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Impacts of Within-Farm Soil Variability on Nitrogen Pollution Control Costs

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ABSTRACT

The effects of considering variable within-farm soil runoff and leaching potential on costs of reducing nitrogen losses are analyzed for a Virginia dairy. Manure applications may cause nitrogen losses through runoff and leaching because of factors such as uncertain nitrogen mineralization. Farmers can reduce nitrogen control costs by applying manure on soils with less nitrogen loss potential. Ignoring within-farm soil variability may result in overstating the farm's costs of reducing nitrogen losses.

Key Words: economic costs, linear programming, manure, nitrogen, nutrient management, simulation, soil variability

Farm costs of controlling nutrient pollution are of concern in the Chesapeake Bay drainage area because the 1987 Chesapeake Bay Agreement committed Virginia, Maryland, Pennsylvania, and the District of Columbia to reducing controllable loads of nitrogen and phosphorus entering the Chesapeake Bay by 40% (Chesapeake Bay Program). Controllable loads include both point sources and nonpoint sources, but exclude natural background loads. The term *nonpoint source pollution* encompasses dispersed sources of pollutants including urban runoff, septic tanks, lawns, and agriculture. Agriculture is a major target of water quality protection programs because agricultural activities are estimated to account for 39% of the nitrogen and 49% of the phosphorus entering the Bay (Chesapeake Bay Program).

In the Bay region, nutrient management planning is promoted to reduce nutrient losses. Although incentives or permitting requirements may be involved, farmers usually agree voluntarily to follow management practices outlined in the plan. To control algae growth in the saline waters of the Chesapeake Bay, nitrogen reduction is necessary in the summer/fall in the Upper Bay and throughout the year in the Lower Bay (Fisher and Butt). Therefore farm nutrient management plans are designed to reduce nitrogen losses. Such plans are elaborated on a field-by-field basis. Nitrogen pollution potential is site specific, depending on how soils, slopes, and depth to groundwater vary within fields and how fields drain through diverse channels to surface water. VanDyke found that nitrogen loss reductions from nutrient management planning on livestock farms are contingent on unique within-farm characteristics, such as soil type and soil slope of fields. Nitrogen losses can be reduced

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beyond levels attained with the standard nutrient management plan through practices which consider soil variability, such as manure routing and rotation selection according to field environmental sensitivity. Further nitrogen loss reductions are important because VanDyke estimated that only one of four Virginia case farms achieved a 40% reduction in total nitrogen losses (the stated goal of the Chesapeake Bay Agreement) with a nutrient management plan.

Soil variability is particularly important in deciding where to apply manure. Commercial fertilizer is better suited than manure for soils with high leaching or runoff potential, because commercial fertilizer is all plant available when applied and can be applied at a time close to plant uptake to minimize the potential for runoff and leaching. Compared to fertilizer nitrogen, manure nitrogen is more prone to runoff and leaching on these soils because of the unpredictability of nitrogen mineralization rates and difficulty in spreading manure uniformly (Evanylo). Approximately one-half of liquid dairy manure nitrogen is in the organic form (Virginia Department of Conservation and Recreation), which is mineralized slowly over several years. Manure nitrogen is susceptible throughout the year to runoff with sediment while it remains in the organic form and to runoff and leaching after it is converted to inorganic nitrogen. Because erosion potential increases at an increasing rate with slope (Wischmeier and Smith), the potential for loss of nitrogen in surface-applied manure increases with slope steepness.

Economic studies of agricultural pollution control policies often use national, regional, or watershed models which do not consider farm spatial variability. The study area may be divided into homogeneous subregions with farm models used to model response to alternative policies (Wade and Heady). A second method of investigating costs of agricultural pollution control is representative farm analysis, which typically evaluates one or a few typical farms for the area of concern (Wossink, de Koeijer, and Renkema; Ellis, Hughes, and Butcher; Schnitkey and Miranda). However, such research generally does not consider the impact of within-farm soil variability on the costs of reducing losses. Failure to account for diverse site characteristics may lead to biased estimates of pollution, production, and income (Opaluch and Segerson; Gorres et al.).

A third approach, the micro-parameter approach, addresses the impact of farm spatial variability on pollution control costs (Antle and Just; Green et al.; Hochman and Zilberman, 1978, 1979; Johansen; Opaluch and Segerson). In this approach, farm-level crop production and pollution are represented by production functions that include variable inputs as well as site-specific land characteristics. Effects of soil variability can be analyzed by using econometric (Antle and Just; Green et al.; Opaluch and Segerson), mathematical programming (Carpentier, Bosch, and Batie), or dynamic programming methods (Braden et al.). However, such studies have overlooked important attributes of soil resources and management practices. For example, Braden et al consider the effects of soil variability and site location on BMP effectiveness but not firm-specific characteristics, such as manure use constraints, managerial capacity, or crop quota constraints. Carpentier, Bosch, and Batie consider variability of soils among farms but not variability of soils within a farm.

Here we present a case study which illustrates the effects of within-farm soil variability on the estimated costs of reducing nitrogen losses. A major finding is that by considering soil heterogeneity in making nutrient applications, farmers can reduce costs of controlling nitrogen pollution.

Procedures

The effects of soil variability on estimated costs of reducing nitrogen losses are analyzed for a Virginia dairy currently operating in the Shenandoah Valley. The farm was chosen through consultation with nutrient management specialists and project managers of the Division of Soil and Water Conservation in the Department of Conservation and Recreation. The variety of rotations, soils, and slopes on the farm permit examination of the potential to reduce nutrient losses below current levels through routing of manure and fertilizers within the farm and through changes in crop rotations and other nutrient application practices.

The costs of reducing nitrogen losses on the Shenandoah dairy are estimated with a linear programming model LPNM, which maximizes profit subject to resource and policy constraints. The farm's nutrient management plan applies to 314 acres, 50 acres of pasture and 264 acres of cropland, as well as the dairy milking and heifer enterprises. About 160 cows are currently milked and all dairy replacements are raised. This farm is representative of many dairies in the area in terms of dairy cow numbers and crop and pasture land. Field-level crop yields and nutrient losses for alternative management practices included in the model are estimated with the Erosion Productivity Impact Calculator (EPIC).

EPIC model

EPIC is a USDA-developed model capable of simulating daily plant growth; crop yields; and nutrient, sediment, and pesticides losses based on weather, hydrology, soil characteristics, and crop management practices (Williams and Renard, Sharpley and Williams). Input data for EPIC simulations are obtained from historical weather records, EPIC soil databases, soil surveys, the case farm's nutrient management plan, and interviews with the operator and nutrient management specialists. Average nutrient content of liquid dairy manure is estimated from farm manure tests conducted from 1988 to 1995.

A set of one hundred simulations is run for each field-level combination of crop rotation, soil, slope, and fertilizer management practice. Initial levels of soil nitrogen are set to reflect any build-up of nutrients in the soil from previous manure applications. A warm-up period of six years is simulated with EPIC to estimate this build-up. Each simulation is run for 14 years, the length of the longest crop rotation. Yields and nutrient losses reported here are annual averages for the one hundred 14-year simulations. Daily weather input for the simulations is randomly generated by EPIC using 1953 to 1993 rainfall and temperature data for the weather station nearest to the case farm. Although the weather generated for each year of the one hundred EPIC simulations is randomly selected, the long-term statistical properties of the resulting weather input variables are identical to those of historical weather distributions. The same one-hundred-year sequence of weather data is then used to model each combination of rotation, soil, slope, and nutrient application within the farm.

EPIC is a lumped, not distributed, parameter model. Therefore, each alternative crop rotation, management practice, soil type, and soil slope combination is modeled individually as a distinct field having uniform soil and slope. Each crop rotation and fertilizer management alternative combination is modeled on Frederick and Nixa soils. The Frederick is a good quality silt loam and the Nixa is a poor quality, very cherty silt loam subject to leaching. Other soils present on the farm in small acreages (but not modeled) possess characteristics similar to one of these soils. The Frederick soil has slopes ranging from B (2% to 7%) to E (25% to 45%). Nixa soil is present in B (2% to 7%) and C (7% to 15%) slopes. To represent these slope classifications, we model each crop rotation on Frederick soil with 4.5% and 10.5% slopes, and on Nixa soil with 4.5% slope. Pasture is modeled on Frederick soil with 4.5%, 10.5%, 16.5%, and 26.5% slopes.

Average crop yields and nutrient losses as estimated by EPIC for each crop rotation, management practice, soil, and slope combination are included as coefficients in LPNM. Soil nitrogen loss pathways include nitrate losses with runoff, organic nitrogen losses with sediment, and mineral nitrogen losses in subsurface flow and percolation. Volatilization losses to the atmosphere of nitrogen are not considered for nutrient management planning purposes and are not reported here. Nitrogen losses estimated by EPIC are losses at the edge of the field or at the bottom of the root zone. Therefore, such losses represent only *potential,* not actual, loadings to water sources. The actual loadings to nearby water bodies depend on environmental characteristics of the farm and of its surroundings, such as distance to ground and surface water and intervening land uses.

LPNM

LPNM maximizes returns minus variable costs subject to constraints on the acreage of specific soils and slopes present on the farm, livestock numbers, feed ration requirements, manure use, and nitrogen losses.

$$\text{Max} - \sum_{i=1}^{7}\sum_{j=1}^{31} c^1_{ij}\text{ROT}_{ij} - c^2\text{DAIRY}$$

$$+ \sum_{p=1}^{10} c^3_p\text{SELL}_p - \sum_{p=1}^{10} c^4_p\text{BUY}_p,$$

subject to

$$\sum_{j=1}^{31} \text{ROT}_{ij} \le \text{SOIL}_i,$$

$$\text{DAIRY} \le 160,$$

$$a^1\text{DAIRY} - \text{DRY} = 0,$$

$$a^2\text{DAIRY} - \text{HEIF} = 0,$$

$$- \sum_{i=1}^{7}\sum_{j=1}^{31} a^3_{pij}\text{ROT}_{ij} + a^4_p\text{DAIRY} + a^5_p\text{DRY}$$

$$+ a^6_p\text{HEIF} + \text{SELL}_p - \text{BUY}_p = 0,$$

$$- \sum_{i=1}^{7}\sum_{j=1}^{31} a^7_{ij}\text{ROT}_{ij} + a^8\text{DAIRY} = 0,$$

$$- \sum_{i=1}^{7}\sum_{j=1}^{31} a^9_{kij}\text{ROT}_{ij} - \text{LOSS}_k = 0,$$

$$\sum_{k=1}^{4} \text{LOSS}_k \le \text{RESTRICT},$$

where

i = 1 to seven crop and pasture soils,

j = 1 to 31 crop rotations and pasture management alternatives,

k = 1 to four nitrogen loss pathways, and

p = 1 to 10 farm products bought or sold.

Activities in the model are grouped into four general categories: 1. crop and livestock production (ROT_j and DAIRY), 2. accounting activities, 3. selling of farm products (SELL_p), and 4. purchase of farm products (BUY_p). Crop or pasture yield per acre for a given crop rotation, soil type, slope, and fertilizer management combination is based on the average annual yield simulated by EPIC for the one hundred 14-year simulations. The annual variable costs of production per-acre for each rotation (c^1_{ij}) include variable costs of machinery, seed, chemicals, fertilizers, and labor. The rotation cost is a weighted average of the annual variable costs of crops included in the rotation. Three crop rotations are currently followed on the farm: 1. corn, winter wheat, and clover cover, 2. corn and barley double-cropped with soybeans, and 3. corn and barley double-cropped with soybeans and alfalfa. Fields seeded to alfalfa remain in production for seven years. All corn, barley, and wheat production is chopped for silage, and no grain is harvested on the farm. The amount of each crop (p) produced in rotation (j) on soil (i) is specified in bushels or tons per acre (a^3_{pij}).

A series of constraints limits the acreage of each soil (SOILi) present on the farm in both cropland and pasture. Although all management alternatives are modeled on each soil and slope as discussed, the acreage of each soil can be adjusted in the LPNM model. Therefore, while the model can be used to evaluation pollution control policies when soil and slope variability is considered, the model can also be limited to only one soil and slope as representative for the entire farm.

Dairy cows milked (DAIRY) are allowed to vary up to the current level of 160 cows. Dry cow (DRY) and replacement heifer (HEIF) numbers must be proportional to milk cow numbers where a^1 is the number of dry cows as a proportion of milking cows and a^2 is the number of heifers as a proportion of milking cows. Annual cost of dairy cow (c^2) production is specified on a per-cow basis and excludes all feed ration costs.

Buying (BUY_p) and selling (SELL_p) activities of feeds and milk in LPNM are dependent on the number of dairy livestock. Feed consumed per dairy cow (a^4), dry cow (a^5), and heifer (a^6) but not produced is assumed to be purchased (BUY_p) at price c^4_p. Any excess crop

Table 1. Alternative Management Practices Included in LPNM

Group No.	Crop Rotation Names[a]	Nutrient Application Amounts and Timing[b]
		Cropland Management Alternatives
(1)	AFTCBS; AFTCBA; AFTCWC	6,000 gallons manure at planting to corn and small grains; 60 lb. N at planting to corn following soybeans and alfalfa; 40 lb. to corn following clover; 50 lb. N in March to small grains
(2)	RYECBS; RYECBA	Rye cover crop planted after harvest of soybeans; same fertilizer management practices as Group 1
(3)	CBS9; CBA9; CWC9	9,000 gallons manure at planting to corn; 4,500 gallons manure to small grains at planting; 4,500 gallons in March; 25 lb N at planting to corn following soybeans; 5 lb. N to corn following clover
(4)	CBS12; DBA12; CWC12	12,000 gallons manure at planting to corn; 6,000 gallons manure to small grains at planting; 6,000 gallons in early March; No N to corn or small grains
(5)	CBS3; CBA3; CWC3	3,000 gallons manure at planting to corn and small grains; 95 lb. N to corn following soybeans and alfalfa; 75 lb. N to corn following clover; 80 lb. N to small grains
(6)	NOMANCBS; NOMANCBA; NOMANCWC	130 lb. N at planting to corn following soybeans and alfalfa; 110 lb. N to corn following clover; 30 lb. N at planting to small grains; 80 lb. N in early March

production and all milk produced is sold ($SELL_p$) at price c_p^3. The pasture constraint is based on usage by current livestock numbers. Unused pasture is assumed to be idled.

All manure production (a^8), which is specified per cow, is converted to liquid equivalents based on nitrogen availability to simplify the LPNM model. All manure must be applied (a^7) to crops and pasture on the farm each year.

Per-acre nitrogen losses (a^9) from each soil, slope, and rotation, as estimated by EPIC, are summed ($LOSS_k$) by individual loss pathways including leaching, soluble runoff, sub-surface flow, and sediment-adsorbed runoff. A constraint is included to allow for the restriction of total farm level nitrogen loss ($LOSS_k$) to a specified level (RESTRICT). Initially, this constraint is set high enough to be nonbinding. Subsequently, RESTRICT is varied parametrically from 0% to 60% to estimate the cost of achieving alternative nitrogen loss reductions.

Management Alternatives

Table 1 shows ten groups of management alternatives for cropland and four groups for pasture, which vary in terms of crop rotations, fertilization amounts, and timing. The management alternatives were selected in consultation with soil scientists at Virginia Tech and nutrient management specialists and program managers from the Virginia Department of Conservation and Recreation. Tillage remains constant across all modeled alternatives. Corn

Table 1. (Continued)

Group No.	Crop Rotation Names[a]	Nutrient Application Amounts and Timing[b]
(7)	SPLTNCBS; SPLTNCBA; SPLTNCWC	60 lb. N to corn at planting; 70 lb. N in early June to corn following soybeans and alfalfa; 50 lb. to corn following clover; 30 lb. N at planting to small grains; 40 lb. in March; 40 lb. in April
(8)	PLT30CBS; PLT30CBA; PLT30CWC	30 lb. N to corn at planting; 100 lb. N in June to corn following soybeans and alfalfa; 80 lb. in June to corn following clover; 30 lb. N at planting to small grains; 40 lb. in March; 40 lb. in April
(9)	AUTOCBS; AUTOCBA; AUTOCWC	Timing and N fertilizer applications decided by EPIC based on nitrogen stress of crop (application rate = 30 lb. per application, maximum total N per crop = 150 lb.)
(10)	IDLECROP	No fertilizer, cropland planted to fescue-clover cover crop
		Pasture Management Alternatives
(1)	AFTPAST	2,300 gallons manure; 40 lb. N in spring
(2)	MANPAST	6,000 gallons manure
(3)	COMMPAST	65 lb. N in spring
(4)	IDLEPAST	No fertilizer, no grazing

[a] CBS—Corn, Barley, Soybean Rotation; CBA—Corn, Barley, Soybean, Alfalfa Rotation; CWC—Corn, Wheat, Clover Cover Crop Rotation.

[b] All application amounts are per acre.

and legumes are planted no-till. No manure is applied to soybeans, clover, or alfalfa.

The first group of management alternatives for cropland includes the farmer's current rotations with current management practices. The second group includes a rye cover crop after the harvest of soybeans. The cover is killed immediately prior to planting corn. Groups (3) through (5) vary the application rate of manure from 3,000 to 12,000 gallons per acre. Commercial fertilizer applications are modified to reflect the change in nitrogen available to the crop from manure in order to keep total plant available nitrogen applications approximately constant (Virginia Department of Conservation and Recreation).[1] The sixth group for cropland uses only commercial fertilizer to meet crop needs. Application of commercial nitrogen is adjusted to keep total nitrogen available to the crop the same as when a combination of manure and fertilizer is used.

Groups (7) through (9) vary the rates of split nitrogen fertilizer applications. The rates of application at planting and sidedressing in Groups (7) and (8) are based on consultations

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[1] By increasing the application of manure to 9,000 gallons, the total plant available nitrogen application to corn is kept constant. However, the application of total plant available nitrogen to small grains is reduced by approximately 20 pounds, because a farmer would not sidedress less than 30 pounds per acre of nitrogen fertilizer. By increasing the application of manure to 12,000 gallons, the total plant available nitrogen to both corn and barley in the corn, barley, soybean rotations is increased by 10 pounds per acre. To corn in the corn, wheat, clover cover rotations, the available nitrogen is increased by 30 pounds per acre.

Table 2. Acreage of Soils and Slopes Included in LPNM Model

	Multiple Soils Scenario	One Soil Scenario
Cropland	79 acres, 4.5% slope Frederick 159 acres, 10.5% slope Frederick 26 acres, 4.5% slope Nixa	264 acres, 8.5% slope Frederick
Pasture	5 acres, 4.5% slope Frederick 20 acres, 10.5% slope Frederick 5 acres, 16.5% slope Frederick 20 acres, 26.5% slope Frederick	50% acres, 16.5% slope Frederick

with nutrient management specialists. The ninth group of alternatives for cropland employs the auto-fertilizer option of the EPIC model. With this option, the application rate and timing of fertilizer applications are based on nitrogen stress to the crop, as determined by the EPIC crop growth process simulator. The application rate is set at 30 pounds per application based on consultations with nutrient management specialists, who stated that most farmers apply at least 30 pounds in any single application. Alternative Group (10) allows for idling land to further reduce nutrient losses.

Pasture (fescue) group alternatives vary application rates of manure and fertilizer to keep available nitrogen constant. The first group represents current practices. The second group increases the application rate of manure, the third group eliminates manure applications, and the fourth group allows for pasture acreage to be idled if livestock numbers are reduced.

Soil Scenarios

In the multiple-soils scenario, cost of achieving nutrient loss reductions is estimated assuming variable soils. Crop and pasture land resources are as described in Table 2 under "Multiple Soils Scenario." These estimates are obtained through examination of a soil survey of the farm. In the one-soil scenario, the cost of achieving nutrient loss reductions is estimated with all cropland assumed to be Frederick soil with 8.5% slope and all pasture assumed to be Frederick soil with 16.5% slope (see Table 2). Frederick is the predominant soil on the farm, while the slopes chosen are a weighted average for the farm based on examination of soil surveys.

Sensitivity analysis is conducted to determine how changes in soil slopes in the one-soil scenario affect farm returns and nitrogen losses. First, slopes are assumed to be flatter with all cropland slopes set at 4.5% and all pastureland set at 10.5%. Then slopes are assumed to be steeper with all cropland slopes set at 10.5% while pastureland slopes are increased to 26.5%.

Results

Multiple Soils

In the multiple-soils scenario, initial nitrogen loss reductions have little impact on farm returns (see Table 3). Crop rotations and livestock numbers are unchanged and nitrogen loss reductions are achieved by rerouting manure applications to soils with less potential for runoff and leaching. Manure applications are reduced on the Nixa soil and the Frederick soil with greater than 10.5% slope and increased on the Frederick soil with 4.5% slope (see Figure 1). Manure applications on these soils are replaced by commercial nitrogen applications, and nitrogen losses decline for reasons discussed in the introduction.

A 10% reduction in losses reduces farm net economic returns by less than 1% (see Table 3 and Figure 2). All cropland is in the rotation of corn and barley double-cropped with soybeans. To achieve a 20% or greater reduction, some land must be rotated to alfalfa, while manure application is shifted away from steep-

Table 3. Effects of Nitrogen Loss Restrictions on Farm Output and Net Returns with One Soil and Multiple Soils

Percent	Multiple Soils					One Soil				
N Loss Restriction	N Loss (lb)	Net Return ($)	Reduced Return ($)	Dairy Cows	Idle Land (Ac)	N Loss (lb)	Net Return ($)	Reduced Return ($)	Dairy Cows	Idle Land (Ac)
0	17,827	101,054	—	160	0	16,137	104,978	—	160	0
10	16,044	100,352	702	160	0	14,523	103,642	1,336	160	0
20	14,261	98,620	2,434	160	0	12,909	101,253	3,725	160	0
30	12,479	96,087	4,967	160	0	11,296	83,952	21,026	129	10
40	10,696	83,878	17,176	131	9	9,682	61,619	43,359	88	23
50	8,913	66,659	34,395	98	72	8,068	38,253	66,725	21	44
60	7,131	39,577	61,477	66	176	6,455	13,598	91,380	0	199

er Frederick soil and the more leaching-prone Nixa soil to the 4.5% Frederick soil. When nitrogen losses are restricted by 30%, farm returns are 5% below those estimated when nitrogen loss is unrestricted.

As the nitrogen loss restriction is tightened further, farm income declines more significantly. Most or all manure is applied to Frederick 4.5% slope soil, crop rotations are altered further, and livestock numbers begin to decline. To achieve a 40% reduction, farm return is reduced by 17% while only 79 acres of cropland remain in the original crop rotation and nine acres of pasture are idled. Dairy cow numbers are decreased by 18%. To achieve a 50% or greater reduction in nitrogen losses, all manure is applied to Frederick soil with 4.5% slope and livestock numbers continue to decline.

Single Soil

In the one-soil scenario, initial nitrogen losses are slightly lower than when soil variability is considered (see Table 3), because the steeper slopes of Frederick soil and the Nixa soil (both of which imply higher nutrient losses) are not included in the model. In comparison to the multiple-soil scenario, farm income, livestock numbers, and the amount of land in production decline rapidly as nitrogen loss is restricted (see Table 3 and Figure 2). This change occurs due to a loss of flexibility in targeting manure and fertilizer management practices within the farm based on soil susceptibility to nutrient losses.

Initial nitrogen loss reductions are achieved through altering the crop rotation mix rather than through targeting of manure to less en-

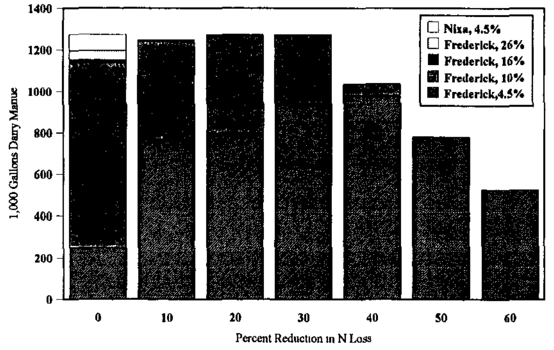

Figure 1. Farm Manure Application Amounts by Soil and Slope When Soil Variability Is Considered

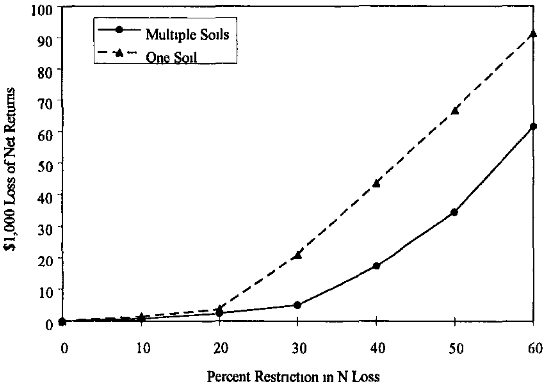

Figure 2. Loss in Farm Net Returns with N Loss Restriction

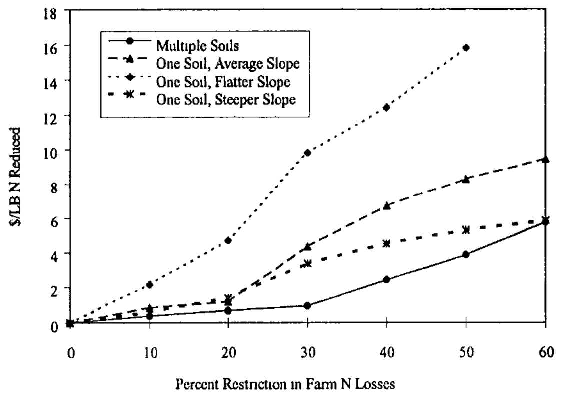

Figure 3. Average Cost Per Pound of Nitrogen Loss Reduction

vironmentally sensitive soils. To achieve a 10% reduction in losses, some land is rotated with alfalfa. Farm returns decline by 1.3%, almost twice as high as the reduction in returns estimated when soil variability is considered. To achieve a 30% reduction, farm returns are decreased by 20% and livestock numbers begin to decline. To achieve a 40% reduction, farm returns are reduced by 41%, more than double the reduction in income estimated when soil variability is considered. The more drastic reduction in income occurs due to a much more rapid decline in livestock (a 45% reduction), removal of more pasture from production, and more significant changes in crop rotations. Only seven acres of cropland remain in the corn, barley double-crop soybean rotation while 23 acres of pasture are idle. Average costs per pound of reduction in nitrogen loss, which equal the reduction in net farm income divided by the pounds of reduced nitrogen loss, are approximately twice as high as under the single-soil scenario compared to the multiple soil scenario (see Figure 3's comparison of one soil, average slope, and multiple soils).

Sensitivity Analysis of Soil Slope

The effects on nitrogen control costs of varying the slope under the one-soil scenario are evaluated. When steeper slopes are assumed, nitrogen losses are higher and costs per pound of nitrogen control are less than with an average soil slope (Figure 3). With steeper slopes, control practices reduce more pounds of nitrogen loss, resulting in a lower cost per pound. Regardless of the slope used in the one-soil scenario, the per-pound cost of controlling nitrogen loss is equal to or greater than the cost with multiple soils (Figure 3), which shows that the finding of lower nitrogen control costs with multiple soils is not sensitive to the selected soil slope. Costs are always higher under the one-soil scenario because of the loss of flexibility in routing manure applications to less environmentally sensitive soils. These results imply that upward biases in cost estimates are unavoidable if researchers simplify models to consider only one type of soil.

Summary and Implications

Nitrogen loss potential increases at an increasing rate with soil slope and is higher on more leaching-prone soils. To develop strategies to reduce nitrogen losses that take soil characteristics into account, farmers can target manure applications to soils with less potential for runoff and leaching. This strategy is generally less costly than idling land, shifting crops, or exporting manure to other farms. When researchers do not consider soil variability, they overlook this low-cost nitrogen loss control strategy and overestimate costs of reducing nitrogen losses.

Because costs of pollution reduction depend on farm-specific resources and practices, interdisciplinary work among economists and soil scientists in policy analysis concerning the spatial costs of pollution control is clearly needed. Study results emphasize the need for detailed information concerning agricultural soils and slopes when estimating pollution control costs. In this study, each slope classification in the soil survey of the farm is represented in the model as a single slope while the number of soils is also simplified. However, in reality, a variety of slopes will be present in a field or farm for each soil. Therefore, while results of the study indicate that consideration of within-farm variability of resource is critical in estimating pollution control costs, the tradeoffs between model complexity and accuracy of cost estimates are unknown. While our model is also a simplification of reality, it contains more information on within-farm soil heterogeneity than previous studies. However, more work is needed to examine the ability to maintain model accuracy while keeping a model tractable.

While we consider some firm-specific attributes such as manure use constraints and soil type, we do not consider the impact of changing field-level management practices on pollution losses to adjoining fields. The study by Braden et al. suggests a need for dynamic programming models which account for the effect of practices on adjoining fields on nutrient loadings to water bodies.

This study does not consider a number of best management practices (BMPs) which farmers could use to reduce nitrogen losses including filter strips, stream buffers, contour stripcropping, terraces, and other crop rotations. If one or more of the options not considered is a more cost-efficient way of reducing nitrogen than the options considered in this study, then the true average cost curve for nitrogen loss reduction lies below those shown in Figure 3.

Our results suggest that policies such as performance standards which give farmers more flexibility in choosing how to reduce pollution are likely to be less costly to farmers than design standards in achieving pollution reduction goals (Abler and Shortle). Similar results were also found by Schnitkey and Miranda. The most cost-efficient reductions in nitrogen loss are achieved through the targeting of manure and crop management practices within the farm to fields with the highest potential for loss reductions. However, transaction costs of performance standards may be higher than design standards (Carpentier).

In order to help farmers implement pollution control practices which target the most environmentally sensitive areas of a farm, nutrient management planners and other conservation specialists need better decision tools such as spatial decision support systems (Densham, Harsh; Armstrong et al). To minimize farm costs of nutrient loss reductions, such tools must encompass whole-farm planning.

References

Abler, D.G. and J.S. Shortle. "The Political Economy of Water Quality Protection from Agricultural Chemicals." *Northeastern Journal of Agricultural and Resource Economics* 20(1991): 53–60.

Antle, J.M. and R.E. Just. "Effects of Commodity Program Structure on Resource Use and the Environment." *Commodity and Resource Policies in Agricultural Systems,* eds. R.E. Just and N. Bockstael, pp. 97–128. New York: Springer-Verlag, 1991.

Armstrong, M.P., G. Rushton, R. Honey, B.T. Dalziel, P. Lolonis, S. De, and P. Densham. "Decision Support for Regionalization: A Spatial Decision Support System for Regionalization Service Delivery Systems." *Computers, Environment, and Urban Systems* 15(1991):37–53.

Braden, J.B., G.V. Johnson, A. Bouzaher, and D. Miltz. "Optimal Spatial Management of Agricultural Pollution." *American Journal of Agricultural Economics* 71(1989):404–413.

Carpentier, C.L. "Value of Information for Targeting Agro-Pollution Control: A Case Study of the Lower Susquenhanna Watershed." PhD dissertation, Blacksburg, Virginia: Virginia Polytechnic Institute and State University, 1996.

Carpentier, C.L., D.J. Bosch, and S.S. Batie. "Using Spatial Information to Reduce Costs of Controlling Agricultural Nonpoint Source Pollution." *Agricultural and Resource Economics Review* 27(1998):72–84.

Chesapeake Bay Program. *1987 Chesapeake Bay Agreement.* Annapolis, Maryland: Chesapeake Bay Program Office, 1987.

Densham, P.J. "Spatial Decision Support Systems." *Geographical Information Systems: Principles and Applications,* eds. D.J. Maguire, M.F. Goodchild, and D.W. Rhind, pp. 403–412. New York: John Wiley and Sons, Inc., 1991.

Ellis, J.R., D.W. Hughes, and W.R. Butcher. "Economic Modeling of Farm Production and Conservation Decision in Response to Alternative Resource and Environmental Policies." *Northeastern Journal of Agricultural and Resource Economics* 20(1991):98–108.

Evanylo, G.K. "Mineralization and Availability of Nitrogen in Organic Waste-Amended Mid-Atlantic Soils." *Perspectives on Chesapeake Bay, 1994: Advances in Estuarine Science,* eds. S. Nelson and P. Elliot, pp. 77–103. Solomons Island, Maryland: Scientific and Technical Advisory Committee, Chesapeake Bay Program, 1994.

Fisher, T.R. and A.J. Butt. "The Role of Nitrogen and Phosphorus in Chesapeake Bay Anoxia." *Perspectives on Chesapeake Bay, 1994: Advances in Estuarine Science,* eds. S. Nelson and P. Elliot, pp. 1–43. Solomons Island, Maryland: Scientific and Technical Advisory Committee, Chesapeake Bay Program, 1994.

Gorres, J.J., J.J. Opaluch, A.J. Gold, H. Besedina, and J. Conrad. "Spatial Modeling of N-Leaching and the Economics of Aquifer Protection." *Clean Water-Clean Environment—21st Century. Team Agriculture—Working to Protect Water Resources. Conference Proceedings. Volume II: Nutrients,* pp. 67–70. St. Joseph, Michigan: ASAE Publication 2-95, 1995.

Green, G., D. Sunding, D. Zilberman, and D. Parker. "Explaining Irrigation Technology Choices: A Microparameter Approach." *American Journal of Agricultural Economics* 78(1996):1064–1072.

Harsh, S.B. "Decision Support Systems—Definitions and Overview." *Proceedings of the American Agricultural Economics Association: Extension Workshop on Maintaining Cutting Edge,* eds. C.L. Mitchell and K.B. Andersons, pp. 197–214. Stillwater, Oklahoma Cooperative Extension Service, 1987.

Hochman, E. and D. Zilberman. "Examination of Environmental Policies Using Production and Pollution Micro-Parameter Distributions." *Econometrica* 46(1978):739–760.

Hochman, E. and D. Zilberman. "Two-Goal Environmental Policies Using Production and Pollution Micro-Parameter Distributions." *Journal of Environmental Economics and Management* 6(1979):152–174.

Johansen, L. *Production Functions: An Integration of Micro and Macro, Short Run and Long Run Aspects.* Amsterdam: North-Holland Publishing Company, 1972.

Opaluch, J.J. and K. Segerson. "Aggregate Analysis of Site-Specific Pollution Problems: The Case of Groundwater Contamination from Agriculture." *Northeastern Journal of Agricultural and Resource Economics* 20(1991):83–87.

Schnitkey, G.D. and M.J. Miranda. "The Impact of Pollution Controls on Livestock-Crop Producers." *Journal of Agricultural and Resource Economics* 18(1993):25–36.

Sharpley, A.N. and J.R. Williams, eds. *EPIC: Erosion Productivity Impact Calculator. Volume I. Model Documentation* Technical Bulletin No. 1768. Temple, Texas: United States Department of Agriculture, Agricultural Research Service, 1990.

VanDyke, L.S. "Nutrient Management Planning on Virginia Livestock Farms: Impacts and Opportunities for Improvement." M.S. thesis, Blacksburg, Virginia: Virginia Polytechnic Institute and State University, 1997.

Virginia Department of Conservation and Recreation. *Nutrient Management Handbook.* Richmond, Virginia: Division of Soil and Water Conservation, 1993.

Wade, J.D. and E.O. Heady. "Controlling Nonpoint Sediment Sources with Cropland Management: A National Economic Assessment." *American Journal of Agricultural Economics* 59(1977): 13–24.

Williams, J.R. and K.G. Renard. "Assessment of Soil Erosion and Crop Productivity with Process Model (EPIC)." *Soil Erosion and Crop Productivity,* eds. Follett, R.R. and B.A. Steward, pp. 68–103. Madison, Wisconsin: American Society of Agronomy, 1985.

Wischmeier, W.H. and D.D. Smith. *Predicting Rainfall Losses—a Guide to Conservation Planning.* Agriculture Handbook No. 537. Washington, DC: United States Department of Agriculture, 1978.

Wossink, G.A.A., T.J. De Koeijer, and J.A. Renkema. "Environmental-Economic Policy Assessment: A Farm Economic Approach." *Agricultural Systems* 89(1992):421–438.