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Alternatives for Dairy Manure Management

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ABSTRACT

Intensive dairy farm operations have adversely affected water quality in the Conestoga Headwaters Rural Clean Waters Program (RCWP) project area of Lancaster County, Pennsylvania. In this study, alternative dairy manure-storage/application systems were evaluated, including their effects on net farm returns and losses of nitrogen and phosphorus. Net farm returns were nominally reduced when nitrogen losses were constrained to 90 percent of initial daily-spreading losses as a means of improving environmental quality. When nitrogen losses were further constrained to 70 and 50 percent of initial daily-spreading losses, net returns were reduced significantly. Alfalfa acreage increased and herd size decreased to meet these more severe constraints. Hauling manure 40 miles away from the farm for use elsewhere to meet the nitrogen constraint increased net returns. It is less costly to haul a dairy cow's manure 40 miles than to give up the additional revenue generated by that cow.

Keywords: Manure, manure management, Conestoga Headwaters Rural Clean Waters Program, net farm returns, dairy farms, nonpoint source pollution, CREAMS.

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PREFACE

The U.S. Congress enacted the Rural Clean Water Program (RCWP) in 1979 as an experimental program to combat agricultural nonpoint source pollution. RCWP, a voluntary program, provides long-term financial and technical assistance to owners of privately held agricultural land in selected project areas to install and maintain best management practices (BMPs) to control water pollution. The Agricultural Stabilization and Conservation Service (ASCS), U.S. Department of Agriculture (USDA), operates the program with technical assistance provided by other USDA agencies and the U.S. Environmental Protection Agency (EPA). The Soil Conservation Service (SCS), USDA, coordinates all technical services.

The Conestoga Headwaters RCWP project (Lancaster County, Pennsylvania) was one of five projects selected for comprehensive monitoring and evaluation (CM&E). The CM&E consists of monitoring and evaluating the physical and the economic effects of the RCWP project. The Economic Research Service (ERS), USDA, is cooperating with the U.S. Geological Survey, the Pennsylvania Department of Environmental Resources, ASCS, and SCS in conducting the economic evaluation.

The economic evaluation includes evaluating RCWP effects on participants and local agriculture, evaluating offsite and community impacts, analyzing cost-effectiveness, and comparing the project's benefits and costs. This report projects the effects on participating farmers of adopting alternative manure storage and handling systems. A subsequent economic evaluation report will provide an indepth economic evaluation of the Conestoga Headwaters RCWP project.

SUMMARY

High animal densities resulting from intensive animal production have led to concern about the effect on water quality of excessive land application of dairy manure. Research directed toward solving this problem has focused on improved manure management. Farmers appreciate the nutrient value of their animal waste and look toward better manure management to improve farm income by reducing purchases of commercial fertilizers.

This study examines 11 systems of manure management with respect to their environmental and economic effects. There were clear differences in the income-producing potential of the storage/application systems evaluated, primarily due to differences in the fixed costs of handling/storage systems and the costs of bedding in the solid manure handling systems. There were also large differences among systems in the nutrient losses that occur after land application of manure. Nitrogen losses to surface and groundwater were highest with the 6-month slurry storage system and lowest with the 6-month uncovered solid storage system. Phosphorus losses were highest for daily spreading and the 6-month slurry storage and lowest under the 6-month solid storage.

Changing manure management practices only limits nonpoint nitrogen loadings. Modeling results indicate that changing from daily spreading to 6-month slurry storage of manure reduced nitrogen losses by 10.8 percent and phosphorus losses by 6.3 percent.

A few trends emerged as nitrogen losses were constrained to 90, 70, and 50 percent of initial daily spreading losses. In most cases, the least restrictive loss constraint could be met by all systems with a nominal reduction in the farm's net returns. In most cases, imposing the constraint merely dictated more even application of manure over farm fields.

Twelve-month slurry storages were more effective in meeting the loss constraints than were the 6-month storages. Although the systems conserve nutrients equally during storage, many nutrients from the fall application of the 6-month storage were lost from the field before plants could use them in the spring. The most effective 6-month storage system for water quality protection was the one that lost nitrogen during storage (the uncovered solid system). This volatilization loss in storage reduced the nitrogen availability for runoff and percolate losses over the winter months from the fall application.

Reducing the number of cows drastically reduced farm income. Manure hauling, when permitted, provided higher net returns than reducing herd size. Some manure storage/application systems are more effective in meeting environmental constraints than others. Some types of storages (12-month slurry storage and 6-month uncovered solid storage) were better than daily spreading, even for the small farms in the study area. The 12-month slurry storages, because they adapted better to nitrogen loss constraints, performed better than did the 6-month slurry storages. The 6-month uncovered storage, because it volatilizes nitrogen, adjusted well to the nitrogen loss constraints.

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INTRODUCTION

Dairy farms contribute directly to agricultural pollution through erosion and runoff from cropland. Dairy farms also face the problems of manure disposal. Properly applied manure contributes nutrients for plants and enhances soil water-holding capacity, organic-matter content, and soil tilth. However, nutrients from manure can run off fields when dissolved in solution or attached to sediment. Manure runoff also contains micro-organisms which may hurt surface waters used for recreation and could cause public health problems. Also, nitrogen from manure becomes mobile within the soil profile and may leach into groundwater in the nitrate-nitrogen form.

Some runoff and leaching of nutrients is natural. But pollution caused by animal wastes is generally intensified by improper handling and/or application procedures. When large quantities of animal wastes are left exposed on the fields during major precipitation, rainwater can transport manure runoff to streams or leach nutrients into groundwater. Manure spread on frozen ground, that is exposed to precipitation and runoff, may be lost to surface waters. A second factor intensifying manure-related pollution relates to animal density. When nutrients from manure application exceed plant needs, the excess nutrients may hurt water quality.

Pollution problems related to the handling and/or application of dairy manure are common to the northeastern quadrant of the United States. We examined alternative dairy manure storage/application systems and compared: 1) the relative effects of each system on net revenue and soil and nutrient losses among storage/application systems, 2) the potential of each system to meet nitrogen loss constraints under changing conditions, and 3) various methods for reducing nutrient losses from fields including alternative animal-to-land ratios and hauling manure outside the study area for disposal. We conducted this study as part of the economic evaluation of the Conestoga Headwaters Rural Clean Water Program (RCWP) project in southeastern Pennsylvania. While the results are somewhat site-specific, the tradeoffs that occur among manure management systems for cost-effectively controlling nonpoint pollution on smaller dairy farms also apply to the northeastern U.S. dairy farming industry.

The Conestoga Headwaters area includes some of Pennsylvania's most fertile and intensively farmed land. The Conestoga River drains the area and is a tributary of the Susquehanna River. Recent studies have shown a significant trend toward decreasing water quality in the area (12, 13).[1/] Pollution of surface water and groundwater in the area may affect about 175,000 water users. Also, concern about nutrients, toxics, and sediment pollution in the northern Chesapeake Bay has increased. The lower Susquehanna River basin has been identified as a major source of agricultural pollutants to the Chesapeake Bay. Due to agricultural pollution in the area, the Conestoga Headwaters Rural Clean Water Program (RCWP) project was implemented to reduce this pollution.

Agriculture in the Conestoga Headwaters area is among the most intensive in the Northeast, with an average farm size of 56 tillable acres. Farmers in the area maintain their incomes by increasing the size of their livestock operations, resulting in high animal densities. The 445 dairy farms in the 188-square-mile area average 47 milk cows and 27 heifer replacements, which produce about 65 percent of the manure and about 55 percent of the manure nitrogen in the RCWP project area (12). These factors have made the Conestoga River Watershed a primary source of agricultural nonpoint pollution in Pennsylvania (11).

The lower Susquehanna River basin is a primary source of pollutants, accounting for 36 percent of the nitrogen and 41 percent of the phosphorus from nonpoint sources delivered to the Chesapeake Bay. Eighty-two percent of the phosphorus and 99 percent of the nitrogen entering the lower Susquehanna River reach the Chesapeake Bay (13). High rates of nutrient delivery from the Conestoga River can be expected since it drains directly into the lower Susquehanna River. Reducing nonpoint source pollution in the project area is an important step toward reducing the nutrient loadings in the Chesapeake Bay.

The RCWP project identified animal wastes, high rates of commercial fertilizer and pesticides applied to cropland, and insufficient erosion and sediment control on intensively farmed cropland as critical sources of pollution. Farms with over 1.5 animal units per acre were defined as critical.[2/] Average farms in the project area have over 2 animal units per acre (12). The RCWP project attempts to reduce stream and groundwater loadings of nitrate, phosphorus, sediment, bacteria, and pesticides by installing best management practices (BMPs) on as many critical farms as possible.

One BMP strives to establish animal-waste management practice to promote the proper use and disposal of animal manure, including building manure storage structures when conditions warrant. With storage, manure can be incorporated into the soil immediately after spreading, potentially reducing the nutrient losses caused by daily surface spreading.

The variety of manure storage structures and handling/application methods vary in their potential to reduce pollution. Different structures and handling systems retain varying amounts of crop nutrients. Crops use nutrients at different rates, so that the effects of changing cropping patterns to reduce pollutants should be considered, as well as identifying alternatives for reducing nutrient losses. Without considering other BMPs, a farmer may reduce nutrient losses on a fixed amount of cropland by reducing the herd size or removing manure from the farm.

1/ Underscored numbers in parentheses refer to items cited in the References.
2/ An animal unit represents a 1,000-pound dairy animal.

To ensure the success of any Government program, the various storage/application systems should be evaluated along with other options to determine their effects on the environment and on the farm operator's income.

THE ECONOMIC OPTIMIZATION MODEL

Separate versions of a linear farm-level programming (LP) model were constructed in this study to measure the effects of various manure-handling systems on dairy farm income and organization, and on the environment (table 1). Alternative systems are described in the appendix.

The Northeast Region Forage-Dairy Systems Technical Committee (NE-111) Forage-Dairy-Systems Model provided the framework for the LP model (10). The NE-111 model integrates the components of a forage-dairy operation into a framework which could be analyzed in a systems context. The model maximizes net returns to fixed resources, combining farming activities that include milk production, heifer raising, crop production, and buying and selling. Manure handling, storing, and spreading activities were added to the NE-111 model to illustrate the effect of a change in any one component on the rest of the enterprise.

This study determines the effects dairy farm waste-handling systems have on the environment. The Chemicals, Runoff and Erosion from Agricultural Management Systems (CREAMS) simulation model was used to generate estimates of total nitrogen and phosphorus losses from the field, using various manure application rates for each crop activity and storage/handling system (5). Soil-loss coefficients were also generated using CREAMS and were included in the crop production component of the model.

This study also evaluates the response of each storage/application system to restrictions in farmwide nitrogen losses. Steps a farm operator might take to meet these restrictions were to:

1) change cropping patterns to reduce both erosion losses and nutrient losses, including application of manure to alfalfa,
2) change nutrient application rates, given the existing cropping pattern,
3) reduce the number of animals in the operation,
4) haul the manure to a distant site, and
5) any combination of these.

To evaluate the fourth option, the costs of hauling manure 30 and 40 miles from the farm were included in the model. Cropland acreage varied from 40 to 120 acres to evaluate the effects of animal density on the responses of the farm operator to the constraints.

Framework of the Linear Programming Model

We took milk production, heifer replacement, and crop production activities from the NE-111 model to represent the core of our model. We also adjusted inputs and sale prices to reflect average 1980 prices (1). These components of the model resemble assumptions made by Partenheimer and Knievel (10), which include:

1) a maximum of 45 cows weighing 1,320 pounds with appropriate heifer replacement,
2) milk production of 14,300 pounds per cow per year,

Table 1--Manure-handling systems evaluated in the RCWP study 1/

Storage period	Storage type	Application	Handling
Months			
0	None; daily spread	Surface spread	Front-end loader
6	Solid storage; roof over concrete slab with 5-foot walls	Surface spread, soil incorporated	Front-end loader
6	Solid storage; uncovered pit with concrete slab and floor entrance ramp	Surface spread, soil incorporated	Front-end loader
6	Slurry; earthen basin with concrete floor	Surface spread, soil incorporated	Agitation and gravity feed loading/pump unloading
6	Slurry; earthen basin with concrete floor	Injection	Agitation and gravity feed loading/pump unloading
6	Slurry; steel tank storage	Surface spread, soil incorporated	Agitation and piston pump loading/pump unloading
6	Slurry; steel tank storage	Injection	Agitation and piston pump loading/pump unloading
12	Slurry; earthen basin with concrete floor	Surface spread, soil incorporated	Agitation and gravity feed loading/pump unloading
12	Slurry; earthen basin with concrete floor	Injection	Agitation and gravity feed loading/pump unloading
12	Slurry; steel tank storage	Surface spread, soil incorporated	Agitation and piston pump loading/pump unloading
12	Slurry; steel tank storage	Injection	Agitation and piston pump loading/pump unloading

1/ See appendix for additional description.

3) a 5-percent slope on all fields,
4) alfalfa acreage fixed at a minimum of 20 percent of the total cropland to represent the average alfalfa acreage in the study area,
5) average yields of 105 bushels of corn, 17 tons of corn silage, and 3.4 tons of alfalfa with appropriate harvest losses, and yield reductions from continuous corn,
6) a stanchion barn with mechanical gutter scrapers. Heifers were assumed to be housed separately but their manure was included with the cows', and
7) a 13.5-percent interest rate.

Manure Storage and Handling

Manure storage, handling, and application affect farm operations in many ways. Labor use and operating costs for these activities vary by storage system. Ownership costs of machinery and storage structures vary by handling/application system. Nutrient retention varies by storage method, storage length, and type. Variable nutrient retention by storage systems means that variable applications of commercial fertilizer are needed to satisfy plant needs. Also, nutrient retention, application methods, and timing affect the losses of nutrients from the fields.

Nutrient Availability by System

In the LP model, we added coefficients to account for the amount (pounds) of each nutrient available for plant uptake from each ton of dairy manure applied. These coefficient ensured that each acre of cropland received sufficient nutrients, either from the manure or through commercial fertilizers. Cropland is assumed to be manured annually. Therefore, decay coefficients were not used and all applied nutrients were asummed to be available in the year that they were applied. The coefficients varied with each system (table 2).

Losses prior to application were considered, and were included in calculating the nutrient availability for each system. Losses were related to system efficiency, exposure to air and runoff during storage and handling, and the length of the storage period. The model also accounted for volatilization losses of nitrogen after application. These losses vary with the type of system (solid or slurry), the type of application (surface spread, surface spread and soil incorporated, and injection), and the length of time between application and when crops begin the nutrient uptake.

We made estimates of losses due to chemical processes and physical movements between the time of application and plant uptake based on available literature. The total losses depend on the time of application (high losses occur between fall application and spring uptake) and the type of system. The coefficients for nutrient availability from manure included all losses. We assumed the resulting nutrient quantities were available to plants. All these factors were included in the plant-available nutrients in the crop production component of the LP model.

Estimates of nutrients available for plant uptake were based on available literature. CREAMS was not used to estimate available nutrients. However, similar assumptions about the nutrients present in manure at the time of application were made to complete the CREAMS results. The two estimates of nutrient availability (one for plant uptake and the other for environmental losses) were separate; yet had compatible calculations.

Table 2--Manure nutrient availability by storage/application system

Storage/application system	Nutrients per manure equivalent metric ton 1/ N	P_2O_5	K_2O
	Pounds		
Daily spread	5.5	3.4	7.0
Covered solid	6.4	3.8	7.0
Uncovered solid	5.8	3.8	7.0
6-month earthern basin, soil incorporated	7.0	4.2	7.4
6-month earthern basin, injected	7.2	4.2	7.6
6-month steel tank, soil incorporated	7.2	4.3	7.6
6-month steel tank, injected	7.4	4.3	7.8
12-month earthern basin, soil incorporated	8.0	4.5	8.1
12-month earthern basin, soil injected	8.2	4.5	8.1
12-month steel tank, soil incorporated	8.4	4.6	8.3
12-month steel tank, injected	8.4	4.6	8.3

1/ See appendix for the definition of a manure equivalent metric ton (MET).

Environmental Losses with CREAMS

A chief concern was to measure the environmental effects of manure storage systems, so coefficients representing nitrogen, phosphorus, and soil losses were included, and the nitrogen losses were constrained in the economic optimization model. These coefficients were derived using the CREAMS model (1). CREAMS is a computer simulation model which estimates losses of runoff, soil, and chemicals (in solution and attached to sediment) from the field. The overland losses of runoff and sediment and the chemicals they carry, and nitrate lost in deep percolation were also modeled (5).

The CREAMS estimates of field losses of nitrogen and phosphorus included losses in surface runoff and deep percolate losses of nitrate. These losses together estimate total nitrogen and phosphorus lost. The environmental implications of this aggregation (total nitrogen as opposed to surface nitrogen losses) are clear: surface and subsurface losses are equivalent in their effect on water quality. This conclusion assumes that 1 pound of nitrogen lost in surface runoff is equal in its effect on water quality as 1 pound of nitrate-nitrogen in deep percolate. Though this is probably not the case, no definite estimates have been developed. This aggregation was done for modeling simplicity. Groundwater in this area has a relatively short residue time until it appears as baseflow in the streams (12).

The summed losses help evaluate the entire environmental system. Some handling systems have higher surface losses and lower percolate losses than other systems, and vice-versa. Both losses affect the environment; reduction of one type of loss might be made at the expense of disproportionately increased losses of another.

We adjusted the CREAMS results to reflect the assumptions made in this study. The CREAMS nutrient-loss estimates reflect differences in manure handling and application; no differences in nutrient retention among storages were modeled. Adjustments to these results were made based on differences in retention rates among storage systems. For additional details on the adjustments see (1).

Manure Hauling

An activity in the LP model provided for hauling of manure away from the watershed. The operator had several options for meeting nitrogen loss restrictions. The spreading rates and practices on the existing crop mix could be changed within the restrictions placed on cropping patterns to rates which cause lower nutrient losses. The animal-to-land ratio could also be reduced to lower the amount of manure spread farmwide, or a contract could be made to have the manure removed.

The cost of hauling manure was based on several assumptions. The manure recipients after the haul were assumed to receive sufficient nutrient value that they would incur all the costs of spreading and pay nothing for the manure.

Manure hauling moves manure to a location where it would no longer lead to excessive land application rates, and to where nutrients were actually needed. The hauling distances of 30 and 40 miles were simulated from Ephrata (located near the center of the study area), and illustrated in table 1. We did not consider shorter distances because such distances did not remove manure far enough from the watershed. Forty-mile hauls move manure to other counties where livestock production is less land-intensive.

The objective function value for the manure hauling activity represents the total cost incurred in hauling 1 manure equivalent ton (MET) of slurry manure 30 or 40 miles from Ephrata.[3/] These costs were derived under the assumptions

3/ While application of manure to alfalfa is not commonly practiced, it is a feasible activity. Alfalfa will substitute manure nitrogen for nitrogen that it would normally fix. The quality of the alfalfa stand will be reduced thereby reducing the duration of the stand (4).

below. We did not calculate the cost of hauling solid manure because we were uncertain about cost factors such as loading and unloading the truck. The costs of hauling slurry manures 30 and 40 miles were also used for solid handling systems.

The hauling costs in the objective function represent a parameterization of a certain cost. We tested how hauling costs affect the amount of waste hauled and their effect on the model results using the parameterized values. For slurry manures, estimated costs of 30- and 40-mile hauls represent the actual costs. However, solid manure can be hauled further for the same cost because 1 MET of solid manure weighs less than 1 MET of slurry manure. A truck designed to haul solid manure versus slurry manure is likely to be less expensive. Therefore, the costs of unloading solid manure versus slurry manure are probably greater.

We used one cost factor in evaluating the two different solid handling systems. These systems were evaluated using slightly different criteria than those for the slurry systems. This tends to slightly bias the study against the solid systems, but we chose it for modeling simplicity in the absence of reliable data.

Hauling costs included all costs (less returns to risk and management) incurred by loading, hauling, unloading, and the return trip. We assumed that the fixed and variable costs of a bulk-milk truck with a 4,000-gallon capacity approximate the costs of a liquid manure hauler (2). We judged operating costs for milk hauling to approximate the operating costs for manure hauling. For example, the cost of a stainless steel tank (needed for hauling milk) would be offset by additional equipment for agitation needed to load and unload liquid manure. We adjusted total costs to account for additional downtime and assumed that manure could be hauled only 800 hours per year because of restrictions on land application.

When computing hauling estimates, we assumed:

1) driver wage of $8.00 per hour,
2) average travel speed of 25 miles per hour,
3) 9.2 miles average from the garage (where the hauling truck is stored) to the farm, and
4) 5 minutes to load and unload the tank, and 5 minutes for hookup and miscellaneous activity.

The calculated cost of hauling manure 40 and 30 miles from the study area ($10.90 and $8.62 per MET, respectively) is presented in (1).[4/]

Additional Considerations

There are several costs and benefits of manure storage which cannot be quantified and are not included in the LP model which can influence a farmer's decision as to whether or not to adopt a storage.

Storage provides flexibility in the time of application. Under daily spreading, manure must be spread during the winter months. The lack of flexibility in spreading times may hurt plant yields because more soil compaction is likely

4/ See the appendix for a definition of MET.

when tractors drive on wet or muddy fields, and because less nutrients, organic matter, and other beneficial manure elements are retained on the field with daily spreading. Slurry systems also may hurt plant yields because slurry spreaders weigh more than solid spreaders, causing more soil compaction (8).

Manure applications may not be uniform over the entire field, particularly under daily spreading where manure is applied until it is all spread. At the next spreading date, farmers continue where they left off. Adverse weather conditions may cause uneven spreading of manure over the field. The additional cost to the farm operator of increased commercial nutrient applications may be preferred to the risk of lower yields caused by inadequate nutrients from manure.

Esthetic considerations may be important. Manure storage creates unpleasant odors, especially when unloading the storage structures and spreading. This odor problem is particularly acute with slurry systems. For this reason, surface spreading of slurry manure in the fall is not considered; it is assumed that all fall applications of slurry manures are injected into the soil.

There are hidden benefits to the farmer who owns a more sophisticated storage system. A steel-tank system has some value as a consumer good. A farmer takes pride in owning it, and this may influence the choice of manure storage and handling systems.

All systems create certain externalities which could not be modeled in this study. Barnyard runoff may vary among systems, particularly under daily spreading where manure is stacked on a temporary basis in the barnyard. Runoff from this stack can be significant, but it is not quantified here because this runoff will vary widely among sites. Odor also varies among systems, but these effects were not included in the analysis.

Applications of the LP Model

We used results from the LP model to compare net returns to the operator under each storage/application system. Nutrient and soil losses and the optimal cropping patterns for each system are reported. We selected the systems that performed the best (in net returns) for further investigation.

Farm acreage was varied for examining changes in each system's relative performance when a different farm size was considered. This simulated the changes in nutrient losses under each system as the animal density changed. Though the existence of economies of size in manure management systems was not a concern of this study, we determined the performance of manure storage systems under varying animal densities.

The nitrogen loss per acre for the daily spread system was the base from which we derived nutrient restrictions for later runs. These nitrogen losses were computed for 40, 60, 80, 100, and 120 tillable acres with a constant herd size (45 cows with heifer replacement). Runs were made restricting the nitrogen loss per acre under each system to 90, 70, and 50 percent of the daily spread losses for each farm size. We used these loss constraints because acceptable limits of nitrogen loss per acre are not well-defined. Delivery ratios of nitrogen losses from the field delivered to the stream or groundwater were not known. The percentage reductions give policymakers the option to evaluate each system's potential for adjustment, or how changing constraint levels affect optimal solution values for each system.

The adjustments needed under each system to meet these loss constraints are reported. We evaluated changes in cropping and spreading practices, animal numbers, and manure hauling, and compared all systems without allowing hauling to evaluate changes made on the farm.

RESULTS

We simulated alternative scenarios with the model to evaluate the storage/application systems. Net returns from milk production and crop sales were maximized. Cash costs of cropping activities and all purchased inputs not contained in the milk production and crop budgets were subtracted from the objective function, as well as ownership costs of machinery and equipment, livestock, and farm buildings. The objective function represents the net returns to operator labor (ranging from 196-217 hours per month), land, and management. Maintenance to buildings, machinery, and fencing activities were not considered.

Net returns, the value that the model maximized, cannot be considered profit. Many costs were not deducted, such as interest on land investment and real estate taxes. Additional family labor was treated as a purchased input. No restrictions were placed on the purchase of inputs. We assumed that unlimited labor was available at a price of $3.30 per hour.

Results With No Nitrogen-Loss Constraints

We initially modeled all manure storage/handling systems for a 60-acre farm, placing no constraints on nutrient losses (table 3). Substantial differences in net returns and nutrient losses exist among systems. Crop nitrogen needs are satisfied by manure under all systems; but phosphorus and potassium purchases are necessary. Although nitrogen retention varied widely among systems, cropping patterns remained unchanged as the different systems were evaluated because their nitrogen needs were satisfied. Alfalfa acreage entered the solution at the lower limit (20 percent of cropland). The crop mix was the same for all systems with 6.5 acres of corn grain, 41.5 acres of corn silage, and 12 acres of alfalfa (4-year stand).

The most profitable systems investigated were the 6-month slurry storage with soil incorporation and the same storage with subsurface injection. Daily spreading was the third most profitable, $800 below the optimal solution. Uncovered solid storage was the fourth best, $1,500 below the optimum. Twelve-month earthen basin storages with soil incorporation and injection were the fifth and sixth best solutions, respectively.

The three systems which produced the lowest net returns, and were subsequently excluded from further evaluation, were the covered solid storage and the liquid systems with steel tank storage. The covered solid storage system produced net returns $4,800 less than the most profitable system. The 6- and 12-month steel tank storages were the least profitable, because of their high capital costs.

Because nitrogen needs were satisfied by all systems with 60 acres, the only differences in the objective function values were due to the costs of handling, application and storage, purchases of phosphorus and potassium, and differences in bedding costs among the most profitable solid and liquid application systems. The costs of additional bedding needed to handle manure as a solid are substantial, accounting for a difference in the cost of bedding of $3,300

Table 3--Model results for alternative manure storage/handling systems for a 60-acre farm

Manure storage/handling	Net returns	Nitrogen loss	Phosphorus loss	Soil loss
	1,000 dollars	Pounds per acre 1/		Tons per acre 1/
Daily spread	18.6	73.20	17.45	7.15
Covered solid	14.6	64.87	17.00	7.15
Uncovered solid	17.9	60.98	16.84	7.15
6-month basin, soil incorporated	19.4	75.83	17.24	7.15
6-month basin injected	19.3	65.32	16.35	7.15
6-month steel tank, soil incorporated	12.0	77.13	17.38	7.15
6-month steel tank, injected	11.9	70.77	16.87	7.15
12-month basin, soil incorporated	17.9	67.35	17.13	7.15
12-month basin, injected	17.5	69.10	16.29	7.15
12-month steel tank, soil incorporated	8.5	67.62	17.31	7.15
12-month steel tank, injected	8.3	72.47	16.38	7.15

1/ Losses represent total farmwide losses divided by total acreage.

between solid and slurry systems (table 4). This additional cost accounts for the difference in total revenue of $1,400 found between these systems.

The least profitable storage structures were not analyzed to simplify the results. The added cost of the roof for the solid storage overshadowed any improvement in nutrient retention or labor/fuel savings. The differences in nutrient retention between earthen basins and steel tanks were so slight that a separate evaluation of these systems would be redundant. The only difference between the costs for the systems were construction costs.

Nutrient and Soil Losses

Table 3 shows nutrient and soil losses from the unconstrained model for each storage/application system. Losses by field were summed over all acreage and

Table 4--Manure and application costs 1/

Item	Uncovered solid storage	6-month basin storage soil incorporated
	Dollars	
Handling	1,015	881
Application	949	956
Bedding	3,976	640
Labor	363	236
Annual fixed cost	1,366	2,911

1/ For a 45-cow dairy herd plus replacements.

divided by total acreage to show average per-acre losses. Cropping patterns and soil losses were the same for each system evaluated.

Plant nutrient losses in table 3 were based on an average application of 19.2 tons of manure per acre (1,151 tons divided by 60 acres), a spreading rate higher than the Lancaster County average of 17 tons per acre but lower than the 25-ton-per-acre average in the Conestoga Headwaters area (12). Plant nutrient losses varied greatly among systems. Nitrogen losses were highest for 6-month slurry storage systems with soil incorporation and lowest with the uncovered solid storage system. Daily spreading losses exceeded all systems' losses except the 6-month slurry systems. Nitrogen losses for the slurry storage system with soil incorporation were greater for 6-month storage than for 12-month storage; but under injection, 12-month storage exhibited greater losses due to increased nitrate leaching (5). Generally, the differences in total nitrogen losses are relatively small between daily spreading and the manure storage options.

The 6-month uncovered solid storage system retains slightly more nitrogen than does daily spreading (5.8 pounds per ton verses 5.5 pounds per ton, respectively). Due to more careful application (half is applied immediately prior to planting in the spring), this system exhibited much lower losses of nitrogen. Daily spreading provided 5.5 pounds of plant-available nitrogen per ton of manure, but caused losses of 12.2 pounds more nitrogen per acre than did uncovered solid storage. Since the differences in fuel and labor costs between these two systems were small, the differences in net returns were due to the capital costs of the storage structure. Uncovered solid storage systems, because of the added volume caused by rainwater, required almost as much labor and fuel as daily spreading (1).

Systems which allowed spreading manure directly on the field surface caused more phosphorus losses than did injection systems, since all phosphorus losses modeled with CREAMS were surface losses dissolved in runoff waters or attached to sediment. Daily spreading caused greater phosphorus losses than did any other storage/application system. The net difference between the system which lost the most phosphorus (daily spreading) and the system which lost the least (6-month earthen-basin storage with injection) was only 1.1 pounds per acre, a difference of less than 7 percent.

Variation in Farm Size

Keeping the herd size constant, we compared each system with varying animal-to-land densities. The intent was not to allow the farmer to meet the nitrogen-loss constraints by increasing acreage. We considered 40-, 60-, 80-, 100-, and 120-acre farm sizes for each system (table 5).

The 6-month slurry storage/application (earthen basin) system exhibited higher net returns at all acreages. When farm size exceeded 80 acres, the two solid handling systems (uncovered solid storage and daily spreading) required the purchase of nitrogen fertilizer. The enhanced nitrogen retention of the slurry systems increased their relative profitability versus the solid systems at larger farm sizes. At 80 acres, the daily spreading option required purchases of 842 pounds of nitrogen at an additional cost of $236. Depending on application methods, at 120 acres, daily spreading required purchases of 2,750 pounds of nitrogen; the 6-month storage required 1,202 pounds; and the 12-month storage required purchases of 153 and 42 pounds.

Nutrient retention by storage systems became increasingly important as acreage was increased. Under all systems, alfalfa entered the solution at the minimum of 20 percent of the total acreage. Differences in net returns among systems as acreage increased were due to differences in purchases of nutrients, particularly nitrogen.

Six-month solid storage did not conserve sufficient nutrients to make net returns comparable with daily spreading as greater acreages were considered. The 310 pounds of additional nitrogen from solid storage did not affect the net returns enough, at 120 acres, to cover the additional fixed costs above those for daily spreading. The slurry storage systems conserved sufficiently more nutrients so that, at 120 acres, the net returns from 12-month slurry storage systems were comparable with the net returns under daily spreading ($30,100 versus $30,500, respectively). The value of additional nutrients overcame the differences in fixed costs among the systems (the costs of handling and spreading remained unchanged over the greater acreages, as did total manure handling and spreading).

At greater acreages, injection became more attractive relative to soil incorporation with tillage equipment. With 12-month storage, soil incorporation was more profitable at 40, 60, and 80 acres; but the bonus provided by enhanced nutrient retention at greater acreages overcame the higher spreading costs of injection.

Soil losses under changing animal-to-land ratios showed a pattern consistent with our expectations (table 5). Average soil losses per acre decreased as farm acreage increased because a lower proportion of the land was devoted to erosive corn silage. Since corn silage cannot be sold, it only entered the solution to meet the feed needs of the animals. Beyond that, additional land was devoted to corn grain.

Nutrient losses were reduced as nutrients provided by manure approached those needed for plant uptake. As the animal-to-land ratio decreased (when the farm acreage increased), nutrient losses decreased. Under all systems, per-acre nutrient losses decreased as acreage increased.

As manure loadings per acre increased, the 6- and 12-month slurry storage systems showed higher field losses of nutrients relative to the other systems

Table 5--Model results for alternative manure storage/application systems, by farm size

Tilled acres	Net returns	Nitrogen losses	Phosphorus losses	Soil loss	Alfalfa	Nitrogen purchased
	1,000 Dollars	Pounds per acre	Pounds per acre	Tons per acre	Acres	Pounds
Daily spread:						
40	13.5	99.01	24.38	7.34	8	0
60	18.6	73.20	17.45	7.15	12	0
80	2.9	57.19	12.34	6.80	16	842
100	26.8	54.54	12.66	6.59	20	1,363
120	30.5	49.22	10.97	6.46	24	2,750
Uncovered solid storage:						
40	12.8	83.85	22.15	7.34	8	0
60	17.9	60.98	16.84	7.15	12	0
80	22.3	50.56	12.49	6.80	16	336
100	26.2	45.81	11.35	6.59	20	1,047
120	29.9	41.10	10.00	6.46	24	2,440
6-month basin storage, soil incorporated:						
40	14.2	101.65	24.17	7.34	8	0
60	19.4	75.83	17.24	7.15	12	0
80	23.4	61.52	13.41	6.80	16	0
100	28.0	53.87	12.07	6.59	20	210
120	31.8	49.08	10.90	6.46	24	1,202
12-month basin storage, soil incorporated:						
40	12.7	91.05	27.07	7.34	8	0
60	17.9	67.35	17.13	7.15	12	0
80	22.3	54.86	13.94	6.80	16	0
100	26.4	46.34	11.95	6.59	20	0
120	30.1	40.81	10.77	6.46	24	153
12-month basin storage, injected:						
40	12.3	92.57	25.83	7.34	8	0
60	17.5	69.10	16.29	7.15	12	0
80	22.1	51.44	13.82	6.80	16	0
100	26.4	42.36	11.95	6.59	20	0
120	30.3	38.39	10.49	6.50	24	92

(particularly daily spreading). Since these systems conserve more nutrients during storage, opportunities for runoff and percolate losses increased when excess manure was applied to fields. At 40 acres, the 6-month earthen-basin storage system with soil incorporation caused more nitrogen losses than did daily spreading. Twelve-month slurry storage with injection lost more nitrogen than did 12-month storage with soil incorporation. Daily spreading caused more nitrogen losses from fields at all acreages than did the other systems, at high loading rates except for the 6-month earthen-basin storages. However, as loadings increased, the differences in losses between daily spreading and all types of storage decreased.

Results With Nitrogen-Loss Constraints

The unrestricted nitrogen losses under daily spreading were used as a base from which the nitrogen loss constraints were calculated. Table 6 presents the calculations for per-acre limitations for all acreages. The 10-percent loss restriction represents a limit that no more than 90 percent of total nitrogen losses from unrestricted daily spreading can be surpassed by any system. For a 60-acre farm, this limits average nitrogen loss per acre to no more than 65.88 pounds.

We formulated the constraints this way because daily spreading was treated as the status quo in this study; all systems were compared with it. Percentage reductions were used because it is easier to understand the implications of these constraints since they focus on percentage reductions in field losses of nutrients. The performance of each system can easily be compared using the status quo as a basis of comparison.

Table 7 presents the results for each of the storage/application systems for a 60-acre farm. No hauling of manure was permitted in these runs.

Ten-Percent Reduction

All systems met the 65.88-pounds-per-acre nitrogen-loss constraint without requiring a reduction in the number of animals on the farm. The constraint was met in various ways under the different systems. The uncovered solid storage required no adjustment; nitrogen losses with this system were already below the

Table 6--Per acre nitrogen-loss constraints

Acres	Daily spread nitrogen loss	10-percent reduction	30-percent reduction	50-percent reduction
	Pounds per acre	Percent		
40	99.01	89.11	69.31	49.50
60	73.20	65.88	51.24	36.60
80	57.19	51.47	40.03	28.60
100	54.54	49.09	38.18	27.27
120	49.22	44.30	34.45	24.61

Table 7--Model results with nitrogen-loss constraints for a 60-acre farm

Percentage reduction in nitrogen losses	Net returns	Cows	Soil loss	Phosphorus loss
	1,000 dollars	Head	Tons per acre	Pounds per acre
Daily spread:				
0	18.6	45	7.15	17.45
10	18.3	45	6.72	14.42
30	14.6	38.9	4.64	9.89
50	9.3	32.8	2.67	5.21
Uncovered solid:				
0	17.9	45	7.15	16.84
10	17.9	45	7.15	16.84
30	16.4	42.2	6.17	12.16
50	11.5	33.4	4.47	6.98
6-month slurry:				
0	19.4	45	7.15	17.24
10	18.6	45	6.18	13.38
30	14.0	35.9	5.07	9.04
50	7.4	28.0	3.28	6.05
12-month slurry:				
0	17.9	45	7.15	17.03
10	17.9	45.	7.15	16.95
30	14.6	38.3	6.80	13.10
50	9.9	29.2	4.21	7.55
12-month slurry, injected:				
0	17.5	45	7.15	16.29
10	17.4	45	7.15	16.19
30	16.5	42.7	6.92	14.05
50	10.9	32	6.04	9.13

10-percent reduction from daily spreading losses before the constraint was imposed. The 12-month storage systems met these restrictions by distributing manure more evenly over the cropland. The daily spreading and 6-month slurry storage systems met the constraints by increasing alfalfa acreage and by spreading more manure (up to the limits imposed by the model) on alfalfa.

A 10-percent reduction in nitrogen losses for a 60-acre farm caused net returns for daily spreading to fall $350 below its unconstrained optimum. The restriction had no effect on the net returns for the uncovered solid system. The net returns from the 6-month slurry storage system with soil incorporation were lowered by $800 after the loss constraint was imposed, yet the system still exceeded the second-best (daily spreading) by $309. The net returns from the 12-month slurry storage system with soil incorporation remained unaffected by the loss constraint because manure was simply distributed more evenly. The 12-month storage systems with soil incorporation and with injection had net returns of $700 and $1,200 less, respectively, than the 6-month slurry storage system.

Systems that incorporated more alfalfa into the crop rotations (daily spreading, 6-month slurry storage) in response to the constraints showed corresponding reductions in both soil and phosphorus losses. Phosphorus losses also decreased under those systems where spreading rates were reduced in response to the nitrogen constraints (12-month storage systems).

Thirty-Percent Reduction

Further reductions were caused in the net returns of each system by restricting nitrogen losses to 70 percent of the unrestricted daily spreading losses. At this reduction, 12-month slurry storage with injection performed best with returns of $16,500. The uncovered solid storage system performed second best with returns of $16,400. Daily spreading and 12-month slurry storage with soil incorporation were the next most profitable systems at $14,600, followed by 6-month slurry storage with soil incorporation at $14,000.

The animal numbers in all systems were reduced to meet these nitrogen-loss constraints. These reductions in herd size ranged from three (from 45 to 42 with uncovered solid storage and 12-month liquid storage with injection) to nine (from 45 to 36 with 6-month solid storage with soil incorporation). With these reductions in milking cows came corresponding reductions in replacement heifers.

Alfalfa acreage increased for all the systems except the 12-month slurry storages. In the case of daily spreading, alfalfa acreage accounted for nearly 50 percent of the total acreage. The 12-month storage systems switched from 4-year to 3-year alfalfa stands in response to the loss constraints. This allowed spreading at 20 tons per acre on a larger acreage of establishment alfalfa, which exhibits less nitrogen field losses at the 20-ton rate than does corn. All systems showed decreases in soil losses with these increases in alfalfa acreage for changes in stand duration. Similar reductions in phosphorus losses occurred because of the lower animal numbers and increased alfalfa acreage.

Fifty-Percent Reduction

When nitrogen losses were constrained to 50 percent of unrestricted daily spreading losses, all systems showed significant reductions in net revenues (table 6). The uncovered solid storage system showed the greatest net returns under the constraint at $11,500. Twelve-month slurry storage with injection was second at $10,800, followed by 12-month slurry storage with soil incorporation at $9,900, daily spreading at $9,300, and 6-month slurry storage at $7,400.

In order to meet this 50-percent constraint, cow numbers were reduced and alfalfa acreage was increased for all systems. Cow numbers ranged from 33 with uncovered solid storage to 28 with 6-month slurry storage and soil incorporation. Alfalfa area ranged from 15.8 acres with 12-month slurry storage and injection to 42 acres with daily spreading. Soil and phosphorus losses decreased as more alfalfa and fewer cows entered the solution.

Manure Hauling

An activity in the model permitted the hauling of manure off the farm to meet the restriction on per-acre nitrogen losses. Manure hauling always reduced the net returns compared with the unconstrained solutions because we assumed the hauling costs were paid by the owner/operator.

Manure hauling allows the operator to be more flexible because the number of cows may remain at 45 while still meeting field-loss constraints. Table 8 presents the results with nitrogen-loss constraints, allowing manure to be hauled 30 and 40 miles from the watershed. In all cases where hauling was permitted, the number of animals remained at the 45-head maximum, such that the profits from one additional cow exceed the costs of hauling the additional manure off the farm.

Hauling is a more attractive alternative than is reducing herd size. At every restriction level, allowing the farmer to pay to haul manure 40 miles as a way of reducing nitrogen losses increased net returns. Permitting a 30-mile haul increased revenues even more. For the 6-month slurry storage system with soil incorporation, allowing the shorter haul (for example, 30 miles from the watershed as opposed to 40 miles) increased net revenues when nitrogen losses were constrained and, in some cases, the amount hauled (table 8). At the 50-percent nitrogen-loss restriction (a maximum of 36.6 pounds of nitrogen lost per acre), net returns of $7,400 were estimated without permitting a haul, while estimated returns were $10,100 and $11,900 when permitting 40- and 30-mile hauls. All systems performed better with hauling as the nitrogen-loss constraints were tightened (table 8).

In the absence of nitrogen-loss constraints, daily spreading was the second-most profitable system. As hauling was permitted, daily spreading performed second-best when 10-percent reductions were imposed, yet showed the lowest net returns among all systems at the 30- and 50-percent reduction levels, regardless of the length of the haul. When a constraint of 51.24 pounds of nitrogen-loss per acre (a 30-percent reduction) was imposed, daily spreading recorded net returns of $14,900 with a 40-mile haul and $15,500 with a 30-mile haul. The other systems had net returns between $15,500 and $16,800 for the 40-mile haul and between $16,200 and $17,000 for the 30-mile haul. With a maximum nitrogen loss of 36.6 pounds per acre (a 50-percent reduction), daily spreading netted returns of $10,000 and $10,800 for 40- and 30-mile hauls, respectively. These returns are $3,300 and $3,400 below the most profitable system (12-month storage with injection).

Hauling manure helped reduce nitrogen losses without forcing farmers to make drastic changes in their cropping patterns. Alfalfa acreage was reduced slightly with a 40-mile haul and somewhat more with a 30-mile haul. Because alfalfa acreage was slightly smaller as hauls were introduced, soil losses were slightly higher, as were phosphorus losses. As hauling distances reduced from 40 to 30 miles, the net returns and the amount of manure hauled increased.

The manure hauling option is important. Incorporation of hauling into the model altered the results so that daily spreading was not economically advantageous. Without hauling, daily spreading remained economically attractive relative to the other systems. Manure hauling is not widespread in the study area. Storage, and paying to haul the manure up to 40 miles to be given away, may be a cost-effective way of meeting limitations on nitrogen losses.

Unless the manure can be sold at a profit, few farmers would pay for the removal of manure from the watershed without enforcement of nitrogen-loss restrictions. However, if nitrogen losses were effectively restricted in the study area, hauling would become a viable option. The method of restricting nitrogen losses

Table 8--Model results for all systems, nitrogen loss reductions, and distances hauled for 60-acre farm

Manure storage/ reduction in nitrogen loss	Distance hauled	Net returns	Cows	Soil loss	Phosphorus loss	Manure hauled
Percent	Miles	1,000 dollars	Head	Tons per acre	Pounds per acre	Tons
Daily spread:						
0	0	18.6	45	7.15	17.45	0
10	0	18.3	45	6.72	14.42	0
30	0	14.6	39	4.64	9.89	0
50	0	9.3	33	2.67	5.21	0
10	40	18.3	45	6.72	14.42	0
30	40	14.9	45	5.46	10.05	221
50	40	10.0	45	2.72	5.25	212
10	30	18.3	45	6.72	14.42	0
30	30	15.5	45	5.96	10.04	260
50	30	10.8	45	3.44	6.21	438
Uncovered solid:						
0	0	17.9	45	7.15	16.84	0
10	40	17.9	45	7.15	16.84	0
30	40	16.5	45	6.37	12.78	89
50	40	12.2	45	5.30	7.93	371
10	30	17.9	45	7.15	16.84	0
30	30	16.7	45	6.95	12.52	134
50	30	13.1	45	5.30	7.92	373
6-month, soil incorporated:						
0	0	19.4	45	7.15	17.24	0
10	40	18.7	45	6.85	13.38	45
30	40	15.5	45	6.11	9.85	315
50	40	10.7	45	3.63	6.59	495
10	30	18.8	45	6.98	13.57	56
30	30	16.2	45	6.42	10.26	334
50	30	11.9	45	4.15	7.31	577
12-month, soil incorporated:						
0	0	17.9	45	7.15	17.13	0
10	40	17.9	45	7.15	17.13	0
30	40	16.0	45	6.99	11.90	184
50	40	11.0	45	4.35	7.34	437
10	30	17.9	45	7.15	17.13	0
30	30	16.4	45	7.00	11.92	186
50	30	12.0	45	4.43	7.44	446
12-month, injected:						
0	0	17.5	45	7.15	16.29	0
10	40	17.5	45	7.15	16.29	0
30	40	16.8	45	6.99	14.24	80
50	40	13.4	45	6.82	10.19	383
10	30	17.5	45	7.15	16.78	0
30	30	17.0	45	7.15	14.35	90
50	30	14.3	45	6.82	10.19	383

chosen in this study would not work in practice. Probably the best method of restricting losses would be to enforce a limit on the tons of manure applied to certain crops. However, there is a conversion between the restrictions placed here (such as the 10-, 30-, and 50-percent nitrogen-loss reduction from daily spreading losses) and the actual amount of manure applied. The results indicate the optimal spreading (and cropping) pattern to be used to meet these restrictions.

Varying Animal Densities with Nitrogen-Loss Constraints

We also examined the performance of the storage/application systems with the nitrogen-loss constraints while varying the animal-to-land ratios. Some variation in farm size exists in the project area. The farm sizes we investigated were for 40 and 100 acres, both with an upper limit of 45 cows with appropriate heifer replacement. The results with various restrictions on nitrogen losses and a 40-mile haul appear in tables 9 and 10 for the 40- and 100-acre farms, respectively.

Forty-Acre Farms

Both the uncovered solid storage system and the 12-month slurry storage system with soil incorporation showed small nitrogen losses before the loss constraints were imposed (table 4). They met the 10-percent reduction (table 5) at no cost to the objective function. These two systems also recorded the highest net returns at this level of nitrogen loss. Daily spreading was third at $12,400. The 12-month slurry storage with injection and the 6-month storage with soil incorporation were fourth and fifth, respectively. All systems which required changes in farming practices to satisfy the constraints without hauling did so by reducing the number of cows.

Without hauling, animal numbers were reduced to meet the 30-percent nitrogen-loss reduction with every storage/application system (table 9). Also, alfalfa acreage increased to meet the constraint. Both soil and phosphorus losses decreased. These adjustments resulted in a large reduction in net returns, especially for the liquid storage systems.

None of the systems were able to meet the 50-percent reduction in nitrogen losses without hauling at the 40-acre farm size. The net returns of $5,600 and $4,200 for the uncovered solid storage and the daily spreading systems were far below their unconstrained values and were judged to be unsatisfactory. We found all other systems to be infeasible with the 50-percent constraint.

When a 40-mile haul was introduced in the analysis, all the systems performed better in response to the nitrogen-loss constraints. When hauling was permitted, the uncovered solid storage system showed increased net returns of $200 and $1,600 at the 30- and 50-percent restriction levels respectively. Similar increases were recorded with all systems.

Hauling tends to equalize the performance of all systems. At the 10-percent reduction level, the best performing system, uncovered solid storage, showed net returns of $12,800. The least profitable system, 12-month storage with injection, had returns of $12,200. At the 50-percent reduction level, the best system, 12-month storage with injection, showed returns of $7,900 while the worst, daily spreading, returned $6,400. Daily spreading, as was the case with the 60-acre farm initially modeled, benefited least from including the hauling option.

Table 9--Model results for all systems, nitrogen loss reductions and distances hauled for a 40-acre farm

Manure storage/ application system	Reduction in nitrogen loss	Distance hauled	Net returns	Cows	Soil loss	Phosphorus loss	Manure hauled
	Percent	Miles	1,000 dollars	Head	Tons per acre	Pounds per acre	Tons
Daily spread	0	0	13.5	45	7.34	24.38	0
	10	0	12.4	45	6.89	21.99	0
	30	0	9.0	42	5.43	15.53	0
	50	0	4.2	34	3.70	9.43	0
	10	40	12.5	26	7.20	22.06	80
	30	40	9.5	45	7.20	15.58	359
	50	40	6.2	45	5.84	9.48	459
Uncovered solid	0	0	12.8	45	7.34	22.15	0
	10	0	12.8	45	7.34	22.15	0
	30	0	10.3	38	6.96	16.65	0
	50	0	5.6	29	5.20	10.58	0
	10	40	12.8	45	7.34	22.15	0
	30	40	10.5	45	7.23	17.14	207
	50	40	7.2	45	7.23	12.03	516
6-month, soil incorporated	0	0	14.7	45	7.34	24.17	0
	10	0	12.1	40	7.01	19.87	0
	30	0	6.4	30	5.15	11.82	0
	50	0	infeasible				
	10	40	12.7	45	7.01	20.16	141
	30	40	9.5	45	7.01	12.90	471
	50	40	7.1	45	6.04	9.78	620
12-month, soil incorporated	0	0	12.7	45	7.34	27.70	0
	10	0	12.7	45	7.34	26.60	0
	30	0	6.8	32	6.81	16.70	0
	50	0	infeasible				
	10	40	12.7	45	7.34	26.60	0
	30	40	9.2	45	7.34	17.56	356
	50	40	7.2	45	7.34	12.96	550
12-month, injected	0	0	12.3	45	7.34	25.83	0
	10	0	12.2	44	7.34	25.28	0
	30	0	7.8	34	7.34	19.35	0
	50	0	infeasible				
	10	40	12.2	45	7.34	25.28	9
	30	40	9.6	45	7.34	19.29	278
	50	40	7.9	45	7.34	15.00	456

Table 10--Model results for all systems, nitrogen loss reductions and distances hauled for a 100-acre farm

Manure storage/ application system	Reduction in nitrogen loss	Distance hauled	Net returns	Cows	Soil loss	Phosphorus loss	Manure hauled
	Percent	Miles	1,000 dollars	Head	Tons per acre	Pounds per acre	Tons
Daily spread	0	0	26.8	45	6.59	12.66	0
	10	0	26.7	45	6.50	10.44	0
	30	0	23.0	45	3.90	6.83	0
	50	0	15.1	40	1.85	3.78	0
	10	40	26.7	45	6.50	10.44	0
	30	40	23.0	45	3.90	6.83	0
	50	40	15.3	45	1.97	4.04	65
Uncovered solid	0	0	26.2	45	6.59	11.35	0
	10	0	26.2	45	6.59	11.35	0
	30	0	25.6	45	5.91	8.63	0
	50	0	20.5	45	3.15	5.33	0
	10	40	26.2	45	6.59	11.35	0
	30	40	25.6	45	5.91	8.63	0
	50	40	20.5	45	3.15	5.33	0
6-month, soil incorporated	0	0	28.0	45	6.59	12.07	0
	10	0	27.9	45	6.52	10.34	0
	30	0	24.1	45	3.87	6.83	0
	50	0	14.8	39	1.67	3.72	0
	10	40	27.9	45	6.52	10.34	0
	30	40	24.1	45	3.87	6.83	0
	50	40	16.3	45	2.20	4.67	300
12-month, soil incorporated	0	0	26.4	45	6.59	11.95	0
	10	0	26.4	45	6.59	11.95	0
	30	0	25.2	45	5.95	9.64	0
	50	0	15.0	36	3.09	5.81	0
	10	40	26.7	45	6.59	11.95	0
	30	40	25.2	45	5.45	9.64	0
	50	40	16.4	45	3.18	5.99	257
12-month, injected	0	0	26.4	45	6.59	11.95	0
	10	0	26.4	45	6.59	11.95	0
	30	0	26.4	45	6.59	11.27	0
	50	0	18.5	39	4.33	7.39	0
	10	40	26.4	45	6.59	11.95	0
	30	40	26.4	45	6.59	11.27	0
	50	40	19.7	45	4.54	7.79	203

One-Hundred-Acre Farms

A 100-acre farm with a maximum herd size of 45 cows and an appropriate number of heifer replacements was modeled to determine the effects of manure storage systems on farms with a lower animal density (table 10).

With 100 acres, all the systems met the 10- and 30-percent reductions in nitrogen losses without either reducing their animal numbers or hauling manure. Only daily spreading and the 6-month slurry storage system with soil incorporation showed lower net returns when the 10-percent loss reduction was imposed.

Only the 12-month storage system with injection met the 30-percent nitrogen restriction with essentially no reduction in net returns. All the other systems showed considerable decreases in net returns. The net returns for the uncovered solid storage system were second best. Daily spreading showed the lowest net returns of all systems at this level of nitrogen-loss restriction. All the systems which had lower net revenues satisfied the constraints by planting more alfalfa and spreading manure at the maximum permissible levels on alfalfa. A corresponding decrease in both soil and phosphorus losses came with the increase in alfalfa acreage.

All systems except for the uncovered solid storage required a reduced number of cows when the nitrogen-loss constraint was set to a maximum of 50 percent of the unrestricted daily spreading losses with no hauling permitted. The number of cows decreased to between 35 (12-month storage with soil incorporation) and 41 (daily spreading). Alfalfa acreage also increased (a maximum of 74.4 acres under the 6-month slurry storage system with soil incorporation) in response to the nutrient-loss reductions (table 10). Some systems shifted from 4-year to 3-year stands of alfalfa.

Consistent patterns emerged as hauling was introduced at the 50-percent nitrogen-loss reduction level. While the uncovered solid storage system required no manure to be hauled, even at the 50-percent level, all other systems did. Even with low animal densities, when severe constraints were placed on losses of nitrogen, manure hauling became an attractive alternative to other methods of reducing nitrogen losses. Hauling is more cost-effective for reducing nitrogen losses than is reducing the number of cows.

IMPLICATIONS

Interpreting these results might be difficult without clearly defining desired policy goals. Economists would suggest reducing nonpoint pollution to the level where the marginal cost of reduction equals its marginal benefit to society. A marginal cost curve requires complete information on the effectiveness and cost of BMPs for controlling pollution. The marginal social benefits curve needs to be derived independently, based on societal preferences for clean water. The intersection of the two curves represents the economically optimal reduction of manure-related pollution. The feasibility of finding the optimal solution is questionable, given the technical information currently available on the links between agriculture and water quality.

Some economists suggest taxing units of discharged wastes so that the polluter internalizes what was previously an external cost of pollution. However, administrative problems usually preclude their use to control agricultural nonpoint pollution. An alternate way of reducing the pollution would be to limit the amount of manure spread per acre.

Limiting the number of animals per acre of land is a relatively easy way to lower nitrogen loadings from manure. The model can be used, given the type of handling/storage system, to produce guidelines for manure distribution systems for alternate herd sizes for a certain nitrogen-loss restriction. The model can effectively simulate alternatives for meeting the reduction once the level of reduction is decided.

However, hauling manure up to 40 miles from the farm is cheaper for reducing nutrient losses from manure loadings than reducing herd size. Requirements can be set on a farm-to-farm basis as to how much manure should be removed for a given farm and herd size.

Provisions are needed to ensure that manure is spread evenly over cropland. As the results showed, uneven spreading of manure leads to higher nutrient losses. If a farmer does not spread manure where it is needed, any potential reduction in nutrient losses made by either hauling manure or reducing animal numbers may be negated. Enforcement of even spreading over a given crop's acreage would prove to be extremely difficult.

In the absence of outside intervention, limited nutrient control measures will be undertaken. Because milk production is the most profitable activity on a dairy farm, the number of cows probably will increase in the area if no provision is made to limit them.

At severe restrictions on nitrogen losses, all systems (for the smaller farm sizes) require large amounts of manure to be hauled or significant reductions in the number of cows. Effective limits on manure applications per acre would force the farmer to comply in one of these ways.

The farm owner-operator cannot decide which storage/application system is optimal until policymakers decide on a desirable level of nitrogen-loss reduction. At almost all acreages, the ordering of net returns from the various storage/application systems changed as different levels of nitrogen-loss reductions were imposed. An operator who adopts one system based on a certain presumption about the loss reduction to be imposed might have erred when a different loss reduction is decided upon. Before the levels of nitrogen-loss reductions are decided, no decision can be made as to the best manure management system to use.

Within the limited options considered to solve the pollution problems, it is apparent that planting more alfalfa reduces both nutrient and soil losses. However, only 10 to 15 tons per acre of manure can be spread on alfalfa without damaging the legume. Including more alfalfa, however, does not drastically alter the spreading pattern of manure on the farm. An attractive avenue of research might be to investigate alternative forages. Certain grasses may have the advantages of alfalfa, such as reducing runoff and soil losses, and also may use larger quantities of nitrogen from manure and the soil.

Input use will be affected as enforced reductions in nutrient loadings are imposed through limits on animal units per acre, enforced hauling requirements, or blanket limits on the amount of manure spread per acre of cropland. The effects of these reductions on demand for each input have to be evaluated on a case-by-case basis. Any changes in input demand are likely to be small and because markets for farm inputs approximate perfectly competitive markets, changes in factor use should not affect the prices of these inputs.

The inputs most likely to be affected are commercial fertilizers, farm labor, and land. While fertilizer use should decrease as manure storage becomes more widespread, it may increase as restrictions are placed on either animal numbers or on the amount of manure which can be spread per acre. A decrease may occur because of the increased plant nutrients available from stored and carefully managed manure. As the amount of manure spread per acre is restricted, however, dairy farm operators might prefer to purchase more commercial fertilizers as insurance against reductions in yields. If farmers feel they are not receiving sufficient nutrients from dairy manure, they may apply commercial nutrients instead. In this way, a policy of restricting manure loadings may not succeed. Provisions should be made to prevent the replacement of manure nutrients with excessive commercial fertilizers.

Because storage structures reduce the total amount of labor needed for spreading, adoption of storage may decrease the demand for hired labor. However, the relative profits of farming in the area will decrease (because animal units per acre are likely to be reduced), causing the demand for farmland to decrease. As manure hauling enters the analysis, demand for land will decrease because land in other areas will be substituted for land use (a disposal site for dairy wastes) in Lancaster County. Since we could not determine the net shift in demand for land, we felt it was insignificant.

Changing manure management practices is only a limited means of reducing nonpoint nitrogen loadings. Results from our economic optimization model of a typical farm indicate that manure storage may not greatly improve the nutrient quality of field runoff. Six-month slurry storage of manure resulted in at most 10.8 percent less nitrogen and 6.3 percent less phosphorus losses than daily spreading. Steel-tank storage is even less effective. Losses of nitrogen and phosphorus were reduced by 3.4 percent and 3.3 percent, respectively. Twelve-month storage was less effective for reducing field nutrient losses than 6-month storage. Earthen-basin storage caused reductions of 5.6 percent of nitrogen and 6.6 percent of phosphorus losses compared to daily spreading, and steel-tank storage reduced nitrogen losses by 1.0 percent and phosphorus losses by 6.1 percent. These structures and practices are those most commonly adopted by farmers with RCWP cost-sharing assistance.

Storage in steel tanks is considerably less profitable than earthen-basin storage. The only other economic storage system is the uncovered solid manure storage. Reductions of nitrogen and phosphorus losses were 16.6 and 3.5 percent, respectively, compared to daily spreading.

Given the relatively large nitrogen losses, and given the relative profits of the more cost-effective manure storage systems, there is some doubt about efficient government cost sharing for installing storage structures. We did not address barnyard runoff problems, but we believe that animal waste management systems can prevent such problems without large, expensive storage structures. Practices should be considered which prevent barnyard runoff, provide short-term storage of manure in areas not subject to runoff, and divert rainwater and runoff away from barnyards. We feel that such approaches are less expensive and more cost-effective for the government, given the small differences among systems for preventing nutrient losses.

The manure storage study did not incorporate the large numbers of animal units normally found on diversified dairy/livestock/poultry farms, but concentrated instead on a typical, small dairy operation. Incorporating all types of livestock on typical RCWP farms would increase the total available manure and nutrients available for land application. This would eliminate some of the profits of manure storage on the representative dairy operation that was modeled, because additional manure nutrients would not have economic value once crop needs were met. Such calculations should be made to determine whether nutrients exceed crop needs before a structure is cost shared. The LP model's results did not include tax deductions for capital improvements or depreciation allowances on structures. For farms where it is determined that storage increases net returns, there should be no need to cost share storage structures.

Most systems were able to meet the 10-percent reduction in nitrogen losses without greatly affecting net returns. Farm income fell significantly as more stringent nitrogen loss constraints were imposed in the LP model. Some storage/application systems showed as much as a 50-percent decrease in net returns when the 50-percent reduction in nitrogen losses was imposed. This factor makes it apparent that farm incomes could be reduced significantly if nitrogen losses are restricted to 70 percent or less of daily spreading losses. Other BMPs are needed to cost effectively reduce field nutrient losses (see 5).

CONCLUSIONS

This study examined the environmental and economic effects of 11 manure management systems. While the results reported apply to the project area, the conclusions can apply to a much wider geographic area. The empirical relationships among systems should describe the relative income-water quality tradeoffs in other regions for similar-sized dairy farms. There were clear differences in the income-producing potential of the storage/application systems evaluated primarily due to differences in the fixed costs of handling/storage systems and the costs of bedding in the solid manure handling systems. There were also large differences among systems in the nutrient losses that occur after land application of manure. Nitrogen losses to surface- and groundwater were highest with the 6-month slurry storage systems and lowest with the 6-month uncovered solid storage system. Phosphorus losses were highest for daily spreading and the 6-month slurry storages and lowest under the 6-month solid storage.

As nitrogen losses were constrained to 90, 70, and 50 percent of initial daily spreading losses, a few trends emerged:

1) In most cases, the least restrictive loss constraint (the 10-percent reduction from unrestricted daily spread losses) could be met by all systems with a nominal reduction in the farm's net returns. Imposing the constraint in most cases merely dictated a more even spreading of manure over the entire farm. Relatively heavy spreading on any one field should be avoided.
2) Twelve-month liquid storages were more effective in meeting the loss constraints than were the 6-month storages. Though the systems conserve nutrients equally during storage, many nutrients from the fall application of the 6-month storage were lost from the field before plants could use them in the spring. The most effective 6-month storage system for water-quality protection was the uncovered solid system, where nitrogen was lost during storage. This

volatilization loss in storage reduced the nitrogen available for runoff and percolate losses over the winter months from the fall application.

3) By imposing nitrogen-loss constraints, the 6-month uncovered solid storage system and the 12-month earthen-basin storage systems provided greater net returns than daily spreading. The ability to better manage the nutrients overshadowed the lowered nutrient retention rates of daily spreading.
4) Increasing alfalfa acreage was viable to meeting the nitrogen-loss constraints. Phosphorus and soil losses were also lowered as an added advantage. Shorter alfalfa stands were a model response to the constraints, allowing 20 tons of manure to be spread on more acreage of establishment-year alfalfa (CREAMS modeling results showed substantially lower losses of nitrogen at a 20-ton manure application rate than did either corn grain or silage).
5) Reducing the number of cows drastically reduced farm income, entering the solution when extreme constraints on nitrogen losses were imposed without allowing hauling manure off the farm.
6) Manure hauling, when permitted, always entered the solution instead of reductions in the number of cows. As the constraints were imposed, the landowner could afford to pay to haul manure from the farm (even to a distance of 40 miles) rather than reduce herd size; hauling reduced net returns less than reducing herd size.
7) At extremely high animal densities (45 cows with less than 60 acres of cropland), meeting the constraints on nutrient losses of 30 and 50 percent below unrestricted field losses under daily spreading resulted in severe reductions in net returns.

The storages can be compared with daily spreading, because it is the most common handling practice in the RCWP area. This comparison gives an idea of what kinds of farm income effects might be expected if field nitrogen-loss restrictions were imposed in the area. Since there is no storage structure as such, and since wastes are allowed to accumulate in the open barnyard in a typical daily spreading operation, losses of nutrients to runoff and leaching during this storage period can be significant. Because of extreme variations in barnyard topography and in prespreading management, this runoff and leaching were not modeled. In fact, the daily spreading practices modeled in this study were much better, in terms of their effect on the environment, than most actual practices. These factors, along with the relatively poor performance of daily spreading when nitrogen-loss constraints were imposed, indicate that common daily spreading practices may be less desirable than manure storage systems for the controlling of nutrient pollution in the study area.

Barnyard losses can be controlled without installing long-term storage structures. We assumed in the LP model that dairy cows were confined and the manure was scraped into a storage structure. If cows are confined, barnyard losses of nutrients would be similar under a daily spreading operation. A roofed area to stack manure would be needed to eliminate runoff losses from the stack. If animals are not confined, installing a curb around a hard-packed barnyard would control runoff losses, and cementing the barnyard area would allow scraping the manure much the same as in a storage system. Improvements can be made, therefore, to a daily spreading operation that can make it comparable to a storage system for controlling water pollution given the minor differences in field losses among storage systems and daily spreading.

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APPENDIX: MANURE STORAGE AND APPLICATION SYSTEMS

The 11 manure storage/application systems investigated in this study vary. Aspects of storage and handling that affect agronomic performance and that can be quantified were included as coefficients in the models. Following is a description of manure handling systems considered.

In-barn manure handling is the same for all systems considered. Inside a stanchion barn, manure collects in grate-covered gutters located behind the stalls. Manure that fails to fall through the gutters is manually scraped. The gutters are cleaned by a chain-driven gutter cleaner which removes the manure from the barn. The only difference between in-barn treatment of solid and slurry manure systems is the amount of bedding used in the stalls.

Solid manure has less than an 85-percent water content, so substantial bedding is added to absorb the urine and liquids present in the manure (9). With a solid handling system, approximately 8 pounds of bedding per animal are used daily. This bedding ensures that the substance can be managed as a solid. Slurry systems have between an 88- and 95-percent water content and require added water to liquify the slurry (9). Also, bedding is finer (usually sawdust), and used no more than 1 pound per animal per day.

The added water in a slurry system comes from milkhouse waste and rainwater, which are dealt along with the manure. Solid handling systems require a separate milkhouse waste handling system. We did not include the costs of operating this separate milkhouse waste system because costs of these systems vary greatly among farms. (Slurry handling systems include more service for their costs than do the solid systems.) However, there's a slight difference because the capital cost of a commonly used system for disposal of milkhouse wastes (gravity-fed sprinkler irrigation) is generally less than $500, with virtually no annual repair and maintenance costs (14).

There is a difference between systems that handle the manure once it is removed from the barn. In an earthen-basin storage system, the manure is transferred by gravity feed, while a piston pump transfers manure to the steel tank storages. With solid handling systems, the manure is deposited outside the barn by the gutter scraper, and a front-end loader transfers it to storage.

A tractor scraper is used in all systems to scrape the exercise lot daily. Given the particular handling system, the waste from this lot enters storage at whatever point is most efficient. We assumed that rainwater runoff from the exercise lot is handled equally under all systems. Costs of controlling this runoff were not included in the analysis.

Manure Equivalent Tons (MET)

This study uses a concept called manure equivalent tons (MET). One MET represents the quantity of waste (waste is defined as manure, feces, and urine, plus any added bedding and water) under any handling system that contains 1 ton of manure as voided. This means that 1 MET with solid handling will be a different weight and volume than 1 MET of waste with a liquid handling system. All costs of handling were based on this concept--when the cost of spreading 1 ton was calculated, it was considered 1 MET.

Assumptions

Under all systems, we assumed retention of 20 tons of manure annually per 1,320-pound animal. When handled as a solid, this manure production equals approximately 2 cubic feet of waste per day. When handled as a slurry, this represents about 2.5 cubic feet of waste per day. Heifers were assumed to weigh 600 pounds, and estimates of their manure production were reduced proportionately by weight.

When deriving the coefficients for the storage/application systems, we assumed that:

1) total annual labor of 156 hours for barn cleaning and gutter scraping was available. Thirty hours were spent in transferring manure for solid handling, and 10 hours were spent annually with slurry handling,
2) bedding of 8 pounds per animal per day under solid systems and 1 pound per animal per day with slurry system,
3) milkhouse waste was handled separately under all solid systems. These wastes were included in the slurry handling systems,
4) a 500-foot average haul from storage to spreading point for all manure systems,1/
5) a 150-cubic-foot spreader for all solid systems and a 1,500-gallon slurry spreader for all slurry systems,
6) injection was assumed to consume 12.5 percent more fuel and 20 percent more total labor than surface spreading and soil incorporation. All 6-month slurry storage systems involved manure injection in the fall to reduce odors,
7) all longrun plant-available nutrients from manure were available the first year. Because excess manure has been spread on land in the project area for many years, decay constants were not considered,
8) application rates were based first on meeting crop needs. Manure provided the nutrient needs for each crop before any additional nutrients were purchased. We assumed a constant cost for fertilizers (no bulk discounts),
9) we assumed that nutrient applications that exceeded crop needs (as specified by 4), have no yield response.
10) efficient nutrient conservation by system varied by handling, storage, and application.

Annual manure applications were modeled in units of 40, 30, 20, 15, and 10 MET per acre for corn and 10, 5, and zero MET per acre for established alfalfa. Twenty, 10, and zero MET per acre could be spread on establishment-year alfalfa. Applications were modeled in this way to accommodate the nonlinear relationship between the amount of manure applied and nutrient losses.

Manure spread on established alfalfa was surface spread and was restricted to a maximum of 10 tons per acre because any more would encourage competition with the legume by weeds and grasses. Manure also introduces additional weed seed to the fields. Both of these effects result in reduced yields of alfalfa (4).

1/ This is the approximate distance that a 40- to 60-acre farm size requires to haul manure. This distance was held constant across the study, and any error in it exists for all the systems considered.

Also, additional nitrogen applications to alfalfa will reduce the fixation of atmospheric nitrogen by the plant.

The coefficients for spreading will be referred to in the following descriptions of the manure storage/application systems. Appendix tables 1 and 2 (also referred to in these descriptions) present the fixed costs by system. These fixed costs were based on a herd size of 45 milk cows and 27.6 replacement heifers.

Daily Spreading

Daily spreading of manure is the most common form of manure management found in the Conestoga Headwaters area (12). The system evaluated in this study was not daily spreading per se; manure was assumed to be stacked openly in the barnyard until a significant amount accumulated. Manure was loaded by front-end loader into a 150-cubic-foot solid spreader. No specific periods of application were assumed in this study; spreading times and labor were distributed throughout the year with the following restrictions. No manure was spread on corn in the summer months because the corn was too tall to permit entrance to the field. Early fall applications were increased to reflect this accumulation. Also, no manure was spread on frozen winter ground because of Pennsylvania Department of Environmental Resources regulations. Manure was spread on alfalfa in its establishment year prior to planting and after the first and last cuttings in established alfalfa meadows.

Because spreading occurs with little regard to periods of plant uptake and without soil incorporation, daily spreading retains the least plant-available nutrients of all systems (text table 2). Fuel and labor use are highest under daily spreading because substantial time is used for hookup and tractor warmup (3,6). There is little flexibility in applications and because manure must be spread during the winter under sometimes harsh conditions, the repair costs for the tractor and spreader increase, and the spreader's useful life decreases from 8 to 5 years (9). However, daily spreading systems require no investment in storage structures.

Six-Month Covered Solid Storage

Six-month covered storage refers to a roofed storage structure with 6-months of waste-holding capacity. This system consists of a concrete slab with wooden walls covered by a roof. For a 45-cow herd with appropriate heifer replacement, 6-month solid storage requires 18,000 to 20,000 cubic feet of storage, or a 5,000-square-foot concrete slab and 4- to 5-feet sidewalls. Manure, loaded into and unloaded from storage by a front-end loader, is spread in spring prior to the first plowing, and incorporated in the soil within 1 day to minimize volatilization losses. In October, manure is spread on corn land, with no soil incorporation; the amount of available nutrients from the manure is adjusted to reflect this practice. Five or 10 tons can be spread on alfalfa after either of the first or last cuttings, not to exceed 10 tons per year.

More nutrients are available to the plants from stored manure than from daily spreading (text table 2). The spring spreading provides nutrients to the plants when the plants need them most, and soil incorporation reduces volatilization losses and surface runoff of nitrogen. The roof helps conserve nutrients by preventing runoff and leaching to the groundwater and by stabilizing the in-storage environment which lowers volatilization losses of ammonia-nitrogen. Soil compaction and deterioration of the spreading machinery are reduced because

Appendix table 1--Annual fixed costs

Costs	Steel tank: 6-month	Steel tank: 12-month	Basin: 6-month	Basin: 12-month	Solid storage: Covered	Solid storage: Uncovered
			Dollars			
Construction	38,800	52,800	11,600	17,900	15,524	5,290
Depreciation	1,940	2,640	580	895	776	262
Interest	5,238	7,128	1,566	2,416	2,096	709
Taxes 1/	1,164	1,584	348	537	466	158
Insurance 1/	582	792	174	269	233	79
Repair and maintenance 2/	804	1,224	243	432	466	158
Total annual cost	9,728	13,368	2,911	4,549	4,037	1,366

1/ Taxes and insurance estimated at 3 percent and 1.5 percent, respectively, of construction costs.
2/ Repair and maintenance estimated at 3 percent of the cost of the structures (excluding pumps).

Appendix table 2--Cost of machinery ownership and total annual fixed costs

Manure storage and application system	Annual fixed costs: Storage	Annual fixed costs: Handling/application	Total annual fixed costs
		Dollars	
Daily spread	0	1,604	18,447
Covered solid	4,037	1,425	22,305
Uncovered solid	1,366	1,425	19,634
6-month earthen basin soil incorporated	2,911	1,940	21,694
6-month earthen basin injected	2,911	1,940	21,694
6-month steel tank soil incorporated	9,728	1,940	28,511
6-month steel tank injected	9,728	1,940	28,511
12-month earthen basin soil incorporated	4,549	1,940	23,332
12-month earthen basin injected	4,549	1,940	23,332
12-month steel tank soil incorporated	13,368	1,940	32,151
12-month steel tank injected	13,368	1,940	32,151

1/ Includes a crop machinery complement of $16,843 for each system.

no manure is spread during the winter months. However, most manure is spread during the early spring, a period of peak labor use, and thus may delay planting if soil and weather conditions delay fieldwork. As with all solid systems, 8 pounds of bedding per animal must be used daily. The roof also requires a large capital investment (appendix table 1).

Six-Month Uncovered Solid Storage

Uncovered solid storage consists of an open pit with a concrete floor. Rainwater falls directly into the pit and increases the volume, yet the added bedding still permits the waste to be managed as a solid. Total volume for 6-month storage with a 45-cow, 26.7-heifer herd is 24,000 to 26,000 cubic feet. The storage is designed with a 3,800-square-foot floor and 8-foot sloping earthen walls. Wastes are loaded and unloaded as solids with a front-end loader. Manure is spread in the same way as with the covered solid storage.

Fewer nutrients are available under this system than with covered solid storage because there is more nitrogen volatilization without the roof. No hardened crust forms to help reduce volatilization as in slurry systems. Labor and fuel used during spreading is higher because the added water increases the volume and weight handled, yet it is still spread with a 150-cubic-foot spreader. Soil compaction also increases because of added weight. The capital investment is lower than under any other storage system. Fencing is needed as a precaution to keep people and animals away from the storage structure.

Although it is clear that a covered in-ground solid storage structure would be less expensive than a covered above-ground structure (the former requires a capital investment of $0.203 per cubic foot of storage while the latter requires an investment of $0.376 per cubic foot of storage), the covered solid storage system was modeled as an above-ground structure because these structures are commonly found in the study area. Construction of covered in-ground solid storage structures is an option which might be included in further studies. However, the inclusion of the roof in the above-ground storage structure is necessary to prevent rainwater from causing undue runoff and leaching of nutrients and microorganisms. No roof is needed with an in-ground structure.

Slurry Handling Systems

Eight different slurry manure handling systems were modeled in this study: 6- and 12-month storage periods in earthen basins and steel tanks, with the manure being injected or incorporated in the soil with tillage operations. The only difference between the 6- and 12-month slurry storage systems is twice the storage capacity. Slurries can be handled through surface spreading and soil incorporating, or injecting below the soil surface.2/ With 12-month storage systems, all the manure is spread prior to plowing or injected after planting, allowing for maximum plant nutrient uptake. Some additional manure may be surface-spread on established alfalfa. When storage is designed for 6-month capacity, half of the manure is spread or injected in the spring or early

2/ Irrigation is a third alternative, but is not practiced in Pennsylvania, and the odor problems prohibit its use because Lancaster County is densely populated.

summer. The remainder was assumed to be injected in the fall after the corn crops are removed.3/

Subsurface injection conserves more nutrients because manure is injected below the soil surface and little volatilization and runoff losses of nutrients occur. Injection in the spring is preferred since it corresponds to plant nutrient needs. Injection in the fall reduces volatilization losses, but nitrate leaching may be exacerbated because of low plant needs. Injection requires a larger tractor, uses more labor and tractor time, and consumes more fuel than does surface spreading.

Surface spreading of slurry manure followed by incorporation conserves more nutrients than does any of the solid systems because of the efficiency of storage and handling. The 1,500-gallon slurry spreader assumed in this study is more expensive than the 150-cubic-foot spreader used with solid handling systems. Fuel use in slurry spreading is higher because of the additional weight and volume. Also, soil compaction may be increased by this additional weight. Labor requirements are lowest for slurry systems because the capacity of the larger spreader fully compensates for the increased volume hauled. Fewer trips to the field are necessary because of the large capacity of the slurry spreader.

Earthen-Basin Storage

Earthen-basin storage requires the lowest capital investment of all liquid systems. It is common in the Lancaster area, consisting of an excavated basin with a poured concrete bottom. The walls are earthen and slope outward. There are systems with concrete walls, but earthen walls are sufficient, cost less, and are more frequently used in the study area. A 6-month storage capacity requires approximately 28,000 to 30,000 cubic feet of storage because of the added volume of the entering rainwater and milkhouse wastes. Twelve-month storage requires twice this capacity. Manure enters the basin by a 24-inch diameter steel pipe which feeds by gravity from the barn. The pipe enters the storage from the bottom, so that adding manure does not break a crust formed on the surface. This crust reduces nitrogen volatilization during storage. The manure is agitated before unloading and pumped into the tank spreader using a tractor-powered agitator/pump.

In addition to the storage basin, this system requires housing for the agitator/pump and a fence surrounding the storage area. Barnyard runoff must be diverted from the basin so that only rainwater falling directly into the structure enters the system. The larger surface area leads to less nutrient conservation relative to a steel-tank storage system. This larger surface area is particularly important during agitation when volatilization losses of nitrogen occur. Odor may be a problem with this system, particularly during agitation and loading of the spreader, because the top of the storage structure is at ground level.

3/ Chisel plowing is common in the fall, but labor and machine requirements were assumed to be the same for chiseling and injection.

Steel Tank Storage

Steel tank manure storage requires the highest capital investment of all the systems investigated; it also retains the most nutrients. The system includes piston pump transfer to storage, and agitator pump agitation and unloading. A 45-cow herd requires a 180,000-gallon steel tank for 6-month storage, and a the 360,000-gallon tank for 12-month storage. Costs include installation, materials, pumps, and all complementary equipment.

Labor requirements for loading and unloading are assumed equal to those for the earthen-basin systems. Cost differences exist because of the electricity used by the piston pump and because of ownership and repair costs. The odor from the manure may be a problem, especially during agitation and loading of the spreader.

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