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Cost Effectiveness of Nutrient Management and Buffers:

Comparisons of Four Spatial Scenarios

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Abstract: Policymakers are seeking cost effective methods to reduce nutrient pollution from agriculture. Predicted costs and pollution reductions from nutrient management and buffers are evaluated under four spatial scenarios describing a watershed. Results will help policymakers evaluate alternative Best Management Practices (BMPs) for water quality protection in agriculture.

Reducing nutrient pollution is a key goal of efforts to improve water quality in the U.S. Forty percent of surveyed water bodies in the U.S. do not meet fishing and swimming use standards (U.S. Environmental Protection Agency, 1997). Non-point source (NPS) pollution is the leading cause of U.S. water quality problems, and agriculture has been identified as a major source of NPS pollution in those lakes and rivers that do not meet water quality goals established by states in compliance with the U.S. Clean Water Act (U.S. Environmental Protection Agency, 2003). The Chesapeake Bay does not meet Clean Water Act water quality standards, and those states and the District of Columbia participating in the Chesapeake Bay Agreement 2000 (CBA2000) have committed to meeting water quality standards by 2010 in order to avoid the potential for required watershed-wide nutrient reductions. Agriculture is estimated to contribute 38% of nitrogen (N) and 43% of phosphorus (P) entering the Bay (Chesapeake Bay Program).

Prior to CBA2000, water quality protection programs of the Bay partners focused on reducing N pollution from agricultural sources. Current programs focus on pollutant reductions resulting from either N or P applications. The Virginia Poultry Waste Management Act (Code of Virginia § 62.1-44.17:1.1) limits litter and any supplementary nutrient applications on permitted poultry farms to the more limiting of either N or P recommended agronomic application rates. Since livestock manures have P concentrations that are higher than required by crops, P application restrictions cause cost-impacting challenges to farmers.

Nutrient management plans and vegetated riparian buffers are frequently recommended practices to reduce nutrient pollution from agricultural land uses. Nutrient management planning consists of a field-specific balance of crop nutrient needs and applications based on desired cropping practices, soil nutrient resources, nutrient concentrations and application methods, and field-specific characteristics. Nutrient management planning also involves a farm-specific balance of total nutrient supply from sources such as fertilizer and manure and total nutrient applications, export from the farm, or other disposal method. Nutrient management plans reduce unnecessary nutrient applications by basing such applications on realistic yield expectations, matching nutrient sources to crop nutrient requirements, and adjusting application methods and timing in order to minimize pollution (U. S. Environmental Protection Agency, 1993). Nutrient management may reduce fertilizer costs but also may involve additional costs associated with developing plans and adjusting nutrient application practices. Riparian buffers (vegetated strips adjacent to waterways) intercept nutrient runoff but entail establishment and maintenance costs 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 this study are relevant both to water quality policy analysis and to the development of appropriate modeling methodology for the study of such issues. Specifically, the objectives are 1) to estimate whole-farm compliance costs and reductions in P deliveries to water bodies as a result of nutrient management plan implementation and installation of riparian buffers in a Virginia livestock-intensive watershed, and 2) to evaluate the effects of alternative spatial representation of farms on estimated compliance costs and reductions in P deliveries. P deliveries to surface water bodies include both insoluble P adsorbed to sediment and P dissolved in runoff water. Compliance costs are reductions in farm net returns as a result of installing and maintaining buffers or of following nutrient management plans. Predicted compliance costs and reductions in P deliveries were estimated for four spatial scenarios in a Virginia watershed: 1) the population of all farms; 2) a single composite farm representing the "average" farm in the watershed, 3) a mega-farm representing the watershed as one farm, and 4) a set of representative farms characterizing the major farm types in the watershed. The analysis was applied to Muddy

Creek watershed, a livestock-intensive watershed in the upper Shenandoah Valley of Virginia.

BMP Cost Effectiveness

Nutrient management

The costs of complete nutrient management plan adoption depend on which nutrients are limiting. P-based plans are generally more restrictive of manure applications and more costly than N-based plans, because the ratio of N to P in manure is lower than the optimal ratio required by crops. VanDyke et al. found that implementation of N-based nutrient management plans led to increased net returns on four Virginia livestock farms. Parsons found that limiting manure applications based on N content would increase dairy and dairy/poultry farmers' net returns and ending net worth modestly, but that limiting manure applications based on P content would reduce net returns and ending net worth, primarily due to increased commercial fertilizer expenses for supplementary N and potash. A regional analysis of poultry and dairy farms showed that welfare could decline 5% with N-based nutrient management plans and 15% with P-based plans (Feinerman, Bosch, and Pease).

Riparian Buffers

There are relatively few studies analyzing the cost effectiveness of riparian buffers in trapping nutrient flows to water bodies. Qui and Prato (1998, 2001) found riparian buffers to be a highly cost effective method of reducing atrazine concentration in surface runoff when compared with other methods such as reduced tillage, reduced atrazine applications and crop rotations. Cost effectiveness of buffers declined with more restrictive standards on atrazine concentrations in surface waters, indicating that buffers are less able to achieve higher reductions in surface pollutant transport (Qui and Prato, 2001). Cost-effectiveness of buffers was comparable to that of reduced tillage in reducing sediment delivery to streams in a study by Nakao and Sohngen. Countryman and Murrow found that income from harvested tree buffers was competitive with that of row crops on low-yielding soils.

Conservation programs such as CREP (Conservation Reserve Enhancement Program) provide incentives to establish and maintain riparian buffers, but may preclude subsequent sale of the adjoining field for development. When such conditions exist, Lynch and Brown found that farmers' decisions to install buffers depend on the potential land resale value for development (higher land resale values reduce likelihood of buffer installation). Other factors encouraging buffer adoption included higher rental rates for land committed to buffers and lower crop prices. Factors encouraging adoption of forest rather than grass buffers included lower crop prices, higher buffer rental rates, higher timber values, lower discount rates, and larger adjoining fields (Lynch and Brown). Field size and crop price affected buffer adoption type because forested buffers are more conducive to higher deer populations and subsequent damage to crops compared to grass buffers.

Representation of Farms and Fields

Watershed analysis of economic and environmental tradeoffs always takes place with limited information. Site-specific physical and socio-economic data are generally not available for individual farms, so researchers are forced to take a model-analytic approach based on available information. There are few opportunities (at reasonable research cost) to capture all socio-economic, physical, and location data for watersheds. Previous studies have tended to analyze policies with model-analytic farms based on typical characteristics of a county or region. Such models, representing alternative spatial scenarios, assume that all or a subset of farms within the study region are homogeneous and will respond identically to economic and policy signals. The use of a single model-analytic farm designed to represent all farms in the study area fails to capture the heterogeneity of farm objectives and resources (Feuz and Skold; Wu and Segerson; Preckle and Senatre). More typically the spatial scenarios reflect contrasting amounts of detail about watershed farms. If field boundary information is available, the entire watershed may be represented as a single mega-farm, with a single operator making allocation decisions across all fields. If field boundary information is sketchy, a single composite farm may be constructed based upon typical characteristics of watershed farms. Multiple representative farms may also be constructed to represent major farm types within the watershed.

Estimating aggregate response from such model farm responses can bias cost estimates. Various socioeconomic, physical, and location characteristics of farms contribute to nonpoint source pollution and control costs (Wu and Segerson; Peng and Bosch; Schwabe; Braden et al.). Socioeconomic characteristics affect managers' resources and production decisions. Livestock facilities and resulting manure production affect nutrient runoff potential from manure applications. Physical characteristics of soils affect both production possibilities and nutrient transport potential via leaching and runoff (National Research Council). Schwabe's study of buffers in North Carolina revealed that failure to differentiate soil characteristics (slope, erodibility, and drainage intensity) within watersheds resulted in overestimates of N runoff reductions and underestimates of total and per unit compliance costs. Field location strongly affects the delivery of pollutants from the source field to the receiving waters. N deliveries are higher for fields located closer to streams and with steeper slopes (Peng and Bosch).

Models using micro-parameter distributions to represent the fixed characteristics of fields can be used to evaluate linkages between land physical characteristics and use, agricultural policies, agricultural output, and agricultural pollution (Hochman and Zilberman 1978 and 1979; Just and Antle; Opaluch and Segerson). Micro-parameter distribution models can also be used with geographic information systems (GIS) to incorporate site-specific attributes in analysis of nonpoint source pollution problems (Opaluch and Segerson). Both econometric and mathematical programming models can be used to represent the distribution of farm characteristics within the watershed (Carpentier, Bosch and Batie). However, Day laid out in 1963 (within the context of linear programming models) the strict conditions for valid extrapolation of firm model results to a larger geographic or industry aggregate. These conditions are proportional variations in constraint vectors and proportional variations in price, output and input matrices. Researchers have since attempted alternative spatial representations that are likely to exhibit only a tolerable degree of aggregation bias.

Watershed Spatial Scenarios

This analysis compared four alternative spatial scenarios influencing profit-maximizing responses to mandatory nutrient management planning and riparian buffer policies. The population scenario provided the most detail, as all farms, their fields, and crop or livestock production were represented. The mega-farm considered the same watershed characteristics, but did not consider farm boundaries, taking instead the perspective that a single profit-maximizing decision maker controlled all allocation decisions within the watershed. The representative farm incorporates resource and production characteristics of the single most important watershed farm type, while the multi-representative farms model resource and production characteristics of major watershed farm types. Both the population and mega-farm scenarios utilize a complete representation of field physical characteristics and yield potentials (Table 1).

Results from the representative and multi-representative farms were extrapolated to the watershed for comparison to the mega-farm and population farm scenarios. Extrapolation was based on farm land acreage of the representative or multi-representative farms relative to total farm acreage in the watershed. Procedures for defining spatial scenarios are described below.

Population

The population scenario was constructed with the most complete information available concerning all watershed farms, using a combination of digitized spatial data and expert opinion. A geographic information system data set describing land uses, field boundaries, and soil characteristics in the Muddy Creek Watershed was obtained from the Virginia Department of Conservation and Recreation and the Natural Resource Conservation Service (NRCS). Expert opinion was solicited to determine an initial distribution of farm types, farm enterprise information, and animal production feed requirements for the watershed (Schroeder; Virginia Department of Environmental Quality; Parsons; U.S. Department of Commerce). Farm generation points were determined from the set of farmsteads and/or poultry houses designated in the land use coverage. Approximately 120 farm generation points were selected within the watershed boundaries and all fields within the watershed were assigned to these farms. Farm generation points were randomly assigned farm types from the following distribution: 65% dairies, 30% beef cattle, and 5% poultry. The distribution of farm types was based on a summary of expert opinion (Parsons; Schroeder; 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 generation point. The farm-point data layer was then converted into a polygon layer. The polygon matrix was draped over the data layer containing land use and field boundaries. Fields with the majority of their acreage in a polygon were aggregated and defined as a farm. The farm boundary coverage was manually checked for discrepancies and modified if necessary and unrealistically small farms were assimilated into adjacent farms. The collection of farms was printed as a large-scale map, which was reviewed by the local NRCS conservationist, who suggested changes to the boundaries and type of individual farms. Farm types were then manually adjusted to make the ratio of farm types more closely match expert opinion. The resulting GIS farm data layer (Table 2) had 121 farms with land area of 13,100 acres including 11,212 acres of crop and pasture land.

Animals were assigned to the farms with dairy and beef cattle based on total farm acreage. Culver et al. estimated that the watershed contains 6,007 acres of pasture, 5,152 acres of harvested crops, 3,134 beef cows, and 6,533 dairy cows. Assuming that pasture is used primarily for beef and harvested crops are used primarily for dairy cows, these estimates imply 0.8 of an acre cropland per dairy cow and 1.9 acres of pasture per beef cow (two beef stockers are assumed equal to one beef cow). Poultry feed is supplied by the poultry integrator, so acreage has no influence on poultry production capacity. Dairy and beef farms with poultry operations were assigned 1 poultry house, while poultry-only farms were assigned 3 houses. In the county surrounding this watershed, approximately 57% of poultry operations raise turkeys and 43% raise broilers (meat chickens). There is no apparent correlation between poultry type and other livestock produced, so to minimize the number of farm types, all dairy with poultry farms were assigned broilers (25,000 broilers capacity per house) and all beef with poultry farms were assigned turkeys (16,000 turkeys capacity per house). Capacities are typical for this poultry-producing region. Among all farms, there were 23 broiler houses and 29 turkey houses with capacity to produce 575,000 broilers and 464,000 turkeys, respectively, per cycle, which are similar to previous estimates of 508,000 broilers and 351,000 turkeys (Culver et al.).

Mega-farm

The mega-farm represented the watershed as a single farm containing the watershed's entire inventory of fields and livestock facilities. The farm had 11,212 acres of crop and pasture land and the capacity for 4,240 dairy cows, 2,750 beef cows, 23 broiler houses, and 29 turkey houses. Soils with the same corn grain yield per acre were aggregated into a single field, thus resulting in 23 homogeneous mega-fields.

Representative Farm

The representative farm, which was based on average farm characteristics for the watershed, was designated as dairy with poultry because it is the most important farm type in the watershed in terms of revenue and of environmental implications because it spreads both dairy and poultry manure. The farm size was determined by dividing the total acres of crop and pasture land in the watershed by the number of farms in the watershed. The result was a farm with 92.7 acres spread over six fields (approximately the average number of fields per farm in the watershed) which were assumed to be of equal acreage. Based on its acreage and the average acreage per dairy cow in the watershed, the farm was assigned the maximum capacity of 115 cows and one broiler house. Crop yields based on average soil productivity in the county (Donohue et al.) were 108.4 bu/acre (corn grain), 15.3 tons/acre (corn silage), 4.1 tons/acre (rye silage), 5.3 tons/acre (alfalfa hay), and 3.2 tons/acre (grass hay).

Multi-representative Farms

The scenario of multiple representative farms included several composite farms each having the average characteristics of a common class of farms in the watershed. The population data were sorted by farm type, and one farm was created to represent each of the following farm types: dairy only; dairy with broilers; beef only; beef with turkeys; and poultry only. The acreage and number of animals of each representative farm were based on the average of farms of that type in the population scenario (Table 3). Crop yields were set at the average crop yield for that farm type in the population (Table 1).

Empirical Model

Farm Economic Model

A mathematical programming model (FARMPLAN) written in GAMS (General Algebraic Modeling System, Brooke et al.) was developed to estimate profit-maximizing solutions for each farm under 3 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) simplified P-based nutrient management, consisting of the restriction that phosphorus applications could be no more than that necessary for crop uptake according to yield potential. Each farm was described by its fields, livestock capacity, and manure storage capacity. The fields were described by soil type and slope, which determine potential crop yield, and by acreage. Farms were assumed to have full-time labor available to meet livestock requirements plus three hours per acre of crop and pasture land. Revenue sources included sales of livestock, milk, crops, and poultry litter. Costs included crop and livestock variable costs, manure storage, crop nutrients and application costs, feed for livestock, part-time labor, off-farm disposal of dairy manure, and nutrient management plan development costs. Full-time labor was assumed fixed, and its cost was not included. Opportunity costs of land, capital, or manager's time were also not included. Compliance costs of buffers or nutrient management requirements were estimated by subtracting total farm gross margins with buffers or nutrient management from total gross margins under the baseline.

FARMPLAN activities were organized into three categories: crops and nutrients, livestock and manure, and nutrient management and buffers.

Crops and Nutrients. Crops included corn for grain or silage, rye for silage, alfalfa hay, and red clover-orchard grass. The latter crop could be used for hay or pasture. Sixteen rotations included continuous corn grain, continuous corn silage, corn grain or corn silage grown in rotation with rye or alfalfa, continuous grass hay, and continuous pasture. Crops could be grown using conventional or no-till tillage methods, except that pasture establishment required no tillage. Corn grain, corn silage, alfalfa hay, and grass hay could be bought and sold. Sale of alfalfa hay was limited to 13% of the potential alfalfa hay yield for the farm because Census of Agriculture data indicated that on average 13% of harvested cropland in Rockingham County was planted in alfalfa in 1987, 1992 and 1997. Buy (sell) prices were \$2.25/bu (\$2.10/bu) (corn grain), \$25/ton (\$22/ton) (corn silage), \$110/ton (\$100/ton) (alfalfa hay), and \$70/ton (\$60/ton) (grass hay) (Virginia Agricultural Statistics Service). Crop variable costs included expenses for seed, lime, pesticides, machinery, and harvesting (Virginia Cooperative Extension Service). Total labor and nutrient costs were determined within the model.

Crop nutrient sources included dairy manure, poultry litter, and commercial fertilizers. Minimum recommended nutrient applications by crop, soil productivity, and soil test were taken from VALUES (Donohue et al.). Because soil test information was not available for specific farms in the study area, farm-level soil P soil test values were assigned based on livestock density. Mullins (2004) reported that 5% of farm land P soil test results from Rockingham County were low (less than 12 lbs./acre phosphorus), 11% were medium (12-35 lbs./acre phosphorus), 24% were high (36-110 lbs./acre phosphorus), and 60% were very high (>110 lbs./acre phosphorus). Taking the median P soil test values within these categories from the county, watershed farms were ranked in terms of manure P production per acre. The highest 60% were assigned P soil test values (Mehlich I) of 279 lbs./acre for all fields, the next highest 24% were assigned P soil test values of 71 lbs./acre, and the remainder were assigned values of 23 lbs. per acre. Because of the density of livestock in the watershed, a category of low was not used. Potassium values were assigned consistent with the P soil test values.

Commercial fertilizer prices were $0.27, $0.24, and $0.15/lb. for N, phosphate, and potash, respectively. Dairy manure could be purchased for $5 per 1,000 gallons and sold for -$26.40 per 1,000 gallons. The negative sell price was due to the high hauling cost of liquid manure, which was assumed to be paid by the seller. Broiler litter (turkey litter) could be bought for $10 to $14 per ton ($9 to $12.50 per ton) and sold for $4 to $8 per ton ($3 to $6.50 per ton), depending on season. Nitrogen, phosphate, and potash content of manure were 25.9, 10.8, and 17.4 lbs. per 1,000 gallons, respectively, for dairy manure (Knowlton) and 71.6, 58.2, and 43.4 lbs. per ton, respectively, for broiler and turkey litter (Pease and Mullins).

Livestock. Livestock included dairy cows, beef cows, beef stockers, broiler chickens, and turkeys. In nearly all instances within this county, broilers and turkeys are produced for a poultry integrator who supplies the birds, rations, and management advice, and markets the finished birds. The farmer provides the labor, housing and utilities, and receives a commission paid by the integrator. Variable costs included expenses for minerals, veterinarian and medical services, supplies, building and fence repair, machinery, and utilities. Feed and labor expenses were determined separately. Annual labor requirements were allocated by season. Dairy cows were fed alternative rations (based on alfalfa hay, corn silage, or ryelage), which were selected by the model. Beef stockers and cows were fed corn grain, grass hay, and pasture. Each lactating dairy cow produced 14,230 gallons of recoverable manure per year. Broiler chicken and turkey houses produced 200 tons and 640 tons of litter per year, respectively. Beef manure was deposited on pasture and was not recoverable. Dairy and poultry farms were assumed to have six months storage capacity, which is common for farms in the area.

Nutrient Management. Nutrient management is a pollution abatement practice that manages the amount, source, placement, form, and timing of the application of nutrients and soil amendments (NRCS). In Virginia, three-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. The focus of a nutrient management plan for a livestock-intensive system is to manage manure applications so as to reduce nutrient losses while achieving crop yield goals. Nutrient management can reduce P losses by 20–90% (Novotny and Olem).

In this analysis, the nutrient management planning exercise was simplified to a nutrient application restriction defined as limiting P nutrient applications on a field-by-field basis to crop uptake requirement. Such a restriction is consistent with state law as applied to poultry operations, but does not entirely reflect the site-specific characteristics of nutrient management plan development. The simplified nutrient management plan limited 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 could not meet all N and potash requirements, supplemental commercial N and potash applications were required. If all manure could not be used on the farm at these application rates, excess manure was required to be sold off farm. Other aspects of nutrient management including limitations on timing and method of applications were not modeled. Nutrient management plans cost $15 per acre, which included initial writing costs, soil tests, and maintenance costs (Patterson). Using an annual interest rate of 5.7% (Yanosek), the annual cost of a nutrient management plan is $5.58 per acre (NRCS).

Riparian Buffers. Buffers are strips of vegetation located along receiving waters that remove pollutants from surface runoff and subsurface lateral flows (USDA, 1998). Buffers function by slowing water velocity and filtering pollutants in runoff, and are most effective when shallow overland flow (sheet flow) passes through the strip (Mostaghimi, et al.). Estimates for reductions in soluble P reaching waterbodies range from 5–50% (Novotny and Olem). Total P loading reductions are likely to be higher because buffers are 35–90% effective in trapping sediment, upon which insoluble P is adsorbed (Mostaghimi, et al.). Establishment of a buffer generates costs of establishing and maintaining the buffer as well as opportunity costs of removing crop or pasture land from production.

The buffer practice consists of placing a 100-foot permanent herbaceous buffer strip on all stream-side borders of fields that are adjacent to receiving waters. The 100-foot width was employed to match buffer size to the size of the cells in the 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 a buffer activity, which is not harvested. The average annual cost of an acre of buffer was $32.79, which included annual maintenance costs and annualized establishment costs. Government incentive and/or cost-share payments are available for both buffers and nutrient management conservation practices, but were not included in order to isolate the social cost of implementing these practices.

P Delivery Index

Using GIS data to map fields and waterbodies, P delivery to streams was estimated with a hydrologic index developed to estimate loadings of P adsorbed to sediment and dissolved in runoff from each field to the nearest water body. Site-specific data inputs included crop management decisions and field slope, cover, and soil characteristics. The index combined 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, 2002b). Total P loadings to streams consisted of sediment-adsorbed P (SP) and runoff-soluble P (RP). Sediment-P is a function of erosion, soil insoluble P concentration, and a delivery factor. Runoff-P is a function of runoff volume, soil soluble P concentration, and a delivery factor. The delivery factor is dependent on slope steepness, slope length, and intervening land use between the field and water body. By reducing P applications, nutrient management reduces estimated runoff P from the field. Buffers lower the sediment and soluble runoff delivery ratio.

Results

Baseline

Estimated total gross margins for the population of farms were $8.8 million under the baseline with no BMP requirements. Compared to the population scenario, the representative farm and mega-farm scenarios overstated total gross margins by $6.7 and 0.3 million (65% and 3%, respectively) while the multi-representative farm scenario understated total gross margins by approximately $0.1 million (1%) compared to the population scenario (Table 4). The representative farm had the largest error in predictions because it overstated the capacity of the watershed farms to produce poultry (121 houses compared to 52 houses for the population scenario) and dairy (13,915 cows compared to 6,667 cows for the population (Table 5).

The population scenario predicted P delivery to receiving water bodies of 30,304 lbs. of which 71% was soluble runoff (Table 6). The representative and multi-representative farms overestimated total P delivery by 118% and 25%, respectively, while the mega-farm's estimated P delivery was nearly the same as that of the population. P deliveries were overestimated by the representative and multi-representative farm scenarios because they overestimated poultry and dairy manure production and applications and corn production relative to the population. Dairy farms with manure surpluses chose to over-apply manure rather than export surpluses due to the high cost. Manure over-applications contributed to high predicted P deliveries.

Mandatory Nutrient Management

Mandatory nutrient management reduced farm returns by approximately $0.9 million (10.2%) under the population scenario (Table 4). Returns were reduced because of lower crop revenue, increased manure export costs, increased commercial fertilizer costs, and costs of nutrient management plan writing. Corn-alfalfa acreage declined reducing the amount of alfalfa for sale. Corn-ryelage acreage increased because its higher utilization of P allowed more manure to be applied. Manure export costs were incurred by dairy farms with excess dairy manure. Commercial fertilizer costs increased to provide supplemental potash and N to compensate for reduced manure applications. While total P delivery declined by 7.6% due to reduced manure applications (Table 6), sediment P delivery increased because of the shift from corn-alfalfa to a more erosive corn-ryelage rotation.

With the mega-farm scenario, gross margins declined modestly (2.2%) due to increases in commercial fertilizer costs, reductions in crop revenues, and the costs of writing nutrient management plans. Revenues for alfalfa hay fell as land was shifted from hay to corn (Table 5). P delivery increased 35.7% due to higher sediment P delivery, which almost doubled due to the near doubling of corn acreage and reduced hay acres. Soluble P runoff changed little because total manure applications were unchanged although applications were shifted among fields so that total P applications did not exceed crop P removal on any field.

The representative farm scenario predicted nutrient management would reduce gross margins by 12.4%. Returns declined as the farm shifted land away from corn-alfalfa to corn-ryelage, reducing crop revenues but also increasing P utilization. The farm also incurred high costs to export dairy manure and for increased commercial fertilizer purchases (Table 5). The farm's P delivery increased 8.6% under nutrient management. Almost all the increase was accounted for by the shift from the corn-alfalfa to the corn-ryelage rotation which increased potential erosion and associated sediment P delivery. Soluble runoff declined by almost 10,000 lbs. reflecting the reduced manure applications.

The multi-representative farm scenario predicted 10.3% reductions in gross margins due to reduced alfalfa sales revenue and costs to export dairy manure, purchase commercial fertilizer, and write nutrient management plans. P delivery declined 5.1% because of large reductions in soluble runoff resulting from reduced dairy manure applications. Sediment delivery increased due to shifts from hay to corn.

Mandatory Buffers

Under the population scenario, buffers reduced total gross margins by 2.3% (Table 4) largely due to reduced alfalfa hay revenue from land taken out of production and costs of buffer establishment. Land in crops and pasture declined by 1,189 acres. Buffers reduced overall P deliveries by only 34 lbs. (Table 6) due to offsetting changes in cropping practices. Installation of buffers was accompanied by a 15% increase in corn production, which is more erosive than the hay and pasture it replaced.

Estimated reductions in net returns by the representative, mega, and multi-representative farms were similar to the population scenario reduction (Table 4). All experienced similar reductions in alfalfa sales as a result of taking land out of production for buffers. Compared to the population scenario, the mega, representative, and multi-representative farm scenarios predicted greater effectiveness of the buffer with reductions of 17.6, 15.9, and 15.0%, respectively, in total P deliveries (Table 6). The different estimates of effectiveness were due to differences in predicted allocations of cropland among more erosive corn and less erosive hay and pasture. The mega-, representative, and multi-representative farm scenarios predicted that acreage in corn would decline by 325, 109, and 112 acres, respectively, while the population predicted an increase of 324 acres. The mega-farm, representative, and multi-representative farm scenarios predicted reductions in hay and pasture of 864, 1,186, and 1,118 acres, respectively, compared to a reduction of 1,513 acres predicted by the population.

BMP Cost Effectiveness

Mandatory nutrient management cost \$695 and \$466 per lb. of reduced P delivery for the population and multi-representative farm scenarios. Costs per lb. were not estimated for the mega and representative farm scenarios because they predicted increased P deliveries. In this analysis, nutrient management is a practice standard requiring that P applications be limited to recommended crop application rates with no restrictions on crop selection. Under all scenarios, the predicted response to the nutrient management restriction was to shift some land from less erosive corn-alfalfa to more erosive corn-ryelage rotations in order to utilize more manure without exceeding P application recommendations. This strategy dominated the representative and mega-farm responses causing predicted P deliveries to increase. The population and multi-representative scenarios predicted high costs per lb. of reduced P delivery because farm costs of nutrient management were spread over modest reductions in predicted P delivery.

All information scenarios predicted similar compliance costs of mandatory buffers. However, compared to the population, the representative, mega-, and multi-representative farm scenarios overestimated the effectiveness of buffers because they overestimated the amount of cropland as opposed to pasture used for buffers. Larger reductions in sediment P were obtained by idling cropland compared to pasture. As result, the mega, representative, and multi-representative scenarios predicted costs per lb. of reduced P delivery of $38, $19, and $35 per lb., respectively, compared to $5,882 for the population.

Summary and Conclusions

Reduction of nutrient runoff from agriculture is an important component of nonpoint source pollution control strategies. This study contrasted the cost effectiveness of nutrient management plans and riparian buffers for controlling nutrient runoff from agriculture with alternative spatial representations of farms in a case watershed.

The nutrient management policy required that field P applications not exceed P removed by crops. All scenarios predicted lower net returns due to costs of nutrient plan writing, increased commercial fertilizer purchases, reduced crop revenues, and, with the exception of the mega-farm case, dairy manure exports. Compliance costs ranged from a low of $0.2 million for the mega-farm scenario to a high of $1.8 million for the representative farm scenario. The population and multi-representative farm scenarios predicted modest reductions in P delivery. Predicted P deliveries actually increased in the representative and mega-farm scenarios as a result of shifting from corn-alfalfa to corn-ryelage rotations having higher P deliveries.

All scenarios predicted similar costs of buffers of $0.2 million, which were incurred due to removal of land from production and buffer installation costs. The population scenario predicted that buffers would be implemented by removing land from hay and pasture while corn acres increased. As a result, predicted effectiveness of buffers was small as the sediment trapping of the buffers was offset by the higher sediment delivery from increased corn acres. The mega-, representative, and multi-representative farm scenarios reduced corn acres as well as hay and pasture acres to install buffers. As a result, these scenarios predicted greater effectiveness of buffers and much smaller costs per lb. of reduced P compared to the population.

The limited effectiveness of nutrient management and buffers in reducing P deliveries 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 in order to reduce costs. The result is to reduce the cost effectiveness of the pollution control practice. These adjustments make it difficult to draw conclusions about the relative cost effectiveness of buffers and nutrient management. Under the population scenario, both practices had very high costs per lb. of P reduction although nutrient management costs were much lower than those of buffers. With the mega-, representative, and multi-representative farm scenarios, buffers had much lower costs per lb. of P reduction.

Performance standards or incentives which focus on the desired pollution reduction rather than requiring specific practices would not be subject to potential offsetting adjustments which limit the practice's effectiveness in controlling pollution. For example, a P index can measure farm P loss potential at the field level for combinations of crop practices and nutrient applications (Giasson, Bryant, and Bills; Mullins et al.). By limiting the total P index for the farm, the policymaker imposes a 'quasi-performance standard'. Farmers can then consider alternative crop cultivation and nutrient application practices which satisfy the index at least cost.

In this study, the representation of nutrient management included only the restriction that P applications not exceed estimated crop P removal rates. In the baseline, farmers were assumed to apply nutrients at profit-maximizing levels. Studies of actual farms which implemented N-based nutrient management plans (VanDyke et al.) have 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 further benefits of nutrient management that were not addressed in this 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 associated databases will help policymakers and program managers better evaluate and implement practices for water quality protection in agriculture.

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Table 1. Cropland and Crop Yields[a] by Farm Type (Population Scenario)

Farm Type	Total # 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	23,762	3,363	899	1,186	715
Dairy with Broilers	88	1,545	9,722	1,372	376	453	285
Beef Only	229	3,668	24,644	3,496	930	1,171	708
Beef with Turkeys	136	2,173	14,856	2,099	565	693	432
Broiler Only	0	0	0	0	0	0	0
Turkey Only	1	5	88	13	3	0	0

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

Table 2. Farms With Livestock Capacities (Population Scenario)

Farm Type	No. of Farms	Dairy Cows	Beef Cows	Broiler Houses	Turkey Houses
Dairy Only	39	2,970	0	0	0
Dairy with Broilers	17	1,270	0	17	0
Beef Only	36	0	1,590	0	0
Beef with Turkeys	26	0	1,160	0	26
Broiler Only	2	0	0	6	0
Turkey Only	1	0	0	0	3
Total	121	4,240	2,750	23	29

Table 3. Farm Size and Livestock Capacity (Multi-representative Scenario)

Farm Type	Farm Size (acres)	# of Fields	Dairy Cows	Beef Cows	Broiler Houses	Turkey Houses
Dairy Only	98	6	123	0	0	0
Dairy with Broilers	91	5	114	0	1	0
Beef Only	102	6	0	54	0	0
Beef with Turkeys	85	5	0	44	0	1
Poultry Only	5	1	0	0	2	1

Table 4. Total Gross Margins of Watershed Farms Under Alternative Policy Scenarios

Spatial scenario	Policy Scenario		
	Baseline	Mandatory nutrient management	Mandatory buffers
Population farms ($m.)	8.8	7.9	8.6
% change from baseline		-10.2	-2.3
Mega-farm ($m.)	9.1	8.9	8.9
% change from baseline		-2.2	-2.2
Representative farm ($m.)	14.5	12.7	14.3
% change from baseline		-12.4	-1.4
Multi-representative farms ($m.)	8.7	7.8	8.5
% change from baseline		-10.3	-2.3

Table 5. Crops and Manure Export under Alternative Policy Scenarios

Spatial scenario	Policy Scenario Baseline	Nutrient management	Buffers
Population farms			
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 ($)	45,048	170,969	46,642
Mega-farm			
Dairy cows	6,667	6,667	6,667
Beef cows	0	0	0
Corn (acres)	2,977	5,526	2,652
Hay and pasture (acres)	8,242	5,693	7,378
Dairy manure application (1,000 gal.)	94,871	94,871	94,871
Dairy manure export (1,000 gal.)	0	0	0
Poultry litter application (tons)	0	0	0
Poultry litter export (tons)	0	0	0
Commercial fertilizer purchases ($)	0	75,258	0
Representative farm			
Dairy cows	13,915	13,915	13,195
Beef cows	0	0	0
Corn (acres)	7,163	11,217	7,054
Hay and pasture (acres)	4,066	0	2,880
Dairy manure application (1,000 gal.)	198,017	142,514	198,017
Dairy manure export (1,000 gal.)	0	55,503	0
Poultry litter application (tons)	0	0	0
Poultry litter export (tons)	24,200	24,200	24,200
Commercial fertilizer purchases ($)	0	359,249	0
Multi-representative farms			
Dairy cows	6,735	6,735	6,735
Beef cows	2,740	2,776	2,724
Corn (acres)	3,716	5,469	3,604
Hay and pasture (acres)	7,532	5,779	6,414
Dairy manure application (1,000 gal.)	95,503	61,953	95,503
Dairy manure export (1,000 gal.)	0	33,550	0
Poultry litter application (tons)	4,763	4,669	5,040
Poultry litter export (tons)	21,705	21,712	21,641
Commercial fertilizer purchases ($)	36,612	189,546	37,656

Table 6. Total P Deliveries Under Alternative Policy Scenarios

	Policy Scenarios								
	Baseline			Mandatory Nutrient Management			Mandatory Buffer		
	Sediment	Runoff	Total	Sediment	Runoff	Total	Sediment	Runoff	Total
Population Farms (lbs.)	8,709	21,595	30,304	13,076	14,933	28,009	9,413	20,856	30,270
% change from baseline						-7.6			-0.1
Mega-Farm (lbs.)	11,930	18,234	30,165	22,539	18,396	40,935	6,685	18,161	24,846
% change from baseline						35.7			-17.6
Representative Farm (lbs.)	28,231	38,053	66,284	43,890	28,083	71,973	17,831	37,932	55,763
% change from baseline						8.6			-15.9
Multi-Representative Farm (lbs.)	14,754	23,140	37,894	19,123	16,839	35,962	8,839	23,364	32,203
% change from baseline						-5.1			-15.0