based nutrient management may reduce net returns, because the high manure P content relative to crop requirements restricts manure applications and increases costs of supplemental commercial N and K fertilizer (Parsons, 1995; Feinerman et al., 2004).

In this study, crop nutrient management is represented by varying manure application rates and methods. Application methods include surface application with and without incorporation. Incorporation is achieved by disking the field after spreading manure. Three application rates are used: 0.5, 1.0, and 3.0 times the recommended P application rate. Higher

application rates can be used to apply sufficient manure to meet N and K nutrient needs of the crop. With lower rates, it may be necessary to apply commercial N and/or K to supplement manure applications.

Runoff and Erosion Control

Runoff and erosion control strategies include no tillage, cover crops, and crop rotations. Twelve continuous corn rotations are included: conventional-till or no-till corn silage or corn grain with (i) no cover, (ii) unharvested rye cover, or (iii) harvested rye silage. Four corn-alfalfa rotations are included: conventional-till or no-till corn grain or corn silage (2 yr) with alfalfa (4 yr). Continuous orchard-grass (*Dactylis glomerata* L.) red clover (*Trifolium pratense* L.) hay rotations with conventional- and no-till establishment are included. No-till corn silage and corn grain yields are 10% higher than conventional-till (Virginia Cooperative Extension, 2001), while alfalfa and orchard-grass-clover hay yields are not affected by establishment tillage.

RESULTS

Scenario 1

With no limit on P runoff and no access to herd nutrient management strategies, the average dairy with poultry has the highest total gross margins (defined as total gross revenues minus total variable costs) followed by the small dairy with poultry (Table 3). All farms produce the limit of milk based on their facilities, which is common in the region. All dairy manure produced is spread on farm, which is the typical practice in the region. The small dairies produce 25 ha of corn silage (10 of which are double-cropped with rye silage) and 16 ha of pasture (Table 4). The average dairies produce

Table 3. Dairy and dairy-poultry farm net returns, milk production, and manure sales with and without herd nutrient management strategies and limits on P runoff.

Output variable	Farm type	No herd nutrient management strategies, no limit on P runoff (Scenario 1)	Crop and herd nutrient management strategies, no limit on P runoff (Scenario 2)	No herd nutrient management strategies, P runoff reduced 40% (Scenario 3)	Crop and herd nutrient management strategies, P runoff reduced 40% (Scenario 4)
Total gross margins, \$	small dairy	137 648	183 301	133 083	182 275
	small dairy-poultry	178 133	224 334	173 568	223 308
	average dairy	146 066	191 703	144 600	190 951
	average dairy-poultry	186 551	232 736	185 085	231 984
Total milk output, Mg	small dairy	969	1267	969	1267
	small dairy-poultry	969	1267	969	1267
	average dairy	969	1267	969	1267
	average dairy-poultry	969	1267	969	1267
Total broiler output, 1000 birds	small dairy	0	0	0	0
	small dairy-poultry	320	320	320	320
	average dairy	0	0	0	0
	average dairy-poultry	320	320	320	320
Dairy manure spread, 1000 L	small dairy	5387	6009	4882	6009
	small dairy-poultry	5387	6009	4882	6009
	average dairy	5387	6009	5387	6009
	average dairy-poultry	5387	6009	5387	6009
Dairy manure sold, 1000 L	small dairy	0	0	505	0
	small dairy-poultry	0	0	505	0
	average dairy	0	0	0	0
	average dairy-poultry	0	0	0	0
Broiler litter sold, Mg	small dairy	0	0	0	0
	small dairy-poultry	363	363	363	363
	average dairy	0	0	0	0
	average dairy-poultry	363	363	363	363
Total manure revenue, \$	small dairy	0	0	-3525	0
	small dairy-poultry	3000	3000	-525	3000
	average dairy	0	0	0	0
	average dairy-poultry	3000	3000	3000	3000

Table 4. Crops grown and purchased on dairy and dairy poultry farms with and without herd nutrient management strategies and limits on P runoff.

Output variable	Farm type	No nutrient management strategies, no limit on P runoff (Scenario 1)	Nutrient management strategies, no limit on P runoff (Scenario 2)	No nutrient management strategies, P runoff reduced 40% (Scenario 3)	Nutrient management strategies, P runoff reduced 40% (Scenario 4)
Crops grown (ha)					
No-till corn silage	small dairy	14.7	0.0	0.0	0.0
	small dairy-poultry	14.7	0.0	0.0	0.0
	average dairy	49.1	41.2	18.7	14.8
Conventional-till corn silage	average dairy-poultry	49.1	41.2	18.7	14.8
	small dairy	10.0	24.7	12.5	16.6
	small dairy-poultry	10.0	24.7	12.5	16.6
Rye silage	average dairy	0.7	10.2	20.9	18.4
	average dairy-poultry	0.7	10.2	20.9	18.4
	small dairy	10.0	24.7	12.5	16.6
Pasture	small dairy-poultry	10.0	24.7	12.5	16.6
	average dairy	0.7	10.2	20.9	18.4
	average dairy-poultry	0.7	10.2	20.9	18.4
Corn grain	small dairy	16.3	16.3	28.5	24.3
	small dairy-poultry	16.3	16.3	28.5	24.3
	average dairy	17.8	16.3	28.0	34.5
	average dairy-poultry	17.8	16.3	28.0	34.5
Crops purchased (Mg)					
Corn grain	small dairy	202.6	245.3	205.6	235.5
	small dairy-poultry	202.6	245.3	205.6	235.5
	average dairy	190.8	228.0	215.9	237.9
	average dairy-poultry	190.8	228.0	215.9	237.9
Corn silage	small dairy	617.0	608.0	953.9	969.4
	small dairy-poultry	617.0	608.0	953.9	969.4
	average dairy	0.0	11.0	18.1	432.9
	average dairy-poultry	0.0	11.0	18.1	432.9
Grass hay	small dairy	66.2	84.0	9.5	46.4
	small dairy-poultry	66.2	84.0	9.5	46.4
	average dairy	58.9	84.0	12.5	0.0
	average dairy-poultry	58.9	84.0	12.5	0.0
Soybean oil meal	small dairy	202.6	245.3	205.6	235.5
	small dairy-poultry	202.6	245.3	205.6	235.5
	average dairy	190.8	228.0	215.9	237.9
	average dairy-poultry	190.8	228.0	215.9	237.9
Alfalfa hay	small dairy	202.6	245.3	205.6	235.5
	small dairy-poultry	202.6	245.3	205.6	235.5
	average dairy	190.8	228.0	215.9	237.9
	average dairy-poultry	190.8	228.0	215.9	237.9

50 ha of corn silage (1 in rotation with rye) and 18 ha of pasture. All farms purchase corn grain, orchard-grass hay, soybean [*Glycine max* (L.) Merr.] oil meal, and alfalfa hay. The small dairies buy 617 Mg of corn silage as well.

Dairy P excretion as P₂O₅ was slightly under 7000 kg (7.2 kg per Mg milk) (Table 5). Farm-level P₂O₅ applications are about double the recommended applications on all farms meaning that about half of the P₂O₅ application is excess P. The small dairies have higher excess P than the average dairies due to higher manure P production per unit of land. Estimated average annual P₂O₅ runoff was 24.3 kg/ha and 35.1 kg/ha from small and average dairies, respectively.

Scenario 2

With access to herd nutrient management, all farms shift cows to bST, LDPP, and 3× milking with no P overfeeding. Total gross margins increase by 25 to 33% as a result of 31% increases in milk sales (Table 3). Purchases of corn grain, grass hay, soybean oil meal, and alfalfa increase to support the higher milk production (Table 4). While dairy manure production increases by 12% with higher feed intake, P excretion declines by 27% and P excretion per Mg of milk sales declines by

almost one half due to reduced P feeding and higher milk yields per cow (Table 5). These trends are also shown in Table 2, where reduced overfeeding lowers P excreted by 1.13 g/kg milk (from 2.95 to 1.82 g/kg) and the use of bST, LDPP, and 3× milking further reduced P excretion to 1.61 g/kg of milk. These reductions occur independently of the forage base of the control diet, as all diets are formulated to contain the same amount of P, and the availability of feed P is assumed to be the same across diets.

Excess P₂O₅ applications decline by 90% or more on all dairies as a result of the lower P₂O₅ content of dairy manure applied (which declines by 27% on all farms) and higher P₂O₅ soil recommendations (+26 to 45%) for the crops produced (Table 5). The P₂O₅ recommendations increase because of the shift from continuous corn silage to a corn silage-rye rotation. The corn-rye rotation increases from 1 to 10 ha on the average dairies and from 10 ha to 25 ha on the small dairies due to higher feed requirements of cows on bST, long-day photoperiod, and three times a day milking. With lower P₂O₅ applications, P₂O₅ runoff declines as well although the reductions are smaller than reductions in applications, 10% on the average size dairies and 21% on the small dairies.

Table 5. Phosphate (P₂O₅) excretion, applications, and runoff on dairy and dairy poultry farms with and without herd nutrient management strategies and limits on P runoff.

Output variable	Farm type	No nutrient management strategies, no limit on P runoff (Scenario 1)	Nutrient management strategies, no limit on P runoff (Scenario 2)	No nutrient management strategies, P runoff reduced 40% (Scenario 3)	Nutrient management strategies, P runoff reduced 40% (Scenario 4)
Dairy P ₂ O ₅ excretion, kg	small dairy	6997	5133	6997	5133
	small dairy-poultry	6997	5133	6997	5133
	average dairy	6997	5133	6997	5133
	average dairy-poultry	6997	5133	6997	5133
Dairy P ₂ O ₅ excreted per Mg milk, kg	small dairy	7	4	7	4
	small dairy-poultry	7	4	7	4
	average dairy	7	4	7	4
	average dairy-poultry	7	4	7	4
P ₂ O ₅ application, kg	small dairy	6997	5133	6340	5133
	small dairy-poultry	6997	5133	6340	5133
	average dairy	6997	5133	6997	5133
	average dairy-poultry	6997	5133	6997	5133
P ₂ O ₅ recommendation, kg	small dairy	3286	4751	3357	3833
	small dairy-poultry	3286	4751	3357	3833
	average dairy	3904	4932	5800	5511
	average dairy-poultry	3904	4932	5800	5511
P ₂ O ₅ excess application, kg†	small dairy	3711	382	2983	1300
	small dairy-poultry	3711	382	2983	1300
	average dairy	3092	200	1196	-378
	average dairy-poultry	3092	200	1196	-378
Estimated P ₂ O ₅ runoff, kg (kg/ha)	small dairy	994 (24.3)	781 (19.1)	596 (14.6)	596 (14.6)
	small dairy-poultry	994 (24.3)	781 (19.1)	596 (14.6)	596 (14.6)
	average dairy	2376 (35.1)	2134 (31.5)	1426 (21.1)	1426 (21.1)
	average dairy-poultry	2376 (35.1)	2134 (31.5)	1426 (21.1)	1426 (21.1)

† Excess P₂O₅ application = P₂O₅ application - recommended P₂O₅ application.

Scenario 3

With mandated 40% reductions in P runoff, P₂O₅ runoff declines to 14.6 kg/ha and 21.1 kg/ha on the small and average dairies, respectively. Milk production, cow numbers, P excretion, and broiler production are not affected. Total gross margins decline from Scenario 1 by about \$4500 (3%) and \$1500 (1%) on the small and average dairies, respectively. Most of the reduction in revenue on small farms is due to cost of exporting dairy manure. The small dairies sell 505 000 L of manure at a cost of \$3525. A part of the revenue reduction on small farms and all revenue reductions on average farms are due to shifting crops and nutrient applications to utilize more manure P and reduce P runoff. Farms have increased costs of \$700 to \$1000 for purchases of commercial N and K made necessary by reduced spreading rates of manure on some fields. All dairies increase double crop corn-rye and grass pasture compared to the baseline at the expense of continuous corn with no rye. These changes increase the small farms' expenditures for purchased feed by over \$6000. Overall P runoff declines because of the much lower P runoff from grass pasture compared to corn silage which it replaces.

Scenario 4

Reducing total P runoff by 40% is less costly when herd nutrient management strategies are available. Compared to Scenario 1, total gross margins increase by 24 to 32%, a slightly smaller increase than is obtained by implementation of herd nutrient management strategies without the restriction in P runoff (Scenario 2). Compared to Scenario 1, total milk output increases and manure P₂O₅ excretion declines. These changes with implementation of herd strategies are similar to the changes

realized under Scenario 2. Farms are able to apply all dairy manure to their crops and only broiler litter is exported. The P runoff reductions are obtained by shifting some crops from corn silage to pasture. While overall P runoff declines, crop changes increase feed expenditures by \$15 000 compared to Scenario 1 primarily due to increased corn silage purchases.

DISCUSSION

Simulation model results indicate that herd nutrient management strategies have potential to create "win-win" opportunities for dairy producers by increasing milk output and farm revenues while reducing the P content of manure and the potential for P runoff. Herd nutrient management strategies alone (Scenario 2) can reduce P runoff by 10 to 21%, one-fourth to one-half of the 40% reduction goal, without reducing cow numbers and without large changes in crop production. The remainder of the 40% reduction goal is achieved by shifting crop rotations, primarily increasing pasture and double-cropped corn silage-rye and reducing continuous corn silage without rye (Scenario 4). Total manure applied increases and some crops or pasture receive higher rates of manure than recommended to meet crop P requirements. However, overall P runoff declines because of lower P content of manure and lower runoff potential of manure applications to pasture. When herd nutrient management strategies are unavailable (Scenario 3), small farms have to export dairy manure, which is costly. Exports of dairy manure may increase potential P runoff in receiving areas unless soils in these areas are low in P.

The farms' compliance costs for a 40% reduction in P runoff equal the reduction in farms' total gross margins compared to the baseline (Scenario 1). Without herd

nutrient management strategies (Scenario 3), simulation results indicate farm costs of \$4565 for small dairies with and without poultry and \$1466 for average dairies with and without poultry (Table 6). With herd nutrient management strategies (Scenario 4), estimated costs are -\$45 175 and -\$44 627 for the small dairy with and without poultry, respectively, and -\$45 433 and -\$44 885 for the average dairy with and without poultry, respectively. Negative costs indicate that farm returns increase with the adoption of herd nutrient management strategies.

Under Scenarios 3 and 4, farms' purchases of corn silage increase due to changes in crop rotations. If many farms in a dairy-intensive area increase silage or other forage purchases, forage prices might rise. The sensitivity of the compliance costs of a P runoff restriction to changes in forage prices is evaluated by raising costs of purchased forages by 10% under Scenarios 3 and 4. The estimated cost of complying with a 40% runoff reduction increases to \$7246 for small dairies and \$1534 for average dairies (Table 6). The sensitivity index for small dairies (calculated as the percentage change in cost divided by percentage change in forage price) is 5.9 indicating high sensitivity of farm compliance costs to changes in forage prices resulting from the runoff restriction. Sensitivity index for the average dairies is 0.5 indicating their costs are less sensitive to forage price changes because they are more self sufficient in forages. Compliance costs under Scenario 4 are less sensitive to forage price changes. The increased forage price reduces farm returns slightly causing the compliance cost to be slightly less negative compared to the baseline for all farm types.

A P runoff restriction could lower manure sale prices if manure surpluses are increased on livestock-intensive farms. Without herd nutrient management strategies (Scenario 3), a 10% reduction in dairy manure prices increases the compliance costs of the small dairy (Table 6). The sensitivity index of -0.8 indicates that a 10% reduction in dairy manure price results in an 8% increase in the small dairies' compliance costs. Average farms are not affected under Scenario 3 and no farms are affected under Scenario 4 because dairy manure is not sold. A

10% reduction in broiler litter price increases estimated compliance costs of the small and average dairies with poultry by 7 and 20% , respectively. The average dairy's costs are more affected in percentage terms because the initial cost of the runoff restriction is less. With herd nutrient management strategies (Scenario 4), farms' compliance costs are not very sensitive to changes in poultry litter prices.

The effect of manure storage on farm costs is investigated by allowing farms to build more storage at an annual cost of \$0.57/1000 L of dairy manure (VanDyke, 1997) and \$2.52/Mg of broiler litter (Bosch and Napit, 1991). Additional storage is not constructed under any scenario and does not affect farms' compliance costs. Six months of storage is adequate for on-farm or off-farm disposal under all scenarios.

CONCLUSIONS

Requiring reductions in P runoff can impose costs on dairy farms. If herd nutrient management strategies are not used to control P content, simulation results show that returns are reduced 3 and 1% on dairy farms with small and average land area, respectively. The reduction in returns is greater on small farms which have less flexibility to adapt crop rotations and are forced to export dairy manure at high cost to meet the restriction. With herd nutrient control strategies available (Scenario 4), the P runoff constraint is less costly. Simulated farm returns with herd nutrient control strategies increase relative to the baseline because the herd nutrient control practices lower P manure content and P runoff potential while increasing milk output and dairy returns per cow. Compliance costs, which equal the reduction in farm returns as a result of the P runoff restriction, may be affected by changes in forage purchase or manure sale prices. Dairy farms with small land area are particularly sensitive to changes in forage prices resulting from P runoff restrictions.

Results demonstrate the importance of considering all sources of nutrient inputs when developing farm pollution control strategies. Livestock-intensive farms may be able to control nutrient pollution at lower costs by

Table 6. Costs to dairy and dairy-poultry farms of achieving 40% P runoff reduction under alternative forage purchase and manure sale prices.

	Cost†	10% increase in forage purchase prices		10% reduction in dairy manure sale price		10% reduction in broiler litter sale price	
		Cost†	SI‡	Cost†	SI‡	Cost†	SI‡
	\$		%	\$	%	\$	%
Without herd nutrient management strategies (Scenario 3)							
Small dairy	4565	7246	5.9	4917	-0.8	4565	0.0
Small dairy-poultry	4565	7246	5.9	4917	-0.8	4865	-0.7
Average dairy	1466	1534	0.5	1466	0.0	1466	0.0
Average dairy-poultry	1466	1534	0.5	1466	0.0	1766	-2.0
With herd nutrient management strategies (Scenario 4)							
Small dairy	-44 627	-41 837	-0.6	-44 627	0.0	-44 627	0.0
Small dairy-poultry	-45 175	-42 384	-0.6	-45 175	0.0	-44 875	-0.1
Average dairy	-44 885	-44 380	-0.1	-44 885	0.0	-44 885	0.0
Average dairy-poultry	-45 433	-44 928	-0.1	-45 433	0.0	-45 133	-0.1

† Cost equals farm's total gross margins under baseline (Scenario 1) minus total gross margins under the scenario being analyzed.

‡ SI equals percentage change in cost divided by percentage change in the indicated parameter.

focusing on ways to adjust nutrient content of manure rather than focusing only on the crop portion of the farm system. Animal nutrient control strategies should be an important part of pollution control policies and programs for livestock intensive watersheds. Further research on animal nutrient control strategies is needed to develop cost effective methods of lowering nutrient loadings from livestock operations.

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