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Cost-Effectiveness of Nutrient Management and Buffers: Comparisons of Two Spatial Scenarios

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Farmers and taxpayers would benefit from more cost-effective agricultural nutrient pollution control measures. The objectives of our study are (1) to assess compliance costs and reductions in phosphorus loadings from implementation of nutrient management and riparian buffers; and (2) to estimate how the spatial scenario, which is the method of representing farms within the watershed, affects estimated compliance costs and reductions in phosphorus deliveries. Estimated compliance costs are quite sensitive to the spatial scenario. Buffers are more cost-effective than nutrient management under one of the two spatial scenarios, whereas nutrient management is more cost-effective under the other scenario. Shifts to more erosive crops reduce the effectiveness of both pollution control measures.

Key Words: compliance costs, geographic information systems (GIS), mathematical programming, nutrient management, phosphorus (P), pollution abatement, riparian buffers, spatial analysis

JEL Classification: Q12, Q52

Nonpoint source (NPS) pollution is the leading cause of U.S. water quality problems. Agriculture has been identified as a major source of NPS pollution in those lakes and rivers that do not meet state water quality goals in compliance with the U.S. Clean Water Act of 1972 (USEPA 2003). The Chesapeake Bay does not meet Clean Water Act water quality standards, and the Bay partners (Chesapeake Bay Commission, District of Columbia, Maryland, Pennsylvania, Virginia, and USEPA) participating in the Chesapeake Bay Agreement 2000 (Chesapeake Bay Program 2005) have committed to meeting water quality standards by 2010 to avoid the potential for required watershed-wide nutrient reductions. Agriculture is estimated to contribute 41% of nitrogen (N) and 47% of phosphorus (P) entering the Bay (Chesapeake Bay Program 2004).

Prior to the Chesapeake Bay Agreement 2000, agricultural water quality protection programs of the Bay partners emphasized adoption of Best Management Practices (BMPs) to reduce N pollution. Current programs focus on both N and P pollutant reductions resulting from nutrient applications. The Virginia Poultry Waste Management Act of 1999 (Code of Virginia §62.1-44.17:1.1) re-

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stricts poultry litter and any supplementary nutrient applications on permitted poultry farms to the more limiting of either N- or P-recommended agronomic application rates. These limitations can increase farmers' costs because poultry litter and other livestock manures typically have N:P ratios that are lower than those recommended for optimal crop growth. If manure applications are limited to the amount that meets the P recommendations for the crop, farmers may need to meet the remaining N, and perhaps potassium (K), recommendations with supplemental N and K fertilizer at additional cost.

Policy makers and environmental protection program managers in the Bay states and elsewhere strongly support nutrient management planning and installation of vegetated riparian buffers to reduce nutrient pollution from agriculture. The Conservation Reserve Enhancement Program (CREP), a cooperatively funded effort of the Bay Partner states and the Natural Resources Conservation Service (NRCS), has set a goal of installing 157,000 miles of riparian buffers, filter strips, and wetlands in Pennsylvania, Maryland, and Virginia (NRCS 2005). All Bay states have programs to encourage voluntary nutrient management planning; animal feeding operations of sizes well below the federally mandated Concentrated Animal Feeding Operation (CAFO) limits are required by law to have nutrient management plans (USEPA 2005). Nutrient management planners estimate a field-specific balance of crop nutrient needs and base applications on desired cropping practices, soil nutrient resources, nutrient concentrations and application methods, and field-specific characteristics. Nutrient management planners also estimate farm-specific balances of total nutrient supply from sources such as fertilizer and manure and total nutrient applications, export from the farm, or other disposal methods. Nutrient management plans reduce unnecessary nutrient applications by basing applications on realistic yield expectations, matching nutrient sources to crop nutrient requirements, and adjusting application methods and timing to minimize pollution (USDA 1998; USEPA 1993). Nutrient management may reduce fertilizer costs but also may involve additional costs associated with developing plans and adjusting nutrient application practices. Riparian buffers are strips of vegetation located along receiving waters that remove nutrients and other pollutants from surface and subsurface lateral flows (USDA 1998). Riparian buffers entail establishment, maintenance, and land opportunity costs. Because field characteristics affect pollutant transport, the spatial orientation of fields and farms affects the cost-effectiveness of buffers and nutrient management.

The objectives of our study are (1) to estimate whole-farm compliance costs and reductions in estimated P deliveries to water bodies as a result of nutrient management plan implementation or installation of riparian buffers, and (2) to evaluate the effects of alternative spatial representations of farms on estimated compliance costs and reductions in P deliveries. The objectives are relevant both to water quality policy analysis and to the development of appropriate modeling methodology for the study of such issues.

P deliveries to surface water bodies include both insoluble P adsorbed to sediment and soluble P in runoff water. Compliance costs are reductions in farm net returns from installing and maintaining buffers or from limiting P applications to estimated crop uptake. Predicted compliance costs and reductions in P deliveries are estimated for two spatial scenarios in Muddy Creek watershed, a livestock-intensive watershed in the upper Shenandoah Valley of Virginia.

Previous Work

BMP Cost-Effectiveness

In previous studies, VanDyke et al.; Parsons; and Feinerman, Bosch, and Pease evaluated costs of N- and P-based nutrient management plans. Studies by Qui and Prato (1998, 2000); Nakao and Sohngen; Countryman and Murrow; and Lynch and Brown evaluated buffer costs, effectiveness, and farmers' adoption decisions. Studies by Schwabe; Braden et al.; and Carpentier, Bosch, and Batie examined the effectiveness of alternative pollution control practices in achieving specified levels of pollution reduction. Most agricultural nonpoint source pollution control practices are implemented as the result of regulations or incentives for adoption of specified practices. However, adoption of practices may give rise to slippages that are policy-induced changes in farming practices. These changes may offset some environmental benefits that the specific nutrient reduction practice is designed to achieve. Slippages (also referred to as leakages) have been discussed with respect to carbon sequestration trading (Aukland, Moura-Costa, and Brown; Chomitz) and enrollment in land conservation programs (Wu). Our study contributes to the evaluation of potential slippages and their effects on cost-effectiveness of practices to protect water quality.

Spatial Farm Representation

Watershed analysis of economic and environmental trade-offs takes place within a context of limited information. Site-specific physical and socioeconomic data are not readily available for individual farms; consequently, researchers take a model-analytic approach based on information available within the research budget. Early research used simple representative (Ellis, Hughes, and Butcher) or highly aggregated regional or national models (Wade and Heady) to evaluate agricultural and environmental policies. More recent studies have suggested conceptual and empirical approaches to relate detailed spatial information to agricultural policies, output, and pollution (Carpentier, Bosch, and Batie; Hochman and Zilberman 1978, 1979; Just and Antle; Opaluch and Segerson). Schwabe analyzed effects of spatial representations on N control costs in a large watershed with counties as the smallest spatial units. Wu and Segerson compared estimates of potentially polluting acres using county average data versus disaggregated National Resource Inventory data. Preckle and Senatre evaluated the effects of farm commodity program payment rates on farm participation under alternative spatial representations. Braden et al. evaluated the effects of alternative site-specific delivery ratios on sediment pollution control costs for a portion of a watershed modeled as a farm. Our study adds to the limited information on spatial farm representation by estimating how spatially referencing farm characteristics affects predicted nonpoint source pollution outcomes and control costs.

Watershed Spatial Scenarios

Our analysis of profit-maximizing responses to mandatory nutrient management planning and riparian buffer policies compared two spatial scenarios. The first is a spatially explicit, farm-specific scenario in which specific types of farms are modeled at specific locations. The second is a multirepresentative farm scenario with a set of farms representing major farm types in the watershed. The farm types in the multirepresentative scenario are not directly linked to locations. Predicted costs and pollution reductions are compared between scenarios. Farm i's cost of complying (C_i) with a practice standard such as buffers or nutrient management is

$$(1) \qquad C_i = NR_{Bi} - NR_{Si},$$

where NR_{Bi} and NR_{Si} are the farm's net revenue under the baseline with no standard and net revenue under the practice standard, respectively. Compliance costs are a function of farm i's physical and economic characteristics $\mathbf{P}_i$ as follows:

$$(2) \qquad C_i = f(\mathbf{P}_i).$$

$\mathbf{P}_i$ is a vector of characteristics that affect farm i's nutrient runoff reduction costs including soil yield potentials, nutrient runoff potential, and number of livestock. Total watershed compliance costs in the farm-specific scenario (C_{wfs}) equal the summation of individual costs over all i farms in the watershed:

$$(3) \qquad C_{wfs} = \sum_{i=1}^{I} C_i.$$

The multirepresentative farm scenario includes resource and production characteristics of major watershed farm types. The farm types included dairy, dairy with broilers, beef, beef with turkeys, broiler only, and turkey only. Compliance costs for multirepresentative farm type represented by subscript q are

$$(4) \qquad C_q = f(\mathbf{P}_q),$$

where $\mathbf{P}_q$ represents a vector of average physical and economic characteristics of watershed farms for a specific farm type. Elements of the farm characteristics vector $\mathbf{P}_q$ are obtained by averaging the associated characteristics $\mathbf{P}_i$ of the subset of i farms in the watershed that are contained in category q. For example, crop yield potential for the representative dairy farm is obtained by averaging crop yields for the subset of watershed farms classified as dairies. The set of representative farms includes all major farm types in the watershed (Parsons; P. Schroeder, pers. comm.; U.S. Department of Commerce; Virginia Department of Environmental Quality).

Farm compliance costs differ among the q representative farms because they have different resource constraints and enterprise opportunities. For example, dairy farms might have higher compliance costs for nutrient management planning compared with beef farms because dairy farms generate more manure per acre of land. Dairy farms produce higher returns per unit of livestock compared with beef farms, but dairy farms also have higher requirements for farm-produced forage. Dairy farms might also have higher incentives for slippage compared with less intensive beef operations. For example, dairy farms might respond to mandatory buffers by intensifying production on remaining harvested land, thereby increasing nutrient runoff potential.

Watershed compliance costs for the multirepresentative farm scenario (C_{wmr}) are estimated as

$$(5) \qquad C_{wmr} = \sum_{q=1}^{Q} C_q \times R_q,$$

where R_q represents the ratio of land occupied by all farms of type q in the watershed to the area of the farm used to represent farm type q. For example if dairy farms occupy 3,000 acres in the watershed and a typical dairy farm has 100 acres, then $R_q = 30$. P delivery reductions for the alternate spatially explicit farm are modeled in the same way as described above for compliance costs. Procedures for defining spatial scenarios are further described in Appendix A.

Empirical Model

Farm Economic Model

A mathematical programming model (FARM-PLAN) written in General Algebraic Modeling System (GAMS; Brooke et al.) was developed to estimate profit-maximizing solutions for each farm under three policy scenarios: (1) a baseline with no riparian buffers or nutrient management (either required or previously existing); (2) required riparian buffers in any field adjacent to a stream; and (3) P-based nutrient management, consisting of the restriction that P applications could be no more than that necessary for crop uptake according to yield potential. Farms in the farm-specific and multirepresentative scenarios are described by livestock type and capacity, manure storage capacity, slope and soil type of their fields, and full-time labor availability, which is assumed to equal that required by livestock plus 3 hours/acre for crop and pasture land. Changes in livestock or crop management practices resulting from mandatory buffers or nutrient management might increase the farm's labor requirements beyond full-time labor availability. Increased labor requirements are reflected in the additional costs of hiring part-time labor. Revenue is generated from sales of crops and livestock products, including sales of poultry litter. Costs are incurred for crop and livestock production, manure storage and application, crop nutrients, livestock feed, part-time labor, off-farm dairy manure disposal, and preparation of nutrient management plans.

Crops and Nutrients

Crops include corn grain and silage, rye silage (ryelage), alfalfa hay, and red clover–orchard

Table 1. Crop Product and Nutrient Prices[a]

Crop or Nutrient	Buy ($)	Sell ($)
Corn grain (bushel)	2.25	2.10
Corn silage (ton)	25.00	22.00
Alfalfa hay (ton)	110.00	100.00
Grass hay (ton)	70.00	60.00
N fertilizer (pound)	0.27	—
P_2O_5 fertilizer (pound)	0.24	—
K_2O fertilizer (pound)	0.15	—
Dairy manure (1,000 gal.)[b]	5.00	−26.40
Broiler litter (ton)[c]	10.00–14.00	4.00–8.00
Turkey litter (ton)[c]	9.00–12.50	3.00–6.50

[a] Source: Virginia Agricultural Statistics Service, 2001 dollars.
[b] Dairy manure contains 25.9, 10.8, and 17.4 pounds/1,000 gallons of N, phosphate, and potash, respectively (Knowlton). Negative selling cost occurs because of high hauling cost of liquid manure, which is assumed to be paid by seller.
[c] Poultry litter contains 71.6, 58.2, and 43.4 pounds/ton of N, phosphate, and potash, respectively (Pease and Mullins).

grass for hay or pasture. Crops can be grown with conventional or no-till methods. Corn grain, corn silage, alfalfa hay, and grass hay can be bought or sold, although alfalfa sales are limited to 13% of potential farm yield, which is the amount of harvested alfalfa land planted in Rockingham County according to the Census of Agriculture. Because of high hay hauling costs, higher acreages of alfalfa for sale would likely depress alfalfa hay prices (shown in Table 1) below those used here. Recommended nutrient applications (Donohue et al.) vary by soil productivity and soil test. Soil test P values are assigned based on livestock density because higher livestock numbers relative to land area generally lead to increased manure production and applications and P accumulations in soil. Dairy and poultry manure can be bought and sold (prices are shown in Table 1). Crop variable costs were obtained from farm management budgets (Virginia Cooperative Extension Service).

Livestock

Dairy gross margins equal gross revenues from milk, calf, and cull sales minus variable costs (Table 2). Dairy cows are fed alternative rations based on alfalfa hay, corn silage, or ryelage, which are selected by the model. Beef gross margins equal revenues from calf or stocker sales minus variable costs (Table 2). Beef cows and stockers are fed corn grain, grass hay, and pasture. Broilers and turkeys are produced for a poultry integrator who supplies the birds, rations, and management advice and markets the finished birds. Farmers' gross margins equal gross revenues from commissions paid by the integrator minus variable costs of labor, housing, and utilities (Table 2).

Table 2. Annual Livestock Yields, Prices, Revenues, and Costs[a]

Livestock	Yield	Sell Price ($)	Gross Revenue ($)	Variable Cost ($)[b]	Gross Margin ($)	Annual Labor (h)	Annual Recoverable Manure Production
Dairy cow	180 cwt	14/cwt	2,666[c]	840	1,826	63	14,230 gal.
Beef stocker	7.15 cwt	85/cwt	608	566	42	1	—[d]
Beef cow/calf	4.25 cwt	88.48/cwt	440[c]	81	359	8	—[d]
Broiler house	160,000 birds	160[e]	26,625	7,609	19,016	730	200 tons
Turkey house	64,000 birds	1,099[e]	70,346	18,630	51,716	1,246	640 tons

[a] Source: Virginia Farm Management Crop and Livestock Enterprise Budgets (Virginia Cooperative Extension), 2001 dollars.
[b] Includes minerals, veterinary service, supplies, building and fence repair, machinery costs, and utilities. Feed and labor expenses were determined separately in the model.
[c] Includes income from sale of cull cows.
[d] Manure is deposited on the pasture.
[e] Commissions received from poultry integrators per 1,000 birds.

Nutrient Management

In Virginia, 3-year nutrient management plans are developed with the assistance of state or state-certified nutrient management planners who assess farm-level nutrient availability and allocate nutrients on a field-by-field, seasonal basis based on soil and crop characteristics. The focus of a nutrient management plan for a livestock-intensive system is to manage manure applications to reduce nutrient losses while achieving crop yield goals. Nutrient management can reduce P losses by 20%–90% (Novotny and Olem).

We simplified nutrient management to a nutrient application restriction, which is consistent with state law for poultry operations but does not reflect the site-specific focus of nutrient management plan development. The simplified plan limits applications of P from manure and commercial fertilizer on each field to the crop P removal rate for the selected crop and given soil. If manure applications cannot meet all N and/or K requirements, commercial N and/or K applications are required. If all manure cannot be used on the farm at these application rates, excess manure must be exported. Other aspects of nutrient management including limits on timing and method of applications are not modeled. Nutrient management plan cost is $5.58/acre/year, based on a $15/acre initial cost (C. Patterson, pers. comm.), a 3-year life, and 5.7% interest rate (Yanosek).

Riparian Buffers

Estimates of reductions by buffers of soluble P reaching water bodies range from 5%–50% (Novotny and Olem). The buffer includes a 100-foot permanent herbaceous buffer strip on all stream-side borders of fields that are adjacent to or contain receiving waters. The 100-foot width is employed to match buffer size to the size of the cells in the geographic information system (GIS) data representing watershed spatial units. When the buffer policy is implemented, FARMPLAN requires the farm to put the designated acreage of each field into an unharvested buffer activity. Annual buffer costs are $32.79/acre, which includes annual maintenance costs and establishment costs of $173.18/acre (NRCS 2001) annualized over 10 years. Government incentive and/or cost-share payments for buffers and nutrient management conservation practices are omitted to isolate social costs of implementing the practices.

P Delivery Index

Using GIS data to map fields and water bodies, P delivery to streams is estimated with a P delivery index developed to estimate loadings of P to the nearest water body (see Appendix B). The index combines soil erosion estimates from the Universal Soil Loss Equation (USLE; Schwab et al.); sediment and runoff routing functions (Veith); and concentrations of P on sediment and in runoff developed for the Virginia Phosphorus Index (Mullins et al. 2002a,b). P delivery is dependent on slope steepness, slope length, and intervening land use between the field and water body.

Results

Baseline

Because the results from the multirepresentative scenario are extrapolated to the watershed, multirepresentative farm results should be comparable with the results from the farm-specific scenario. Differences in estimated results are due to differences in the way farms are modeled in each scenario. Estimated total gross margins for the farm-specific scenario are $8.8 million ($787/acre) under the baseline with no BMP requirements (Table 3). The multirepresentative farm scenario understates total gross margins by a small amount compared with the farm-specific scenario, approximately $0.1 million or $11/acre (1%; Table 3). Differences in predicted gross margins between scenarios are due to the averaging of soil productivity and land area under the multirepresentative scenario. The two scenarios are similar in terms of predicted numbers of dairy and beef cows (Table 4). The multirepresentative scenario predicts higher acreage of

Table 3. Total Gross Margins of Watershed Farms Under Alternative Policy Scenarios

	Policy Scenario		
Spatial Scenario	Baseline	Nutrient Management	Buffers
Farm specific ($/000)	8,823	7,871	8,600
Farm specific ($/acre)[a]	787	702	767
Farm specific % change from baseline		−10.8	−2.5
Multirepresentative farm ($/000)	8,699	7,760	8,469
Multirepresentative farm ($/acre)[a]	776	692	755
Multirepresentative farm % change from baseline		10.8	2.7

[a] Total gross margins divided by 11,212 acres of farm crop and pasture land in the watershed.

corn and lower acreage of hay and pasture compared with the farm-specific scenario. Overprediction is largely due to differences in predicted crop acreages between the farm-specific and multirepresentative dairies. The multirepresentative dairy farms are predicted to grow 3,463 acres of corn and 1,615 acres of alfalfa (on a watershed basis) compared with 1,999 acres of corn and 2,954 acres of alfalfa for the farm-specific dairies in the watershed. The averaging of soil yield potentials for the multirepresentative dairies tends to favor corn relative to alfalfa. Some dairies have all or a large proportion of land not suited to alfalfa, in which case alfalfa is assigned a zero yield, which pulls the average yield down and makes alfalfa less competitive with corn in the multirepresentative scenario. However, on the majority of farm-specific dairies, alfalfa yields are high, which contributes to higher acreages of alfalfa in the farm-specific scenario.

The farm-specific scenario predicts P deliv-

Table 4. Crops and Manure Export under Alternative Policy Scenarios

	Policy Scenario		
Spatial Scenario	Baseline	Nutrient Management	Buffers
Farm-specific			
Dairy cows	6,667	6,667	6,667
Beef cows	2,971	2,971	2,927
Corn (acres)	2,364	4,767	2,688
Hay and pasture (acres)	8,854	6,297	7,341
Dairy manure application (1,000 gal.)	94,877	58,226	94,877
Dairy manure export (1,000 gal.)	0	36,651	0
Poultry litter application (tons)	3,440	3,138	3,540
Poultry litter export (tons)	22,711	22,919	22,761
Commercial fertilizer purchases ($)	45,048	170,969	46,642
Multirepresentative farm			
Dairy cows	6,735	6,735	6,735
Beef cows	2,740	2,776	2,724
Corn (acres)	3,716	5,469	3,604
Hay and pasture (acres)	7,532	5,779	6,414
Dairy manure application (1,000 gal.)	95,503	61,953	95,503
Dairy manure export (1,000 gal.)	0	33,550	0
Poultry litter application (tons)	4,763	4,669	5,040
Poultry litter export (tons)	21,705	21,712	21,641
Commercial fertilizer purchases ($)	36,612	189,546	37,656

ery to receiving water bodies of 30,304 pounds (2.7 pounds/acre), of which 71% is soluble runoff (Table 5). Under the multirepresentative scenario, total P delivery is 3.38 pounds/acre, 25% higher than predicted under the farm-specific scenario. Estimated P delivery is higher under the multirepresentative scenario because poultry and dairy manure applications and corn production are higher compared with the farm-specific scenario.

Mandatory Nutrient Management

Mandatory nutrient management reduces returns on all farm types in the watershed by approximately \$0.95 million (10.8%) or \$85/acre under the farm-specific scenario (Table 3). Returns decline because of lower crop revenue, increased manure export costs, increased commercial fertilizer costs, and costs of nutrient management plan writing. Dairy farm returns decline by more (average decline of \$167/acre) compared with beef farms (average decline of \$10/acre) because recoverable manure production is higher on dairy than on beef farms. Dairy farms must make more costly adjustments to dispose of dairy manure. The acreage of corn-ryelage rotation increases because its higher utilization of P allows more manure to be applied. The acreage in the corn-alfalfa rotation declines, which reduces the amount of alfalfa for sale. Manure export costs are incurred by dairy farms with excess dairy manure. Commercial fertilizer costs increase because of supplemental N and K needed to compensate for reduced manure application rates. Although total P delivery declines by 0.2 pound/acre (7.6%) as the result of reduced manure applications (Table 5), sediment P delivery increases because of the shift from corn-alfalfa to a more erosive corn-ryelage rotation.

With the multirepresentative farm scenario, gross margins are reduced by \$84/acre (10.8%) due to reduced alfalfa sales revenue and increased costs to export dairy manure, purchase commercial fertilizer, and prepare nutrient management plans. Although sediment P delivery increases due to shifts from hay to corn, total P delivery declines 0.17

Table 5. Total P Deliveries Under Alternative Policy Scenarios

	Baseline			Nutrient Management			Buffers		
Spatial Scenario	Sediment	Runoff	Total	Sediment	Runoff	Total	Sediment	Runoff	Total
Farm-specific									
Total pounds	8,709	21,595	30,304	13,076	14,933	28,009	9,215	20,856	30,072
Pounds/acre[a]	0.78	1.93	2.70	1.17	1.33	2.50	0.82	1.86	2.68
% Change from baseline						−7.6			−0.8
Multirepresentative farm									
Total pounds	14,754	23,140	37,894	19,123	16,839	35,962	8,623	23,364	31,987
Pounds/acre[a]	1.32	2.06	3.38	1.71	1.50	3.21	0.77	2.08	2.85
% Change from baseline						−5.1			−15.6

[a] Total P delivery divided by 11,212 acres of farm crop and pasture land in the watershed.

pound/acre (5.1%) because of large reductions in soluble runoff resulting from reduced dairy manure applications.

Compared to the prenutrient management baseline, increased manure exports could reduce manure sale prices and revenue from sales of excess manure, further raising the costs of nutrient management. Feinerman, Bosch, and Pease, in a regional analysis of P-based nutrient management policies, estimated that a P-based standard would lower average poultry litter demand price by 12% ($2.69/ton) relative to no nutrient standard. We applied the 12% reduction first to the poultry litter export price and then to the dairy manure export price to determine the effects on nutrient management compliance costs. A 12% reduction in the poultry litter export price would raise compliance costs of nutrient management in our study by about $61,600 (6%) or $5.49/acre in the farm-specific scenario. A 12% reduction in the dairy manure sale price (from −$26.40 to −$29.57) would raise compliance costs in our study by $116,000 (12%) or $10.35/acre.

Mandatory Buffers

Under the farm-specific scenario, buffers reduce total gross margins by $20/acre (2.5%) largely because of reduced alfalfa hay revenue from riparian land taken out of production and costs of buffer establishment. Buffers reduce gross margins by similar amounts across farm types. Land in corn, hay, and pasture declines by 1,189 acres, or about 10%. Buffers reduce overall P deliveries by only 0.02 pound/acre (0.8%). Buffer effectiveness is limited due to changes in crops, rather than the lack of physical effectiveness of buffers. Installation of buffers is accompanied by a 14% increase in upland corn production, which is more erosive than the hay and pasture it replaces. On 23 of the 121 farms, corn acres increase by more than 10%, reflecting the shift from a corn-alfalfa to a corn-ryelage rotation to increase forage production.

The estimated reduction in net returns under the multirepresentative farm scenario is similar to the reduction under the farm-specific scenario. Under both scenarios, similar reductions in alfalfa sales result from taking land out of production for buffers. Under the multirepresentative farm scenario, buffers are predicted to reduce P deliveries by 15.6% (0.53 pound/acre) compared with a 0.8% reduction predicted by the farm-specific scenario. The higher predicted effectiveness is due to differences in predicted allocations of cropland among corn, hay, and pasture. The multirepresentative farm scenario predicts that acreage in corn will decline by 112 acres, whereas the farm-specific scenario predicts an increase of 324 acres (Table 4). The multirepresentative farm scenario predicts reductions in hay and pasture of 1,118 acres compared with a reduction of 1,513 acres predicted by the farm-specific scenario. By putting more land in corn, the farms under the farm-specific scenario offset somewhat the reductions in sediment loadings by buffers.

Table 6. Costs of Reducing P Deliveries

Spatial Scenario	Nutrient Management ($/pound)	Buffers ($/pound)
Farm-specific	415	961
Multirepresentative farm	486	39

Slippage and BMP Cost-Effectiveness

Wu suggests that land retirement programs can give rise to slippages due to output price and substitution effects. In our study, BMP adoption can induce substitution toward more intensive and polluting practices that offset some of the environmental benefits of the BMPs and lower their cost-effectiveness. Slippage occurs with both buffers and nutrient management but is most noticeable with buffers under the farm-specific scenario. Under the farm-specific scenario, buffers result in only small reductions in P delivery due to substitution toward corn and away from hay after buffers are introduced. The substitution effect is induced by the livestock's need for forage and the high cost of buying forage. The slippage contributes to the high estimated cost of $961/pound of reduced P delivery (Table 6).

We analyzed the effect of slippage on reductions in P delivery by buffers by running the model for the farm-specific scenario with corn silage acreage for each farm constrained to 90% of its baseline value. This restriction required that corn acres decline in the same proportion as overall crop and pasture acres. With this restriction, buffers reduce total P delivery to 27,105 pounds (2.42 pounds/acre), a reduction of almost 3,200 pounds (11%) compared with the baseline. Total gross margins are $8,592,000 ($766/acre), a reduction of $231,000 ($21/acre) relative to the baseline. Reduced P delivery costs $72/pound compared with $961/pound with slippage.

We analyzed the effects of slippage under nutrient management for the farm-specific scenario by not allowing the acres of corn to increase with nutrient management. With this restriction, nutrient management reduces total P delivery to 18,479 pounds, a reduction of 11,825 pounds (39%) compared with the baseline. Total gross margins are $7,481,000 ($667/acre), a reduction of $1,342,000 ($120/acre) relative to the baseline. Reducing P delivery costs $113/pound compared with $415/pound with slippage.

Cost-Effectiveness of Spatial Information

Is obtaining and analyzing spatial information for individual farms in a watershed cost-effective when assessing impacts of pollution control policies on farms? Although we did not maintain records of researcher time spent evaluating each scenario, our experience suggests that for the watershed size in our study, analyzing the farm-specific scenario may take twice as long as analyzing a few representative farms. If we assume a watershed similar to this case study, evaluating the nutrient management and buffer options for a set of representative farms would require 4 months of time versus 8 months for the farm-specific scenario. If the annual cost for salary and fringe benefits of an M.S.-trained economist is $66,000 (disregarding overhead costs), the cost of evaluating nutrient management and buffers for the farm-specific scenario is $44,000 versus $22,000 for the representative or multirepresentative scenarios. This estimate assumes that digitized data and aerial photographs of watershed fields and farmsteads are available.

The value of spatial information depends upon the effect information has on pollution control policies and programs (Wu and Segerson). Our study results imply that the value of spatial information in relation to its cost depends on the pollution control policy being evaluated. The cost-effectiveness of spatial information on all watershed farms is low for the nutrient management scenario and high for the buffer scenario. Evaluation of all watershed farms adds little to the understanding of nutrient management outcomes provided by the multirepresentative scenario. Both spatial scenarios predict slippage caused by increasing corn acres, which reduces the effectiveness of restricting P applications. Both spatial scenarios have similar predicted costs per pound of P reduction as a result of nutrient restrictions. In contrast, the analysis of mandatory buffers under the farm-specific scenario provides insights not forthcoming from the multirepresentative scenario. The farm-specific scenario shows potential for slippage on some farms as adoption of buffers results in substitutions toward more row crops and away from hay and pasture, which raises the costs per pound of P reduction.

Summary and Conclusions

Reduction of nutrient losses from agricultural fields is an important component of nonpoint source pollution control strategies. Our study compares the cost-effectiveness of nutrient management plans and riparian buffers for controlling nutrient runoff from agriculture. Cost comparisons are done with alternative spatial representations of farms in a specific watershed.

The nutrient management policy requires that P applications to any field not exceed P removed by crops. For the farm-specific scenario, estimated P deliveries decline by 0.2 pound/acre, and estimated compliance costs are $0.95 million ($85/acre) due to costs of nutrient plan preparation, increased commercial fertilizer purchases, reduced crop revenues, and costs of dairy manure exports. The estimated cost under the multirepresentative scenario is $0.94 million ($84/acre) for a P delivery reduction of 0.17 pound/acre. Both multirepresentative and farm-specific scenarios predict similar modest reductions in P delivery with nutrient management.

Predicted compliance costs of buffers are $0.23 million ($20/acre) under the farm-specific scenario. P delivery is reduced by 0.02 pound/acre. Buffers are implemented by removing land from hay and pasture; however, corn acres are predicted to increase, which reduces predicted effectiveness of buffers. Predicted buffer costs for the multirepresentative farm scenario are similar to those predicted by the farm-specific scenario, but corn acres are predicted to decline to make room for buffers. As a result, predicted effectiveness of buffers is greater (0.53 pound/acre reduction in P delivery), and costs per pound of P reduction are smaller under the multirepresentative scenario compared with predictions of the farm-specific scenario.

The limited reduction in P deliveries when buffers or nutrient restrictions are imposed is due to slippage caused by substitution toward more polluting crops, rather than a lack of effectiveness of the practices. This finding indicates a potential limitation of practice standards for pollution control. Farmers may implement the practice as required but thwart its intent by switching to more runoff-prone crops or making other farm adjustments to reduce costs, thus reducing the cost-effectiveness of the pollution control practice. In our study, these adjustments make it difficult to draw conclusions about the relative cost-effectiveness of buffers and nutrient management. Performance standards or incentives that focus on the desired pollution reduction, rather than requiring specific practices, would be less subject to slippages but would entail their own implementation problems. Further research should be done to evaluate ways to use performance standards to reduce slippage potential and lower costs of attaining pollution control goals for varying farm types.

In our study, the representation of nutrient management includes only the restriction that P applications not exceed estimated crop P removal rates. To achieve loadings reductions, nutrient management plans must recognize interactions among choices of tillage, crop type, nutrient quantity, and timing and method of nutrient application. Further development of nutrient management planning tools such as a P index can help ensure that loadings reductions are obtained. Regulations or incentives that focus only on the relationship between P applications relative to crop requirements (as modeled here) may not be successful in reducing P loadings. In the baseline of our study, we assumed farmers apply nutrients at profit-maximizing levels. VanDyke et al., in a study of actual farms that implemented N-based nutrient management plans, found that such plans can educate farmers to reduce unprofitable nutrient applications while reducing nutrient pollution potential. More studies of actual farm implementation of P-based nutrient management plans might uncover other benefits of nutrient management that are not addressed in our study.

The spatial representation of farms significantly affects the estimated costs and effectiveness of pollution-control practices. If spatial information can be obtained at a reasonable cost, analysts should use maximum spatial resolution of farms in evaluating policies. Continued development of spatial decision support systems and databases will help policy makers and program managers to evaluate and implement water quality protection practices.

Even the detailed farm-specific spatial representation of farms in our study simplifies spatial and socioeconomic variability found in agricultural watersheds. Variations among farmers' perceptions and attitudes are not considered. Land, capital, and management resources also display greater variation than considered here. Further studies with more in-depth information on farm characteristics within a watershed can shed additional light on the relative impacts of these types of physical and socioeconomic variations on costs and effectiveness of pollution-control policies.

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Appendix A: Farm Spatial Scenarios

Farm-Specific Scenario

The farm-specific scenario was constructed using digitized spatial data from the Virginia Department of Conservation and Recreation and the Natural Resources Conservation Service (NRCS); published sources (Virginia Department of Environmental Quality; Parsons; U.S. Department of Commerce); and expert opinion (P. Schroeder, pers. comm.). The farmsteads and/or poultry houses designated in the land use coverage were used to locate farms. Farm locations were randomly assigned farm types from the following distribution: 65% dairies; 30% beef cattle (cow calf or stocker); and 5% poultry (Parsons; W. Patterson, pers. comm.; P. Schroeder, pers. comm.; Virginia Department of Environmental Quality). All farms that were generated from a poultry house location were designated as poultry, dairy with poultry, or beef with poultry.

The Thiessen Polygon method (Thiessen and Alter) was used to assign land to the closest farm. Fields with the majority of their acreage in a polygon assigned to a farm were aggregated and defined as a farm. After review and revisions by the local NRCS conservationist (W. Patterson, pers. comm.), the resulting GIS farm data layer (Tables A1 and A2) has 121 farms with land area of 13,100 acres including 11,212 acres of crop and pasture land. Each type of farm is found throughout the watershed; however, concentrations of dairy (with and without poultry) farms are found in the central and lower sections, whereas beef (with and without poultry) farms are more concentrated in the upper section. Farm sizes vary throughout the watershed.

Multirepresentative Farms

The acreage and number of animals for each farm in the multirepresentative farm scenario are based on the average of farms of that type in the farm-specific scenario (Table A3). Crop yields are set at the average crop yield for that farm type in the farm-specific scenario (Table A1).

Appendix B: P Delivery Index

P loadings are estimated as the sum of sediment-adsorbed P and runoff-dissolved P delivered to streams from agricultural fields in the watershed via surface runoff. Subsurface lateral flows are not modeled because the majority of P loss from agricultural lands occurs via surface flow (National Research Council, p. 300). Sediment-adsorbed P loading (*SP*), the quantity of P attached to sediment delivered to the watershed outlet from cell j, is estimated as

$$SP_j = \alpha_j Y_j. \tag{6}$$

where α_j is the sediment-P enrichment coefficient and Y_j is sediment yield delivered to the watershed outlet. The sediment-P enrichment coefficient is estimated based on soil test P in each field (Mullins et al. 2002b). Sediment yield (Y) from cell j to the watershed outlet is estimated using a sediment routing function (Veith) shown in Equation (7).

$$Y_j = m_j \prod_k^K \delta_k A_j. \tag{7}$$

Y_j is sediment yield delivered from cell j; A_j is average annual soil loss of cell j; m_j is area of cell j; δ_k is sediment delivery coefficient to cell k, where cell k is in the flow path of cell j; and K indexes cells in the flow path of cell j. The sediment delivery coefficient depends on slope and land cover (Bonham; Veith). Average annual soil loss (A_j) is estimated by the Universal Soil Loss Equation (USLE).

Runoff P loading (*RP*) is estimated as

$$RP_j = \phi_{jj} RY_j + AP_j AF_j. \tag{8}$$

RP delivered from cell j is equal to the sum of soluble P in runoff from soil and soluble P in runoff from nutrient applications. *AP* is P applied to cell j, and *AF* is the product of fertilizer source and application factors from the Virginia Phosphorous Index, which for surface-applied manure or litter is a constant value of 0.04. *RY* is runoff from rain, and ϕ is concentration of P in runoff, which Mullins et al. (2002b) estimated for soils in the study region.

Runoff yield (*RY*) is estimated as (Veith)

$$RY_j = m_j \prod_k^K \sigma_k RO_j. \tag{9}$$

RO_j is average annual runoff of cell j; m is the area;

and σ_k is the runoff delivery coefficient of cell *k*, where cell *k* is in the flow path of cell *j*. The runoff delivery coefficient is specified in the same manner as the sediment delivery coefficient. The NRCS curve number method is used to define *RO* (U.S. Soil Conservation Service). Curve numbers are defined by the hydrologic soil group with the greatest area in the field and its land use description, such as row crops or pasture (USDA 2002). The land use description results from the crop rotation selected by FARMPLAN. Further details are provided in Bonham.

Table A1. Cropland and Crop Yields[a] by Farm Type (Farm-specific Scenario)

Farm Type	Total No. of Fields	Total Production (acres)	Corn Grain (bushel)	Corn Silage (ton)	Rye Silage (ton)	Alfalfa Hay (ton)	Grass Hay (ton)
Dairy only	221	3,821.2	107.6	15.2	4.1	5.5	3.3
Dairy with broilers	88	1,545.0	109.2	15.5	4.2	5.1	3.2
Beef only	229	3,667.6	108.3	15.4	4.1	5.4	3.3
Beef with turkeys	136	2,172.6	109.3	15.5	4.2	5.2	3.2
Broiler only	0	0	0	0	0	0	0
Turkey only	1	5.3	88.0	13.0	2.8	2.8	1.3

[a] Yields by farm type are potential yields per acre (Donohue et al.) averaged across all cropland contained by farms of that type.

Table A2. Farms With Livestock Capacities (Farm-specific Scenario)

Farm Type	No. of Farms	Dairy Cows[a]	Beef Cows[a]	Broiler Houses[b]	Turkey Houses[b]
Dairy only	38	4,459	0	0	0
Dairy with broilers	18	2,208	0	18	0
Beef only	36	0	1,930	0	0
Beef with turkeys	26	0	1,143	0	26
Broiler only	2	0	0	6	0
Turkey only	1	0	0	0	3
Total	121	6,667	3,073	24	29

[a] Dairy and beef animals are assigned to farms based on farm acreage with 0.8 of an acre cropland required per dairy cow and 1.9 acres of pasture per beef cow (Culver et al.).

[b] In the county surrounding this watershed, approximately 57% of poultry operations raise turkeys and 43% raise broilers (meat chickens). No correlation is apparent between poultry type and other livestock produced; therefore, to minimize the number of farm types, all dairy with poultry farms are assigned broilers (25,000 broilers capacity per house), and all beef with poultry farms are assigned turkeys (16,000 turkeys capacity per house).

Table A3. Farm Size and Livestock Capacity (Multirepresentative Scenario)

Farm Type	Farm Size (acres)	Dairy Cows	Beef Cows	Broiler Houses	Turkey Houses
Dairy only	98	123	0	0	0
Dairy with broilers	91	114	0	1	0
Beef only	102	0	54	0	0
Beef with turkeys	85	0	44	0	1
Poultry only	5	0	0	2	1
Total (all farms)[a]	11,248	6,735	2,776	23	29

[a] Totals obtained by expanding the values for each representative farm by the area of that farm type in the watershed and summing. For example, dairy only and dairy with poultry farms comprise 3,821 and 1,545 acres in the watershed, respectively. Total dairy cow numbers = $(3{,}821/98) \times 123 + (1{,}545/91) \times 114 = 6{,}735$.