Managing Nutrient Losses: Some Empirical Results on the Potential Water Quality Effects

C. Edwin Young and Bradley M. Crowder

Over-application of manure on cropland can cause water quality degradation. This paper reports a modeling approach for assessing tradeoffs among manure storage and handling systems as they relate to the nutrient loadings in cropland runoff, including nitrate losses to groundwater. The CREAMS simulation model provided estimates of nutrient losses. A linear optimization model was used to determine the income-nutrient loss tradeoffs. Six-month storage was profitable for fanners with average-size dairy herds, but compared to daily spreading caused increased nitrate leaching through the soil to groundwater resources. Twelve-month storage systems decreased farm profitability while decreasing the total nitrogen losses from farm fields.

Introduction

Livestock and poultry manures benefit both soils and crops, and application to cropland has been a convenient method for farmers to use these wastes. Proper animal-waste management requires that manures be managed and applied to land in ways that allow crops to utilize the nutrients, and that prevent nutrients and other pollutants from entering water supplies. This paper evaluates the costs and effectiveness of manure storage relative to field losses of nutrients.

Recently, attention has focused on the impacts that manuring cropland has on surface and groundwater supplies. Section 208 of the Clean Water Act (P.L. 92-500 as amended by P.L. 95-217) emphasizes the importance of establishing guidelines to encourage manure management practices that will foster crop use of nutrients while minimizing water pollution. Many areas of the nation now have local or regional water quality problems due to excessive applications of animal manures to cropland. Lancaster County, in southeastern Pennsylvania, is among the most intensively farmed areas in the United States. About 80 percent of the county's land is in farms, and manure applications to cropland now average 40 tons/acre/year, double the crop needs. Many wells in the county's most productive farming areas have nitrate-nitrogen levels two to three times the EPA's standards for safe drinking water (10 mg/1). In addition, southeastern Pennsylvania is a major source of nutrients and pesticides entering the Chesapeake Bay.

An experimental Rural Clean Water Program (RCWP) project was initiated in the northeastern portion of Lancaster County in 1981. It was established by the U.S. Department of Agriculture to address the water quality problems of the region, primarily the groundwater pollution by nitrates. An evaluation of the RCWP project was conducted by the Economic Research Service (Crowder and Young, 1985). Computer simulation and optimization techniques were used to evaluate the effectiveness of management practices for controlling nutrient pollution. In this paper, we report the effects that manure management could have on net returns to land and management and on field nutrient losses. These results demonstrate that switching from daily spreading to manure storage and management has a relatively minor effect on net farm re-

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Leader, Program and Policy Analysis Section and Agricultural Economist, Externalities Section, respectively, with the Natural Resource Economics Division, ERS, USDA. The authors gratefully acknowledge the helpful comments of Arthur Daugherty and Elizabeth Nielsen of NRED, ERS and two anonymous reviewers. Thanks are extended to Jeffrey Alwang, former graduate research assistant in the Department of Agricultural Economics and Rural Sociology at Pennsylvania State University, for research assistance. The views expressed in this paper are the authors' and do not reflect official policy of the USDA.

turns and on environmental losses. Estimates of field nutrient losses were made with the CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems) model. CREAMS is a computer simulation model built by USDA's Agricultural Research Service that is used to compare field losses of pollutants among different management practices (Knisel, 1980).

Some of the CREAMS estimates were incorporated into a representative farm linear programming model developed for this study to evaluate storage systems. The model is based on the NE-111 Forage-Dairy Systems Model (Partenheimer and Knievel, 1983), and allows the simultaneous analysis of forage and dairy activities on a representative farm. The only modifications to the model were the inclusion of the manure storage and handling activities and the CREAMS estimates of pollutant losses.

The effects on field pollutant losses and farm income were estimated using the linear programming model. Eleven manure storage and handling systems for dairy operations were evaluated (Young, Alwang, and Crowder, 1986). The results reported here are for the three most common and profitable systems in the RCWP project area: (1) daily spreading, (2) 6-month slurry storage in an earthen basin, and (3) 12-month slurry storage in an earthen basin. A herd of 45 milking cows with replacements, an average herd size for Pennsylvania, was modeled as the typical southeastern Pennsylvania dairy operation.

While the model was developed for a specific location, we would expect similar results for dairy farms throughout the northeast. A study of the St. Albans Bay RCWP project in Vermont by Shortle, Young, and Akerman (1986) predicted similar relationships between changes in net farm income and environmental losses. They modeled a medium-sized farm with 58 cows and 125 acres of cropland and a large farm with 100 cows and 225 acres of cropland.

Cropland acreage was modeled for 40 to 120 acres (in 20-acre increments) with the same soil and slope so that the effects of varying animal densities could be determined. Most dairy farms in the RCWP project areas have from 40 to 60 acres. However, the 40- to 120-acre range makes it possible to extrapolate the results for the manure storage and handling systems to other farms and regions. A corn-alfalfa rotation was modeled for the representative farm. The model optimized the acreage in corn and alfalfa, and thus the length of the rotation and the alfalfa stand. The proportion of corn and alfalfa acreage varied depending on the manure storage system, and on the acreage and manure nutrients available for crop production (see Young, Alwang, and Crowder, 1986). Corn grain and hay purchases were allowed, but corn silage had to be produced entirely on the farm.

The nutrients available in manure varied by the type of storage and application system. A ton of manure that is spread daily contains 33 percent less plant-available nitrogen than a ton of manure from a 12-month storage structure. In order to simplify the modeling it was assumed that all manure nutrients are available in the year that they are applied. Since the fields in the study area have been heavily manured for many years, the total nutrients in the manure applied in the current year approximates the nutrients available from decay of previous applications.

Field Losses of Nutrients

The effects of manure storage on annual field nutrient losses at different manure loading rates are illustrated for continuous corn grain in Table 1. The effects when conventional tillage is used without soil conservation practices are shown in the top half of the table. The lower half of the table illustrates the effects when a set of best management practices (BMPs) have been implemented under the same soil and field conditions.

Soil losses were 7.3 tons per acre without BMPs and 0.6 tons per acre with BMPs. Nitrogen losses in Table 1 are divided into percolate losses of nitrate-nitrogen leached out of the crop root zone, and surface losses which included nitrogen dissolved in surface-runoff waters and attached to suspended sediment particles. Phosphorus losses included both dissolved and suspended sediment fractions as well. Because manure storage primarily affects nitrogen losses, the discussion of the results will focus on changes in nitrogen losses due to changes in manure management. The CREAMS modeling results compared favorably to monitoring results for field sites in the RCWP study area (Crowder and Young, 1985).

Nutrient losses are shown for 20- and 40-tons-per-acre loadings, though manure appli-

Table 1. Effects of storage period on annual nutrient losses tor continuous corn gram, 5-percent-slope land, and 20 and 40 tons of manure per acre using the CREAMS model.

Manure Application	Nitrogen losses Percolat	Surface	Total	Phosphorus losses
			Pounds per acre	
Conventional tillage				
(7.3 tons/acre soil loss)				
20 tons per acre				
Daily spreading	33	40	73	18
6-month storage	33	38	71	17
12-month storage	27	37	64	17
40 tons per acre				
Daily spreading	53	70	123	31
6- month storage	63	64	127	28
12-month storage	65	65	130	28
BMPs[a]				
(0.6 tons/acre soil loss)				
20 tons per acre				
Daily spreading	35	12	47	4
6-month storage	34	10	44	3
12-month storage	30	9	39	3
40 tons per acre				
Daily spreading	55	23	78	7
6- mo nth storage	66	17	83	5
12-month storage	68	17	85	4

[a] BMPs include conservation tillage (chisel plowing and disking), impoundment-type terraces, contouring, stripcropping, residue management, and sod waterways. Source: Crowder and Young (1985).

cations were modeled ranging from 10 to 40 tons per acre (see Crowder and Young, 1985). Application of approximately 20 tons of manure per acre provides sufficient nutrients for corn production. When manure applications were modeled without BMPs at 20 tons per acre, nitrogen losses were similar for daily spreading and 6-month storage (Table 1). Nitrate-nitrogen losses with 12-month storage were considerably less—18 percent less than those for daily spreading and 6-month storage. More nitrogen is available for plant uptake or environmental loss from manure which has been stored in a manure storage structure and incorporated in the soil than there is under a daily spreading system. The CREAMS modeling and the linear programming accounted for the differences in nutrient availability for crop production and for runoff among manure storage and application systems (see Young, Al-wang, and Crowder (1986) for a description of the adjustments). When stored manure is applied in the spring prior to planting, it is used more efficiently by crops. Six-month storage and daily spreading of manure result in significant amounts of manure (one-half or more of the total) being applied on fields when no plant uptake of nutrients is occurring. Therefore, even though there are fewer plant-available nutrients applied under these two systems, the applications after the growing season resulted in greater nitrate leaching than with 12-month storage.

When manure was applied in excess of crop needs at 40 tons per acre, the effectiveness of storage decreased. Percolate and total nitrogen losses were greater for 6- and 12-month storage than for daily spreading (Table 1). This indicates that nutrient conservation in storage structures on farms where manure nutrients significantly exceed crop needs result in *increased* degradation of on-site groundwater supplies. This finding, while intuitively obvious, has important policy implications for animal-waste management. Long-term manure storage may exacerbate water quality problems on livestock-intensive farms that have soil, climatic, and geological factors which render them vulnerable to groundwater contamination. In addition to nutrients, fecal coliform and other bacteria can leach through the root zone to groundwater wells and further degrade drinking water supplies.

What happens when manure is stored on a

Table 2. Effects of animal density and manure storage on net returns to land and management and on field pollutant losses with no BMPs implemented, 45 -cow dairy herd.

Cropland acreage	AU acre[3]	Net returns ($/yr)	Nitrogen losses (Ib/Ac)	Phosphoru losses (Ib/Ac)	Soil losses (T/Ac)	Nitrogen purchased (lb)
			Daily Spreading			
40	1.63	13,500	99	24	7	—
60	1.08	18,600	73	17	7	—
80	0.81	22,900	57	13	7	842
100	0.65	26,800	55	13	7	1,363
120	0.54	30,500	49	11	6	2,750
			6-Month Slurry Storage			
40	1.63	14,200	102	24	7	—
60	1.08	19,400	76	17	7	
80	0.81	23,900	62	13	7	
100	0.65	28,000	54	12	7	210
120	0.54	31,800	49	11	6	1,202
			12-Month Slurry Storage			
40	1.63	12,700	91	24	7	—
60	1.08	17,900	67	17	7	—
80	0.81	22.300	55	13	7	—
100	0.65	26.400	46	12	7	
120	0.54	30,100	41	11	6	153

[a] One animal unit (AU) is defined as one-thousand pounds of animal live-weight. For example, a 1,320-pound dairy cow is equivalent to 1.32 AU.
Source: Young, Alwang, and £rowder (1986).

farm where good soil conservation is practiced? Surface nitrogen losses were reduced to less than one-third of what they were compared to no BMPs (Table 1). Reductions in phosphorus losses were even more pronounced. Total nitrogen losses were reduced because of the reduction in surf ace-runoff losses in spite of increases in nitrate leaching. Nitrate leaching losses again were less for daily spreading than for 6- or 12-month storage at both manure loading rates (Table 1).

Effects of Manure Management on Farm Income and Nutrient Losses

The effects of manure handling systems and animal units/available cropland (AU per acre) on net farm returns and field pollutant losses (nitrogen, phosphorus, and soil) as calculated by the linear programming model are shown in Table 2. Commercial nitrogen fertilizer purchases are also shown to indicate crop nitrogen needs not met by manure.

For a given acreage, net returns were relatively constant among the three manure handling systems. Six-month storage was found to be more profitable than daily spreading. Twelve-month storage provided returns $400 to $800 less than daily spreading, depending on available cropland. Manure storage systems compared more favorably to daily spreading when animal densities were lower. This is because nitrogen is conserved by manure storage structures so that more is available for crops during the growing season (Young, Alwang, and Crowder, 1986).

For the daily spreading system, manure provides more nitrogen than crops can utilize with 60 acres or less cropland (last column, Table 2). Similarly, 6-month and 12-month storage result in excessive nitrogen applied at less than 100 and 120 acres of available cropland, respectively. Therefore, manure nitrogen has positive marginal value to farmers who are spreading it daily when 80 or more acres of cropland are available. Storage systems which conserve nitrogen require still greater amounts of land for the manure nitrogen from a 45-cow dairy operation to have positive marginal value.

For a given acreage, the optimal cropping pattern for the corn-alfalfa rotation is the same regardless of the manure management system. In other words, the model always allocates the same percentage of cropland acreage to corn and alfalfa. Thus, soil losses are not affected by manure practices.

Nutrient losses increase as the animal density and manure loadings per acre increase. At

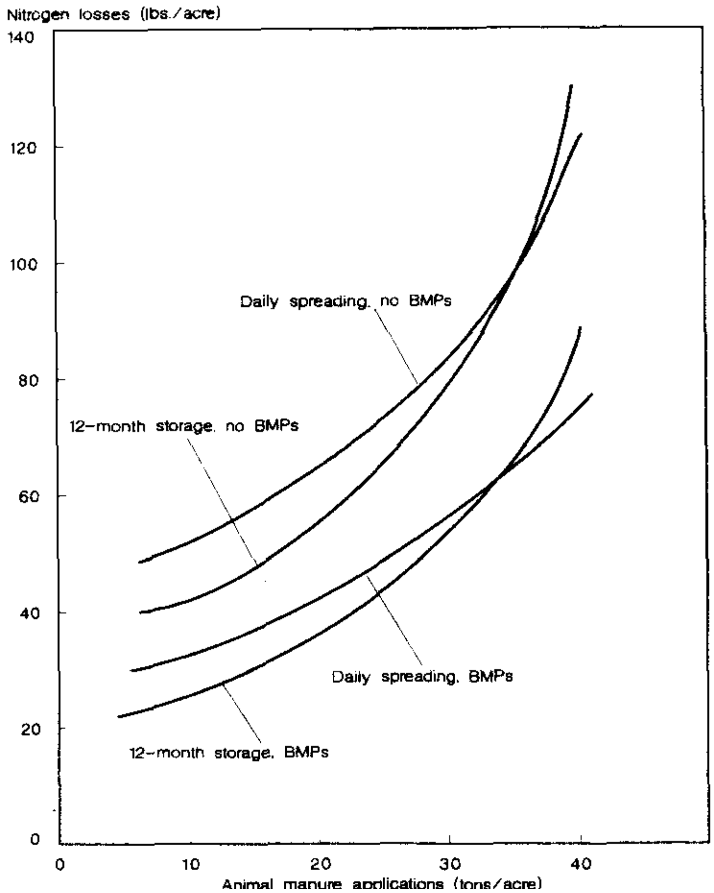

Figure 1. Marginal nitrogen losses from increasing levels of manure application.

relatively low nutrient applications, the curve will flatten out; i.e. incremental reductions in animal density will result in relatively smaller marginal reductions in nutrient losses. At the other extreme, marginal nitrogen losses are expected to increase more than proportionally to the increases in animal density as total nutrient applications further exceed crop requirements.

The relationship between total nitrogen losses from an individual field and manure loadings is illustrated in Figure 1. Nitrogen losses are shown for both daily spreading and 12-month storage. The effect of BMPs is also shown. The inclusion of BMPs reduces nitrogen losses regardless of manure loadings because surface-runoff losses are reduced substantially more than the increase in nitrate leaching. Therefore, the curves representing the use of BMPs are below those without soil conservation practices. The use of BMPs does not, however, change the relationship between manure loadings and nitrogen losses. Figure 1 illustrates that storage reduces nitrogen losses when manure application is reasonably consistent with crop needs. When approximately 37 or more tons of manure per acre were applied on the representative field, nitrogen losses were greater for storage systems and increased at a more rapid rate than for daily spreading.

Nutrient retention is no longer desirable at high animal-to-land ratios because it further exacerbates the nutrient-loss problems. This is because nitrogen, in a mass-balance framework, must be lost increasingly to surface runoff or groundwater percolation as additional nitrogen can no longer be taken from the soil through crop uptake. Increased nitrogen retention from storage structures thus results in greater losses, most of which are in the form of nitrate leaching. The same relationship cannot be presumed in the short run for phosphorus at high loadings because phosphorus can accumulate in the soil profile, as evidenced by soil test data (USDA, 1984).

The critical policy implications of the results in Table 2 are related to the effectiveness of manure management systems for reducing field nutrient losses. Compared to daily spreading, 6-month manure storage systems show practically no improvement for nutrient control. A slight (3 percent) increase in nitrogen losses occurred for the smaller crop acreages, and losses were reduced at most 1 percent when acreage was 100 acres or more. The advantage of timing spring application so that nutrients are available when crops need them is offset by the conservation of excess nutrients that must be disposed on the land in the fall (in quantities greater than those available from daily-spread manure). Basically no difference in nutrient losses exists between daily spreading and 6-month storage, while annual net returns are greater for 6-month storage.

The 12-month storage system is somewhat more effective than daily spreading when cropland is limited, but performs much better when the cropland exceeds 100 acres. Nitrogen losses are reduced by up to 17 percent with 120 acres of cropland. This is because 12-month storage allows manure to be applied in the spring when crops need the nutrients. When enough land is available to dispose of all the manure (more than 100 acres for the 45-cow herd), this advantage results in lower field losses of nitrogen. When nutrient applications exceed crop requirements (less than 100 acres

Six-month storage structures, the more common ones because of their smaller capital costs and space requirements, actually result in greater precolate and total nitrogen losses than daily spreading. Because of less labor requirements, and because of smaller fertilizer purchases when cropland exceeds 60 acres, the six-month storage was more profitable than daily spreading for the dairy operation that was modeled. Conservation of excess nutrients is expected to result in their loss to water supplies. Careful consideration of a farm's nutrient production, land resources, cropping practices, and geological characteristics is needed before a manure storage structure is installed with government cost sharing. The public should not subsidize a farmer's manure handling practices with a storage structure when it results in greater farm, income or further degrades public water supplies.

Other Solutions

Any environmental protection policy should consider the entire system affected by a production activity. This study indicated that manure storage can do little to improve the nutrient quality of cropland runoff when manure nutrients exceed crop needs. Before cost-sharing is provided for storage structures, the efficacy of storage for solving the problems should be determined and other solutions considered.

Aside from soil conservation BMPs, which control surface-runoff losses, less attractive alternatives from the farmers' viewpoint are necessary to control nitrate leaching where elevated groundwater nitrate levels are due to animal manures. These range from spreading manure nutrients more evenly on cropland where crops will use them more efficiently, to reducing the number of animals or hauling the manure to other farms or sites where it can be used without degrading water quality. Spreading manure evenly is the least costly of these alternatives, although weather conditions sometimes make it difficult or inconvenient to spread manure on some fields. Better spreading equipment and other technological innovations will likely further the efficiency of manure spreading.

Reducing the manure for field application involves either cutting the herd size or exporting some of the manure off the farm. The costs of these practices vary according to the farm and the region considered. Some restrictions on the number of animal units per acre may be necessary for farmers with severe water quality problems. In our comprehensive report of this study, hauling manure off the farm was more profitable than reducing the size of the dairy herd (see Young, Alwang, and Crowder, 1986). These and other innovative solutions to the animal manure/water quality problem, such as community methane digestion plants and refeeding of animal manures, should be pursued where storage structures do little to improve water quality.

Summary and Implications

Liquid and other manure storage structures are being installed on farms throughout the nation as a means for controlling on-site as well as off-site nutrient pollution of water supplies. Our results for a typical southeastern Pennsylvania dairy operation indicate that 12-month manure storage can reduce nitrate leaching losses to local groundwater and regional water supplies, if enough cropland is available to dispose of the manure at rates that are consistent with or less than crop needs. This conclusion assumes that farmers accurately account for the nitrogen in their manure and do not over-apply commercial fertilizer.

Another important conclusion, alluded to earlier, is that storage structures should not be implemented to conserve nutrients when manure nutrients substantially exceed crop needs. If storage structures are implemented, agitation and surface spreading are desirable where practical to volatilize unwanted nitrogen. At 40 tons of manure per acre of cropland, the nutrient losses from storage systems were considerably greater than those from daily spreading. Greater manure loadings would result in greater differentials between the nutrient losses of daily spreading and storage systems because less nitrogen is conserved under daily spreading systems and thus not available for loss to water supplies. Another option for farmers with excess nutrients would be short-term storage. Short-term solid storage would allow farmers who spread manure daily under normal conditions to avoid spreading when field activity would result hi accelerated runoff losses, and still minimize the conservation of excess nitrogen.

Significant reductions of nutrient losses in surface runoff are dependent on either BMPs which control runoff and erosion or reductions in manure loadings. Reducing loadings is accomplished by exporting manure off the farm for use elsewhere and is not addressed in this paper (see Young, Alwang, and Crowder, 1986). Total nutrient losses are reduced substantially by BMPs, although on-site water pollution will increase somewhat because of increased nutrient retention on fields and the increased percolation of water and dissolved pollutants through the soil profile. Thus if there is a groundwater problem on a farm, soil conservation may increase nitrate and other pollutant concentrations and further degrade the resource.

This last implication is an important one for many areas in the northeastern and north-central regions in the United States. Both soil conservation practices and manure storage will increase nitrate deliveries to groundwater when excessive amounts of animal manure and other nitrogen sources are applied to cropland. If the water quality concerns are primarily for surface water, BMPs can improve the resource unless groundwater recharge from polluted areas is a primary source of stream baseflow, as it often is in the ridge-and-valley farming areas of the northeastern and north-central regions. Dissolved nitrates in ground-water, which are more biologically available than nitrogen in surface runoff which is attached to suspended sediment, will eventually find their way to streams and further degrade the aquatic environment. In such cases, the potential exists for elevating nitrogen levels in both surface and groundwater supplies. Policy-makers must be aware of the overall effects such practices may cause in the aquatic environment.

The modeling approach used in this paper can be used to address some concerns associated with manure management and water quality. The CREAMS model was used because it is a readily available state-of-the-art model for estimating surface-runoff and percolate losses of nitrogen, and surface-runoff losses of phosphorus. Related physical and chemical models can be used with economic analysis tools such as linear programming to address other water-quality concerns related to manure management.

References

Crowder, B.M., and C.E. Young. *Modeling Agricultural Nonpoint Source Pollution for Economic Evaluation of the Conestoga Headwaters RCWP Project.* ERS Staff Report No. AGES850614, Natural Resource Economics Division, Economic Research Service, U.S. Department of Agriculture, Washington, D.C., September 1985.

Knisel, W.G., editor. *CREAMS: A Field Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems.* Conservation Research Report No. 26, Agricultural Research Service, U.S. Department of Agriculture, 1980.

Partenheimer, E.J., and D.P. Knievel. *Forage-Dairy Systems for the Northeast-A Modeling Approach.* Bulletin 845, Pennsylvania State University, College of Agriculture, Northeast Region Forage-Dairy Systems Technical Committee (NE-111), University Park, Pa., 1983.

Shortle, J.S., C.E. Young, and M.K. Akerman. "Economic Evaluation." *St. Albans Bay Rural Clean Water Program, Annual Report.* Agricultural Stabilization and Conservation Service, U.S. Department of Agriculture, Burlington, Vt., 1986.

U.S. Department of Agriculture, Agricultural Stabilization and Conservation Service. "Conestoga Headwaters Rural Clean Water Program - 1984 Progress Report." Lancaster County, Pa., January 1985.

Young, C.E., J.R. Alwang, and B.M. Crowder. *Alternative for Dairy Manure Management.* ERS Staff Report No. AGES860422, Natural Resource Economics Division, Economic Research Service, U.S. Department of Agriculture, Washington, D.C., 1986.