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Russell Parker and Luther H. Keller*

INTRODUCTION

This study was undertaken to develop a comprehensive method for determining the optimum size of a liquid manure storage structure for any given dairy farm. Particular attention was given to the substitution of manure for commercial fertilizer and to quality and quantity characteristics of manure as they impact on the optimum size of a liquid manure system.

Between 1960 and 1980 the average dairy herd in Tennessee almost tripled in size. Accompanying this expansion was an increase in animal confinement by the conversion of conventional barns to free-stall barns. Dairymen who previously had removed manure from conventional barns were unprepared for handling the volume of manure under a free-stall system.

During this same period, regulations stemming from environmental concerns were passed at the state and federal level. Until recently Tennessee pollution control guidelines specified that the maximum quantity of manure that could be spread on a single acre of land could not exceed the amount produced by two mature dairy animals.

Increased energy costs and labor scarcity have an impact on the type of dairy waste systems used. McCarty (8) estimated that waste handling systems may consume as much as 17 percent of the energy requirements of dairy farms. According to the North Carolina Dairy Farm Planning Guide (19), a typical 60 milking cow herd utilized 30 hours of labor per month solely for the disposal of dairy waste.

Rising costs and concerns about the future availability of commercial fertilizer have led to renewed interest in the value of manure as a substitute for commercial fertilizer.

Three general types of waste management systems are utilized on Tennessee dairy farms; the solid storage/daily haul system, the lagoon

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system, and the liquid manure system. The solid storage/daily haul system has been the prevalent system in the state and meets the need for a low investment waste disposal system. A 1974 study indicated that the daily haul system was used by over 80 percent of the dairy farms in East Tennessee (3) and by over 90 percent of the dairy farms in Middle Tennessee (17). Historically, this system has been the least-cost method of dairy waste management in Tennessee (5).

A study by Henderson indicated that the lagoon system can be the most expensive alternative for manure handling. Based upon the 1973 price level and a 100 milking cow herd, Henderson (5) estimated the annual ownership cost of a lagoon system at $17.82 per cow; a liquid manure system with one month's storage at $16.15 per cow; and a solid storage/daily haul system at $9.54 per cow. In normal operation, the lagoon system sacrifices the nutrient value of manure but utilizes less labor, and has greater flexibility than other systems.

Because the liquid manure system is designed primarily to exploit the nutrients found in dairy manure, it was investigated in this study to the exclusion of alternative waste management systems. Liquid manure systems typically include barn cleaning equipment, manure collection pits, pump/agitators, storage structures, and manure spreaders. However, systems differ considerably in operation because of differing housing and feeding arrangements.

Research Objectives

The development of a comprehensive method for determining the optimum size of manure storage structure involved a series of research objectives. The first objective was to formulate a computer model of a liquid manure and commercial fertilizer application system which would minimize the combined cost of operating a liquid manure system and the cost of meeting the plant nutrient requirements of cropped acreage on any given dairy farm. The second objective was to determine the effect of a selected group of variables on the optimum size manure storage structure for hypothetical dairy farms. The variables considered included the type of storage structure, the price of commercial fertilizer, the final moisture content of manure prior to application, the nutrient content of manure as-produced, plant nutrient loss rate, and pollution control standards.

Procedures

The objectives of the study were addressed by constructing a computer model of a liquid manure and commercial fertilizer application system. Key variables in the model, such as commercial fertilizer price, were altered in a systematic way to determine their impact on the optimum waste management system for hypothetical dairy farms.

A linear programming (LP) model was utilized in selecting the optimum liquid manure and commercial fertilizer application system. It required a list of the choices available to the dairymen and the cost associated with each choice. The computer program was used to select the group of choices which minimized the cost of operating the system.

Three types of choices (or activities) were made simultaneously with the determination of manure storage size:

1. The amount of manure to apply to each crop each month.
2. The amount of commercial fertilizer to apply to each crop and field.
3. The amount of manure to save each month for application at planting time.

Additional requirements insured that all manure produced on the farm was eventually spread on cropland. Furthermore, the constraints required that the plant nutrient requirements of all crops were fulfilled either from manure or commercial fertilizer. Whenever manure was selected for storage, sufficient space in the storage structure was required. A separate constraint insured that this was the case.

Liquid manure systems utilize different types of storage structures (earthen, concrete-stave, metal) which vary widely in cost. The effect of storage structure type on the optimum amount of manure storage was determined by adjusting the cost of storage in the computer model and noting the optimum size structure that would achieve least-cost for a wide range of storage cost levels.

The effect of commercial fertilizer price on the optimum amount of manure storage was determined by increasing the cost of commercial fertilizer in the computer model and noting the corresponding change in the choices made by the model. The fertilizer price was increased by 10, 25, and 50 percent above the 1980 Tennessee price level for bulk commercial fertilizer.

For the basic model the moisture content of manure as applied was assumed to be 90 percent. The effect of moisture content on the optimum amount of manure storage was determined by altering the model coefficients which describe the quantity and quality of manure produced on a farm, as a substitute for commercial fertilizer. The N, P, and K content of manure and the quantity of manure produced on the farm were adjusted in the computer model to correspond to moisture contents of 91 and 92 percent. The effects of an increase in moisture content on the solutions obtained with the computer model were determined.

The effect of the nutrient content of manure on the optimum amount of manure storage was determined by varying the N, P, and K coefficients over the range of values obtained in prior empirical investigations. The effect of alterations in nutrient content on the solutions obtained was seen to be a reflection of the absolute amounts of each nutrient as well as the ratio of the three nutrients.

The part of a liquid manure system responsible for increasing the amount of commercial fertilizer that can be replaced with manure is the storage structure. Whenever manure is spread daily, as is normally the case with the solid storage/daily haul system, part of the nutrients present in manure are lost due to volatilization, runoff, and leaching. The

term that was used in this study to describe the rate of loss of nutrients from field applied manure prior to the onset of plant nutrient uptake was the plant nutrient loss rate. A loss of 2 percent of the plant nutrients found in manure was assumed to occur for every month between the month in which the manure was surface applied and the month in which commercial fertilizer otherwise would have been applied (March). The effect of a greater or lesser rate of loss on the optimum amount of manure to store was determined by adjusting the appropriate coefficients in the model to reflect a loss rate of 1.5 percent and 2.5 percent. The choices made by the adjusted model were compared to those obtained with the 2 percent loss rate assumption.

A pollution control guideline, in effect during the 1970's, was incorporated in the computer model as a restriction or constraint. When the objectives of cost minimization and pollution control conflicted, the restriction forced the pollution control objective to dominate. Variables such as manure quality and quantity were varied in the computer model to determine at what point the pollution control guideline would force a given dairy farm to operate its liquid manure system suboptimally.

DEVELOPING THE RESEARCH MODEL

Three "hypothetical" dairy farms were constructed from an array of information on dairying in Tennessee (14) and North Carolina (19). The case study dairy farms were used as a model representation to examine the interrelationships between variables expected to have an important impact on the optimum size of manure storage structure.

Farm A was a 60 cow dairy herd utilizing pasture; Farm B was a 100 cow herd utilizing pasture; and Farm C was a 100 cow herd utilizing a drylot system. Characteristics of the three study farms with respect to size of milking herd, management practice, crops grown, and acreages are shown in Table 1. Each farm was assumed to have the acreage of various crops required to supply the necessary forage required by the

Table 1. Characteristics of Three Hypothetical Tennessee Dairy Farms[a]

	Farm A	Farm B	Farm C
Number of Cows	60	100	100
Forage System	Pasture	Pasture	Drylot
Acres of Corn Silage	40	67	87
Acres of Alfalfa Hay	21	35	35
Acres of Clover/Timothy Hay	12	20	20
Acres of Permanent Pasture	79	132	85
Acres of Summer Pasture	30	50	0

[a]Feed requirements were calculated on the basis of large dairy breeds producing 13,000 pounds of milk per cow. Assumed crop yields per acre were 15 tons for corn silage, 3.5 tons for alfalfa hay and 2.5 tons for clover-timothy hay. Acres of feed crops would be just sufficient to meet the needs of the milk cows and replacement animals. All concentrates would be purchased.

dairy animals and were adapted from enterprise budgets shown in the Farm Planning Manual (14). Standard fertilizer requirements were assumed for each crop as shown in Table 2. Required crop nutrients could be supplied from manure, commercial fertilizer, or a combination of both.

Table 2. Assumed Nutrient Requirements and Cost Per Acre for Forage Crops Used in Dairy Production[a]

Crop	N Required Per Acre	P_2O_5 Required Per Acre	K_2O Required Per Acre	Cost[b] Per Acre
Corn Silage	120	80	150	$61.66
Alfalfa	15	90	180	$47.85
Clover/Timothy Hay	30	90	90	$42.16
Permanent Pasture	30	90	90	$42.16
Summer Pasture	120	60	60	$48.66

[a]Nutrient requirements were adapted from Farm Planning Manual (14).

[b]These costs were calculated assuming a price of $.18/pound of N, $.23/pound of P_2O_5, and $0.093 pound of K_2O. A spreading charge of $7.66 per acre was added to the nutrient cost for the bulk spreader, a 60 hp tractor, labor and fuel.

Farm acreage devoted to corn silage, alfalfa, clover/timothy hay, and summer pasture was assumed to be available for surface application of manure from October 1 to March 31. Permanent pasture acreage was assumed to be available for surface application of manure in all time periods.[1]

The monthly value of manure input to the liquid manure system on each farm was estimated using standards for animal confinement suggested by a North Carolina planning guide (19). For dairy animals utilizing pasture, the assumed confinement period was 100 percent in January, November, and December; 90 percent in February, March, April, and October; 70 percent in May, July, August, and September; and 60 percent in June. For the drylot system, 100 percent of the manure produced by milking animals was retained by the liquid manure system; the amount of manure retained from that produced by dry stock and young stock varied according to the amount of animal confinement specified for dairy animals utilizing pasture.

The input to the storage structure was assumed to be composed of feces and urine; no bedding or milk parlor waste water was permitted to enter the storage structure.[2]

[1]The effect of crop rotation on liquid manure management was not considered in this study.

[2]Manure was assumed to be produced at the rate of 9.9 gallons per day per 1,000 pound animal unit with a moisture content as produced of 87.3 percent.

The monthly manure retention in gallons for each hypothetical farm is listed in Table 3. Manure retention was defined as the amount of manure which would be collected during barn and lot cleaning operations and entered into the storage structure.

Table 3. Estimated Amount of Manure Retained by Liquid Manure Systems on Three Synthetic Tennessee Dairy Farms by Month[a]

Month	Manure Retained on 60 Milking Cow Farm w/ Pasture System (gal.)	Manure Retained on 100 Milking Cow Farm w/ Pasture System (gal.)	Manure Retained on 100 Milking Cow Farm w/ Drylot System (gal.)
JAN	45,034	75,057	75,057
FEB	40,530	67,550	72,342
MAR	40,530	67,550	72,342
APR	40,530	67,550	72,342
MAY	31,524	52,540	66,912
JUN	27,020	45,033	64,197
JUL	31,524	52,540	66,912
AUG	31,524	52,540	66,912
SEP	31,524	52,540	66,912
OCT	40,530	67,550	72,342
NOV	45,034	75,057	75,057
DEC	45,034	75,057	75,057
Annual Production	450,338	750,564	846,384

[a]Manure retained was calculated at 90% moisture content. The amount of lot and roof runoff entering the manure storage was assumed to be less than or equal to the amount of water necessary to bring the manure to a moisture content of 90% prior to agitation and spreading.

Cost Of Manure Application

The cost per gallon of manure application was composed of costs which depend upon the quantity of manure applied and costs which depend upon the time required for spreading the manure. Costs on a quantity basis included the cost of a liquid manure spreader and the cost of a manure agitation pump. Costs on a time basis included tractor cost and labor cost. Separate cost budgets were constructed for each size of equipment. (See Table 4 and Table 5).

The cost of surface-applying manure to an acre of cropland was composed of the following:

1. The annual ownership cost of the liquid manure spreader and manure agitation pump.
2. The cost of labor for agitating and spreading manure.
3. The cost per unit of time for the tractor utilized for manure agitation and application to the land.

The technique for determining the cost of surface-applying manure can be illustrated for the 60 cow herd utilizing an 800 gallon liquid manure spreader with the following values (taken from Tables 4 and 5):

1. The estimated annual cost of owning an 800 gallon liquid manure spreader was $1,250.83.
2. The annual ownership cost of a 60 hp manure agitation pump was $1,459.83.
3. The labor cost was assumed to be $3.00 per hour.
4. The estimated cost of utilizing a 60 hp tractor for agitation and land application of manure was $8.75 per hour.
5. The labor time requirement per manure spreader load for agitation and spreading was 27.8 minutes (including travel to and from field).
6. The total amount of manure handled by the system was estimated to be 450,338 gallons.

Using the above values, the cost of surface-applying manure per gallon, with an 800 gallon liquid manure spreader, was estimated to be: (1250.82/450,338) + (1459.83/450,338) + (27.75/60) (3/800) + (14/60) (8.75/800) + (13.75/60) (8.75/800) = $.0128

Table 4. Estimation of User Cost per Gallon of Manure for Liquid Manure Handling Equipment, 1980 Machinery Cost Data

Item	Purchase Price ($)	Expected Life (Yr.)	Depreciation[1] ($)	Repair[2] Cost ($)	Interest[3] Cost ($)	Annual Cost ($)	Cost Per[4] Gallon ($)
800 Gal. Spreader	3,800	6	633.33	475.00	142.50	1,250.83	.002778
1,625 Gal. Spreader	5,100	6	850.00	637.50	191.25	1,678.75	.003728
2,222 Gal. Spreader	8,827	6	1,471.77	1,103.38	331.01	2,905.56	.006452
3,264 Gal. Spreader	10,688	6	1,781.33	1,336.00	400.80	3,518.13	.007812
4,500 Gal. Spreader	13,940	6	2,323.33	1,742.50	522.75	4,588.58	.010189
60 HP Agitator	3,766	5	753.20	564.70	141.23	1,459.33	.003241

[1]Straight line depreciation with no salvage value.

[2]Repair cost over life of equipment equal to 75% of purchase price.

[3]Yearly interest cost equal to 7.5% of average value of equipment.

[4]Equipment is utilized with 450,338 gallons of manure per year.

Cost of manure application was computed on a per gallon basis for spreaders of various sizes. Annual costs for owning spreaders ranged from $1,251 for the 800 gallon spreader to $4,589 for the 4,500 gallon spreader (Table 4). A 60 hp agitator pump was assumed for all situations. Annual ownership and operating costs for tractors ranged from $8.75 per

hour for the 60 hp tractor to $20.00 per hour for the 150 hp tractor (Table 5). Time required for application was a function of distance to field, size of spreader and size of tractor used. The labor cost used for the estimates was $3.00 per hour for all situations analyzed.

Tractor size was increased to accommodate larger spreader sizes. Labor requirements per gallon of manure spread decreased greatly with increases in tractor and spreader size. For example, time required per spreader load was 27.8 minutes for 800 gallon spreader, 35.1 minutes for 2,200 gallon spreader and 46.9 minutes for 4,500 gallon spreader.

Table 5. Determination of User Cost Per Hour for Auxiliary Manure Handling Equipment Based Upon Estimated Hours of Annual Use and 1980 Machinery Cost Data

Item	Purchase Price ($)	Estimated Hours of Use Annually (Hrs.)	Diesel Fuel Consumption Rate (Gal./Hr.)	Fuel/Oil[1] Filter Cost ($)	Annual[2] Depreciation ($)	Annual[3] Repair Cost ($)	Annual[4] Interest Cost ($)	Total Cost per Hour ($/Hr.)
60 HP Tractor	13,340	600	3.7	2,220	1,334	1,200	448	8.75
70 HP Tractor	14,600	600	4.6	2,760	1,460	1,314	546	10.13
80 HP Tractor	16,300	600	5.3	3,180	1,630	1,467	612	11.49
100 HP Tractor	23,560	600	7.3	4,380	2,356	2,120	882	16.23
125 HP Tractor	25,268	600	8.0	4,800	2,527	2,274	748	17.58
150 HP Tractor	28,763	600	9.1	5,460	2,876	2,588	1,080	20.00
10 Foot Fertilizer Spreader	1,213	60	—	—	202	182	46	6.66

[1]Fuel price of $.87 per gallon plus 15% of fuel cost for filter, grease, lube.

[2]Straight line depreciation with no salvage value, 10 years expected life for tractors, 6 years for fertilizer spreader.

[3]Repair cost over life of equipment equal to 90% of tractor purchase price and 75% of fertilizer spreader purchase price.

[4]Yearly interest cost equal to 7.5% of average value of equipment.

Cost of Commercial Fertilizer Application

The cost of commercial fertilizer application was estimated for corn silage, alfalfa, timothy hay, permanent pasture, and summer pasture using standard fertilizer recommendations. The estimated total cost of the commercial fertilizer application for corn silage was $61.61 per acre. The per acre cost of commercial fertilizer application was estimated to be $47.85 for alfalfa, $42.16 for timothy hay, $42.16 for permanent pasture, and $48.66 for summer pasture (Table 6).

The amount of nitrogen, phosphorus, and potassium supplied per unit of commercial fertilizer application was identical to the fertilizer requirements of each field due to custom blending. No nutrient losses were modeled for commercial fertilizer. It was assumed to be applied in March. The linear programming model permitted the joint application of manure and commercial fertilizer to the same land.

Table 6. Estimated Cost for Meeting the Plant Nutrient Requirements of an Acre of Corn Silage with Commercial Fertilizer

Item	Unit	Amount Required	Cost Per Unit ($)	Total Cost Per Acre ($)
N	lb.	120	.18	21.60
P_2O_5	lb.	80	.23	18.40
K_2O	lb.	150	.093	13.95
Labor	hr.	.5	3.00	1.50
60 HP Tractor Service	hr.	.4	8.75	3.50
10 Foot Fertilizer Spreader	hr.	.4	6.66	2.66
			Per Acre Cost	$61.61

Cost of Manure Storage

The cost of manure storage was determined by 1978 cost data on manure storage structures (16). These cost data are listed by storage structure size and type in Table 7. The cost of a concrete stave structure to store 149,600 gallons was approximately 17.5 times the cost of an earthen storage structure of the same size. On many farms, the soil structure precludes earthen storage structures. Per unit storage costs diminished with increasing storage structure size for all types of

Table 7. Estimated Cost of Manure Storage Structures by Size and Type, 1978[1]

Size of Storage Structure (Gal.)	Cost of Earthen Storage w/ Concrete Bottom ($)	Cost of Earthen Storage w/o Concrete Bottom ($)	Cost of Metal Storage ($)	Cost of Concrete Stave Storage ($)
74,800	*[2]	*	10,000	15,199
149,600	4,533	1,133	14,953	19,801
224,400	6,200	1,400	*	21,002
299,200	*	*	23,200	23,596
374,000	9,500	1,667	26,000	*
523,600	*	*	30,093	*

[1]Data obtained by Safley (16).

[2]Asterisk indicates cost data not available.

structures. At approximately 300,000 gallons of storage capacity, the purchase price of a manure storage structure built of metal was equivalent to one built of concrete staves.

Estimates of the annual cost of manure storage per gallon of capacity for each type and size of structure are shown in Table 8. These cost estimates provided a basis for determining whether the cost savings, obtained by storing manure rather than applying it as produced, exceeded the annual cost of the manure storage structure.

Table 8. Estimated Annual Cost of Manure Storage per Gallon of Capacity by Size and Type of Structure, 1978[1]

Size Storage Structure (Gal.)	Annual Cost of Earthen Storage w/ Concrete Bottom[2] (mills)	Annual Cost of Earthen Storage w/o Concrete Bottom[2] (mills)	Annual Cost of Metal Storage (mills)	Annual Cost of Concrete Stave Storage[3] (mills)
74,800	*[4]	*	13.03[3]	19.81[3]
149,600	3.56	.8902	9.74	12.09
224,400	3.25	.733	*	9.12
299,200	*	*	7.56	7.68
374,000	2.98	.524	6.77	*
523,600	*	*	5.60	*

[1]Purchase prices were obtained from an unpublished dissertation by L. M. Safley (16).

[2]Expected life was 15 years; straight line depreciation with no salvage value; repair costs were equal to 20% of the purchase price over the life of the structure; and annual interest on investment was 7.5% of the average value of the structure.

[3]Expected life was 20 years; straight line depreciation with no salvage value was used; repair costs were estimated to be 20% of the purchase price over the life of the structure; and annual interest on investment was assumed to be 7.5% of the average value of the structure.

[4]Asterisk indicates cost data not available.

Nutrients Supplied by Manure

Unless otherwise stipulated, the nitrogen, phosphorus, and potassium contents of manure as produced were assumed to be .0426, .0076, and .0280 pounds/gallon, respectively (9). Manure was assumed to be produced at 87.3 percent moisture content. Manure moisture content was assumed to be raised to 90 percent to facilitate agitation which reduced the nitrogen, phosphorus, and potassium content of dairy manure to .0335, .0060, and .0220 pounds/gallon, respectively. Using a procedure suggested by the MWPS (16), the phosphorus content of dairy manure as produced was divided by .44 to acquire the P_2O_5 equivalency. The potassium content of dairy manure as produced was divided by .83 to acquire the K_2O equivalency. The N, P_2O_5, and K_2O content of dairy manure (90 percent

moisture content) utilized in the linear programming model was .0335, .0136, and .0266 pounds/gallon, respectively.

The number of gallons of manure which must be applied to an acre of land to meet the crop's nutrient requirement depends upon the chemical composition of the manure at the time it is substituted for commercial fertilizer and the commerical fertilizer application rate stipulated for the crop.

The nitrogen supplied per gallon of surface-applied manure was dependent upon the amount of loss which occurred between the time when the manure was produced and the time when commercial fertilizer would otherwise have been applied. Nitrogen volatilization was assumed to reduce the amount of nitrogen present in fresh manure (urine plus feces) by 50 percent between the time when it was produced and the time when commercial fertilizer would otherwise have been applied. A loss of 2 percent of the nitrogen, remaining after allowing for volatilization loss, was assumed to occur for each month between the month in which the manure was surface applied and the month in which commercial fertilizer otherwise would have been applied (7).

Phosphorus runoff loss of 2 percent of the phosphorus present in fresh manure was assumed to occur for each month between the month in which the manure was applied and the month in which commercial

Table 9. Amount of March-Applied Elemental Commercial Fertilizer Replaced per Gallon of Manure by Month of Application and Element

Month of Manure Application	Amount of Commercial Fertilizer Supplied N Replaced by a Gallon of Manure[1] (Pounds)	Amount of Commercial Fertilizer Supplied P_2O_5 Replaced by a Gallon of Manure[1] (Pounds)	Amount of Commercial Fertilizer Supplied K_2O Replaced by a Gallon of Manure[1] (Pounds)
JAN	.0161	.0131	.0255
FEB	.0164	.0133	.0261
MAR	.0168	.0136	.0266
APR	.0131	.0106	.0207
MAY	.0134	.0109	.0213
JUN	.0138	.0112	.0218
JUL	.0141	.0114	.0223
AUG	.0144	.0117	.0227
SEP	.0148	.0120	.0234
OCT	.0151	.0122	0.239
NOV	.0155	.0125	.0245
DEC	.0158	.0128	.0250

[1]Assumes commercial fertilizer would be replaced in the month of March, 50% volatilization loss of nitrogen in manure; and all elements would be lost at a rate of 2% for each month between application and the month of March. It was asssumed that no loss of plant nutrients occurred while manure was in storage.

fertilizer would otherwise have been applied. A runoff loss of 2 percent per month was also assumed for potassium (7).

Since some portion of the nitrogen, phosphorus, and potassium present in manure was not in a form accessible to plants during the year in which it was applied, this study assumed that the nutrients not available from the manure were balanced by residual nutrients from previous applications of manure which became available during the year.

The nutrient composition assumed for manure production on all synthetic case farms is shown in Table 9. Each entry shows the amount of elemental commercial fertilizer, applied in March, which could have been replaced by a gallon of manure applied during the month indicated at the beginning of each row.

Determining the Optimum Size of Manure Storage Structure

The principal results of this study were derived by solving a linear programming model which determined the optimum amount of manure to store for various levels of annual unit cost of a liquid manure storage structure. The linear programming objective function called the size equation was farm specific and was constrained by a series of equations relating manure quantity and quality and the nutrient needs for crop production. Solutions obtained from the size equation assumed a liquid manure system would be used and answered the question: "if the annual cost per unit of storage structure was some specified amount, such as 1 mill, what would be the optimum amount of manure to store?" By obtaining solutions for a wide range of possible costs of annual storage, the relationship between cost of storage and optimum amount of storage could be obtained. The optimum amount of storage was defined as the amount of storage that would minimize the combined cost of disposing of the manure (utilizing a liquid manure system) and meeting the nutrient requirements of the crops produced on each of the hypothetical farms.

In this study the optimum amount of manure to store was described only in a conditional sense; it depended upon the annual per unit cost at which storage structures were available and upon factors specific to the dairy farm such as herd size, acreage, degree of animal confinement and crop mix. For purposes of illustration a second type of equation, called a cost equation, was derived which described the per unit annual cost of manure storage structures according to their size. The cost equations (one for each structure type) were fitted to the cost data shown in Table 7.

OPTIMUM MANURE STORAGE STRUCTURE SIZE

The LP models of the three "hypothetical" dairy farms were designed to examine the effect of a number of factors on the optimum manure

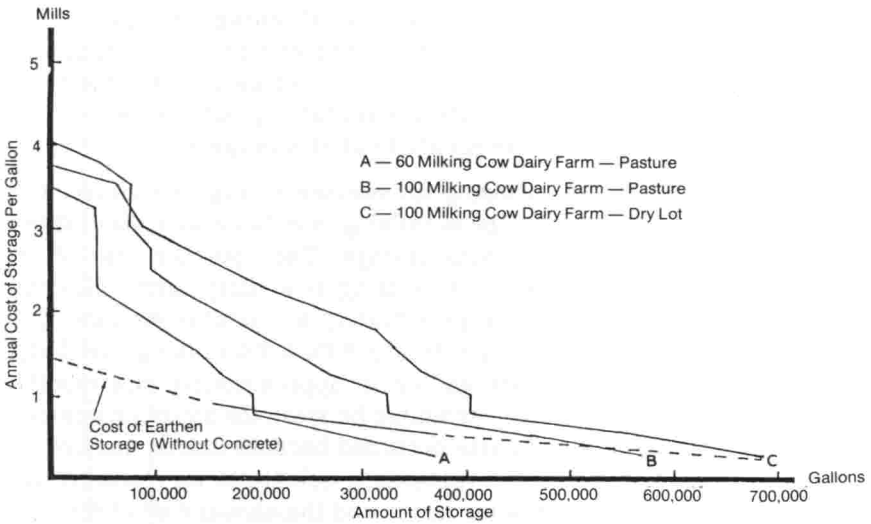

Figure 1. Amount of Storage Which Minimizes the Cost of Operating a Liquid Manure System and the Cost of Meeting the Plant Nutrient Requirements of Cropped Acreage by Type of Farm and Cost of Storage

storage structure size. Two of the more important factors were the size of the dairy herd and the cost of the storage structure.

Dairy farms with large acreages of field crops have a greater requirement for commercial fertilizer than those with small acreages. Since the cost of commercial fertilizer utilization on synthetic dairy farms was dependent upon the acreage planted, the value of manure as a substitute for commercial fertilizer was likewise dependent upon the acreage planted. On synthetic farms where stored manure had a higher value, larger manure storage structures were justified.

The optimum manure storage structure size for a wide range of annual cost of storage is shown in Figure 1 for each of the three hypothetical farms. The size equation designated with a letter A was obtained by solving the linear programming model using data for Farm A and standard manure quantity and quality characteristics described earlier.[1] The optimum manure storage structure size for various possible structure costs is shown for Farm B by the line designated with the letter B and for Farm C with the line designated by the letter C.

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[1] Values derived were influenced by a large number of factors including quantity and nutrient composition of the manure, nutrient requirements and acreage of various crops, distance to various fields, manure nutrient decomposition rates and costs and performance rates of machinery and equipment.

For comparison purposes the annual cost of storage per gallon for earthen storage structures is also shown in Figure 1 for a wide range of sizes of storage structures. Cost equations are not shown for other type structures since the cost level for these structures greatly exceeded the justified cost as shown by the size equations at all storage levels.

Based upon 1978 prices, utilizing an earthen storage structure, the optimum amount of storage for the 60 milking cow dairy farm was 193,646 gallons or approximately 6 months storage. The optimum size of an earthen storage structure for a 100 milking cow dairy farm, utilizing pasture, was 500,000 gallons or approximately 8.5 months storage. The optimum size of an earthen storage structure for a 100 milking cow dairy farm, utilizing drylot was 630,000 gallons or approximately nine months storage. The positive relationship exhibited between the optimum number of months of storage and farm size occurred because stored manure on the larger farms had a greater value as a substitute for commercial fertilizer than it did on the smaller farms and the annual cost of manure storage per gallon was a decreasing function of the storage structure size.

Stored manure was always allocated to corn silage land in preference to alfalfa, hay, or pastureland—all other things being equal. This allocation pattern occurred because the ratio of plant nutrients required by corn silage was closer to the ratio assumed for manure than were the ratios of plant nutrients required by the other crops considered. The amount of corn silage acreage assumed for the "hypothetical" farms was 40 acres for the 60 milking cow dairy farm, 67 acres for the 100 milking cow (pasture) dairy farm, and 87 acres for the 100 milking cow (drylot) dairy farm. The amount of corn silage grown on the larger farms accounted in part for the positive relationship between farm size and optimum manure storage structure size.

The relationship between optimum manure storage structure size and the type of construction material utilized was primarily a reflection of the cost of the construction material. Based upon the results obtained with the LP model, the estimated maximum annual cost of storage at which cost savings are possible on Tennessee dairy farms, operating liquid manure and commercial fertilizer application systems, was approximately $.004/gallon of storage capacity. The 1978 per gallon annual cost of manure storage structure, fabricated from concrete staves, ranged from $.0077/gallon to $.0198/gallon depending upon the size of the structure. The annual cost of manure storage structures, fabricated from steel, ranged from $.0056/gallon to $.0130/gallon depending upon the size of the structure. Consequently, had a cost equation [cost=f(storage size, storage type)] for either a metal storage structure or a concrete stave storage structure been plotted in Figure 1, no additional intersections would have been obtained. If other considerations (such as soil structure) mandate the use of storage structures fabricated with metal or cement stave,

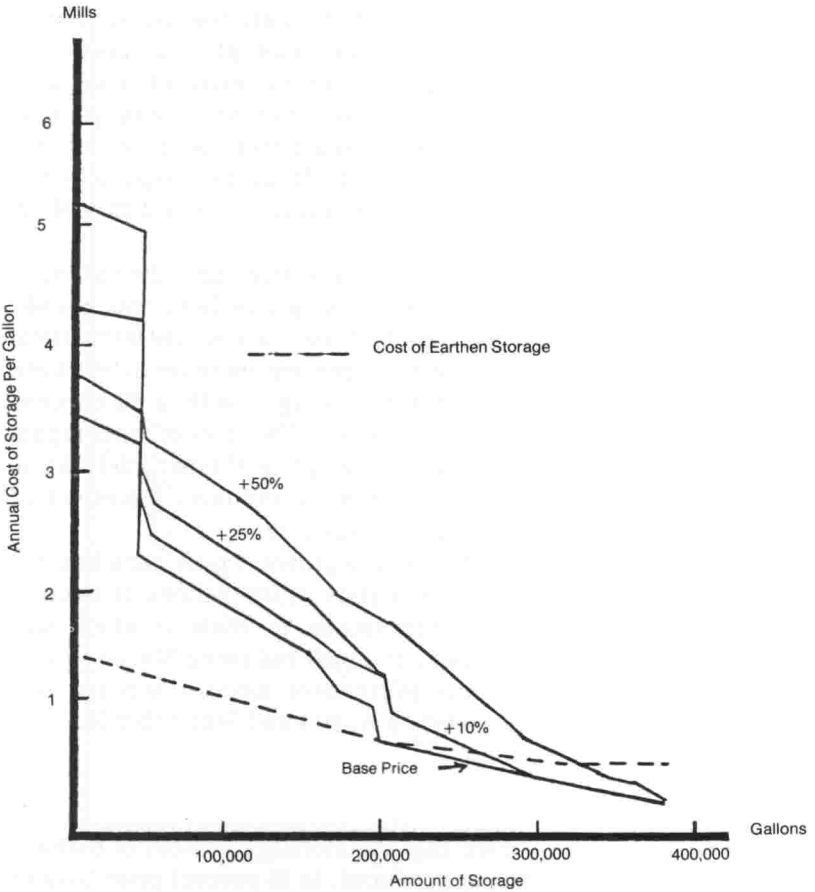

Figure 2. Effect of 10, 25, 50% Commercial Fertilizer Price Increase on Optimum Storage Size for a 60 Milking Cow Dairy Farm

installation of the smallest size unit that is commercially available would minimize the cost of operating the liquid manure and commercial fertilizer applications system.

Effect of Fertilizer Price on Optimum Manure Storage

Commercial fertilizer prices of \$.18/pound for N, \$.23/pound for P_2O_5 and \$.093/pound for K_2O were utilized in determining the optimum manure storage structure size for each of the hypothetical dairy farms shown in Figure 1. The optimum manure storage structure size for a given dairy farm was also determined for fertilizer prices of 10, 25 and and 50 percent above the base level. The optimum structure size is shown in Figure 2 for each fertilizer price level for a wide range of annual costs

of manure storage for the 60 cow dairy herd. A single cost equation was plotted to represent the cost of earthen manure storage structures. The optimum structure size, for a particular commercial fertilizer price, was determined from the intersection of the cost equation with the respective size equation. The size equations were obtained from solutions of the linear programming model utilizing input data from the "hypothetical" 60 milking cow dairy farm and assuming the utilization of a 2,222 gallon liquid manure spreader.[2]

Based upon 1978 prices for an earthen storage structure, the optimum amount of storage for a farm with a 60 milking cow herd was 193,646 gallons (six months storage) at the base fertilizer prices; 260,000 gallons (7.5 months storage) with a 10 percent or 25 percent increase in fertilizer prices; and 320,000 gallons (nine months storage) with a 50 percent increase in fertilizer price above the base levels. The price of other inputs were held constant. Coinciding increases in the price of labor, fuel and/or liquid manure system equipment would tend to diminish the effect of increases in fertilizer price on optimum storage size.

Each size equation in Figure 2 has a segment which parallels the annual cost of storage axis at approximately 41,000 gallons of manure storage. This volume of storage corresponds to manure which was produced in April and stored for application the following March. Under the assumptions of the model only permanent pasture acreage was available for manure distribution between April 1 and September 30.

Moisture Content of Manure

In the LP model it was assumed that the moisture content of manure was increased from 87.3 percent, as produced, to 90 percent prior to land application. A 90 percent moisture content was the standard suggested by manure agitator manufacturers as a minimum for efficient agitation.

Increases in moisture content reduced the quality of manure as a substitute for commercial fertilizer and increased the amount of liquid handled by the system. Increases in the moisture content uniformly increased the cost of operating the liquid manure and commercial fertilizer application system. If the annual cost for manure storage was 1 mill ($.001) per gallon, the total cost for applying commercial fertilizer and operating a liquid manure system for the 60 milking cow dairy farm was $11,568.81 when manure was applied at a moisture content of 90 percent; $12,258.60 when applied at a moisture content of 91 percent; and $13,121.26 when applied at a moisture content of 92 percent. Thus increasing manure moisture content from 90 percent to 91 percent, increased total cost by 6 percent; increasing manure moisture content from 90 percent to 92 percent, increased total cost by 13.4 percent.

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[2] This analysis was not done for the 100 cow dairy herds.

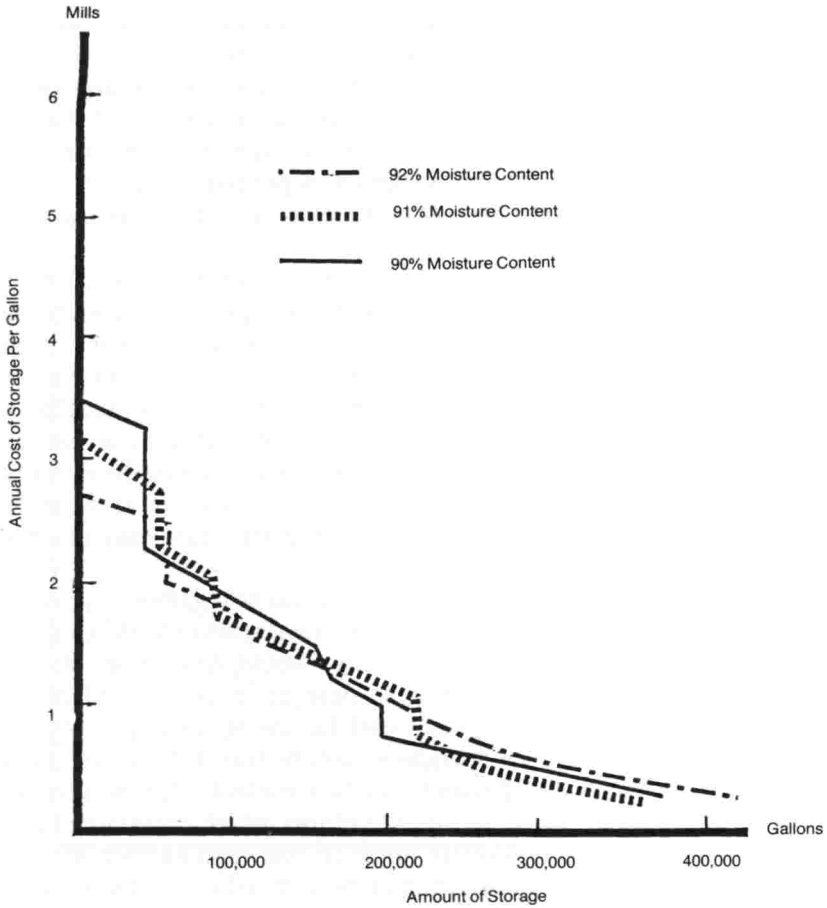

Figure 3. Amount of Storage Which Minimizes the Cost of Operating a Liquid Manure System and the Cost of Meeting the Plant Nutrient Requirements of Cropped Acreage on a 60-Milking Cow Dairy Farm According to the Final Manure Moisture Content and the Annual Cost of Manure Storage

Increases in moisture content shifted the size equation as shown in Figure 3. At an annual cost of 1 mill/gallon, the size equation specified for 90 percent moisture content was shifted from 193,646 gallons to 215,163 gallons for a moisture content of 91 percent and to 202,653 gallons for a moisture content of 92 percent. The shifts in the size equation were not uniform. The 91 percent and 92 percent moisture content size equations were not everywhere higher or lower than the 90 percent moisture content size equation.

This nonuniformity occurred because alteration in the moisture content of manure prior to land application affected the allocation of manure among the different crops (fields) as well as the amount of manure stored. As the per unit cost of a storage structure in the LP model was increased, reduction in the optimum storage structure size was required, but the extent of the reduction depended upon how much manure was allocated among the crops which in turn depended upon the moisture content of the manure.

During this analysis an attempt was made to clarify the relationship between moisture content and the most suitable type of manure storage structure for any given dairy farm. Storage structures fabricated from metal or concrete staves usually have a smaller surface area exposed to the elements than do earthen storage structures and are capable of maintaining manure at a lower moisture content than that of earthen manure storage structures. A storage structure fabricated from metal may maintain manure at approximately 90 percent moisture content. The moisture content of manure stored in an earthen structure may reach 95 percent (12).

If a metal manure storage structure of 193,646 gallons had been incorporated in the liquid manure system on the synthetic 60 milking cow dairy farm, the total annual system cost would have been $13,013 assuming manure was maintained at 90 percent moisture content. As stated earlier the total annual system cost for the 60 milking cow dairy farm with an earthen manure storage structure was $13,131, assuming manure was maintained at 92 percent moisture content. This comparison of costs indicated that metal storage structures which maintained a 90 percent moisture level were slightly lower in cost than earthen manure storage structures which maintained manure at moisture contents higher than 92 percent.

As-Produced Manure Chemical Composition

The effect of an increase in nutrient content of manure (as produced) on the cost of operating the liquid manure and commercial fertilizer application system was to decrease the cost; the effect of a decrease in nutrient composition was to increase the cost. In the basic model it was assumed that the nutrient content of manure as produced, on the case dairy farms was .0426 pounds N/gallon, .0076 pounds P/gallon, and .028 pounds K/gallon. When the assumed nutrient content was increased to .0467 pounds N/gallon, .0166 pounds P/gallon, and .0331 pounds K/gallon, and the annual cost of manure storage was assumed to be $.001 per gallon, the operating cost of the system decreased from $11,568.81 to $9,742.59. When the assumed nutrient content was decreased to .0340 pounds N/gallon, .0075

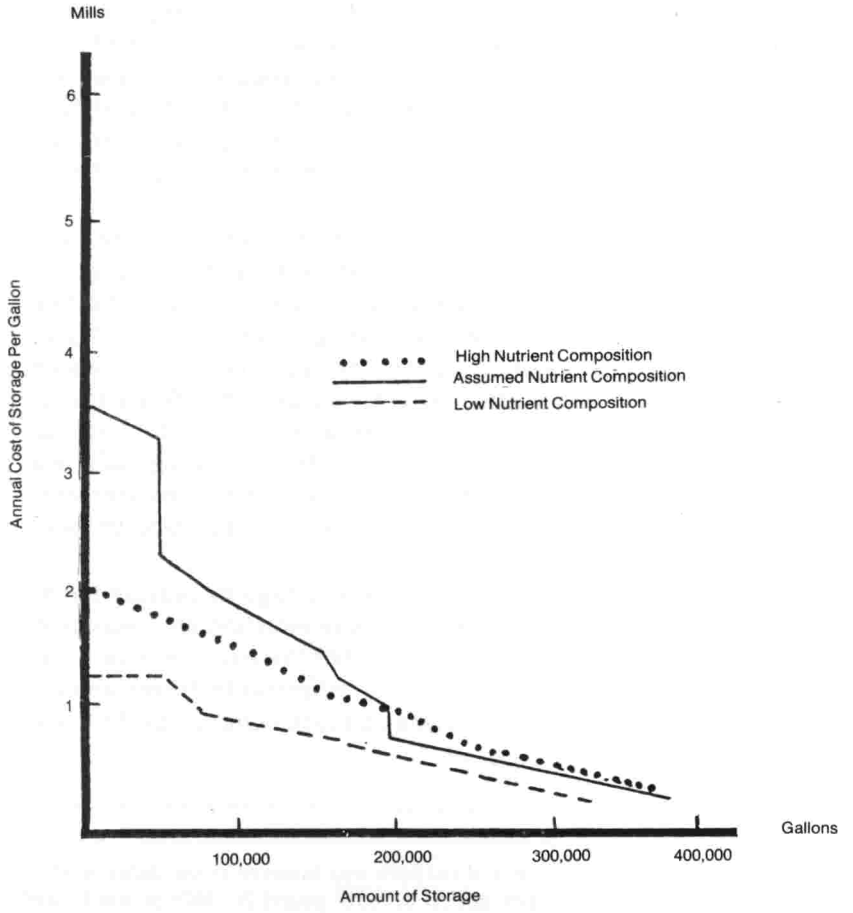

Figure 4. Amount of Storage Which Minimizes the Cost of Meeting the Plant Nutrient Requirements of Cropped Acreage on a 60 Milking Cow Dairy Farm According to the Initial Nutrient Composition of Manure and the Annual Cost of Manure Storage

pounds P/gallon, and .0144 pounds K/gallon[3] , the operating cost of the system increased from $11,568.81 to $12,363.56 (using an annual cost for manure storage of 1 mill/gallon). This analysis indicated that the LP model was sensitive to the parameter value assumed for the as-produced nutrient content of manure.

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[3]Research literature (16) suggested that the N content of fresh dairy manure ranged from .0340 pounds/gallon to .0467 pounds/gallon. The P content ranges from .0075 pounds/gallon to .0166 pounds/gallon. The K content ranges from .0144 pounds/gallon to .0331 pounds/gallon. These extremes represent not only a difference in the absolute amount of nutrients but also a difference in the ratio of the nutrients. The value of manure as a substitute for commercial fertilizer is a function of both the quantity and the ratio of the nutrients contained in the manure.

Increasing and decreasing the as-produced nutrient content of manure shifted the size equation as shown in Figure 4. At an annual cost of .75 mill/gallon of manure storage, lowering the as-produced nutrient composition of manure[4] shifted the size equation from 193,646 gallons to 162,122 gallons. At an annual storage cost of .75 mill/gallon of manure, raising the as-produced nutrient composition of manure[5] shifted the size equation from 193,646 gallons to 240,000 gallons.

The shifts in the size equation were not uniform over the entire range of manure storage costs. For annual storage costs of 1 mill/gallon or greater the size equation was shifted down when the as-produced nutrient composition of manure was reduced.[6] At costs greater than 1 mill/gallon for manure storage was justified mainly by the opportunity to store manure for subsequent application to corn silage land. When the as-produced nutrient composition of manure was increased[7], enough nutrients were produced during the same time the corn silage land was open (October to March) to meet the corn silage nutrient requirements, making storage for subsequent application to corn silage land unnecessary.[8]

At costs less than 1 mill/gallon for manure storage increasing the as-produced nutrient composition[9] shifted the size equation up; decreasing the as-produced nutrient composition[10] shifted the equation down. The costs of operating the liquid manure and commercial fertilizer application system were minimized by replacing as much commercial fertilizer

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[4] The as-produced nutrient content of manure was lowered from .0426 pound N, .0076 pound P, and .028 pound K per gallon to .0340 pound N, .0075 pound P, and .0144 pound K per gallon.

[5] The as-produced nutrient content of manure was raised from .0426 pound N, .0076 pound P, and .028 pound K per gallon to .0467 pound N, .0166 pound P, and .0331 pound K per gallon.

[6] Ibid.

[7] Ibid.

[8] When the annual cost of manure storage was greater than 1 mill/gallon, decreasing the as-produced nutrient composition of manure should have shifted the size equation up since between October and March an inadequate amount of nutrients would have been produced to meet the corn silage land's nutrient requirements. This shift did not occur because the amount of low nutrient composition manure required to meet the plant nutrient requirements of corn silage land exceeded the maximum application rate of the pollution control constraint. Since low nutrient content manure could not be applied to corn silage land, it was necessary to store manure for that purpose.

[9] See footnote 5.

[10] See footnote 4.

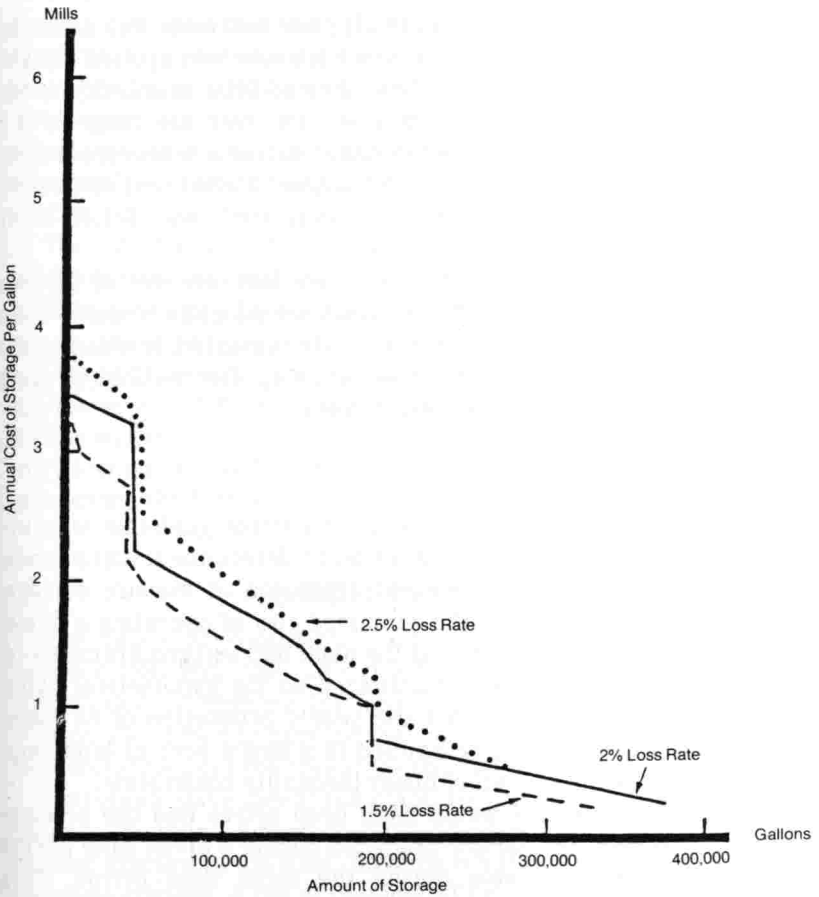

Figure 5. Amount of Storage Which Minimizes the Cost of Operating a Liquid Manure System and the Cost of Meeting the Plant Nutrient Requirements of Cropped Acreage on a 60 Milking Cow Dairy Farm According to the Plant Nutrient Loss Rate and the Annual Cost of Manure Storage

as possible with manure. Since manure with a high nutrient content replaces more commercial fertilizer than manure with a lower nutrient content, the decay of manure with a higher nutrient content represented a greater potential loss than the decay of manure with a lower nutrient content. Consequently, at any given price for the storage of manure, storage of greater amounts of high nutrient composition manure than of low nutrient composition manure were justified.

Plant Nutrient Loss Rate from Field Applied Manure

Nutrient loss from field applied manure varies greatly from year to year, and is affected by such factors as weather, soil type, and topography

(7). In the LP model a 2 percent loss in all plant nutrients was assumed for every month between the month in which manure was applied and the month of March. Results from the model showed little sensitivity to the value assumed for the plant nutrient loss rate over the range of 1.5 percent to 2.5 percent per month. When either extreme was compared to the base rate of 2 percent per month, the largest annual cost difference over the range of manure storage costs evaluated, was $81.00 or .7 percent.

Increases and decreases in the plant nutrient loss rate shifted the size equation as shown in Figure 5. Shifts, although occasionally large,[11] were uniform over the range of manure storage costs evaluated. Increasing the plant nutrient loss rate shifted the size equation up. Decreasing the plant nutrient loss rate shifted the size equation down.

Pollution Control Standard

A recently discarded Tennessee pollution control guideline was incorporated in the linear programming model to determine if compliance with the guideline would have required expansion of manure storage facilities beyond the point where the combined cost of operating a liquid manure system and the cost of meeting the plant nutrient requirements of cropped acreage would have been minimized on the hypothetical dairy farms. The guideline, requiring that the yearly production of no more than two mature dairy animals be applied to a single acre of land, was incorporated in the model as a set of linear inequality constraints.

Some pollution constraints would have been active had the acreage required by the amount of manure produced during a given time period exceeded the acreage available during the same time period. This precondition was not met because the synthetic Tennessee dairy farms, as constructed, displayed a low ratio of mature dairy animals to acreage available for manure spreading. From April through September, land devoted to corn silage, alfalfa, clover/timothy hay, and summer pasture was assumed unavailable for manure application to all synthetic farms. During this period an amount of manure equivalent to the yearly production of 34 mature dairy animals was produced on the 60 milking cow dairy farm and 79 acres were available for application. The ratio of mature dairy animals to acres available was .425 on the 100 milking cow dairy farm utilizing pasture and .827 on the 100 milking cow dairy farm utilizing drylot during the same period of limited land availability.

Since the pollution control guideline translated into a maximum manure application rate (11,498 gallons) for an acre of cropland, the

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[11] The largest shift occurred at an annual cost of .5 mill/gallon for manure storage. At this cost level, decreasing the plant nutrient loss rate from 2 percent to 1.5 percent shifted the size equation from 193,646 gallons to 279,210 gallons. The cost difference represented by the two storage sizes was $20.98 or .2 percent.

corresponding constraint could have been active had the amount of manure required to meet the plant nutrient requirements of an acre of cropland exceeded this figure. Pollution control constraints were effective when the as-produced nutrient composition of manure was reduced to .0340 pounds/gallon for N; .0075 pounds/gallon for P; and .0144 pounds/gallon for K. This composition was a combination of the lowest empirically observed value for each element reported in various research studies.

The combination of low quality manure and compliance with the guideline did not increase the optimum manure storage size on the 60 milking cow dairy farm; it merely shifted manure application from corn silage land to pasture-land.

Compliance with the recently rescinded manure land application guideline would have adversely affected some Tennessee dairy farms characterized by limited acreage in relation to cow numbers, manure of a very low quality and/or if manure storage costs were too high to justify preserving the fertilizer value of the manure.

SUMMARY AND CONCLUSIONS

The price of commercial fertilizer in Tennessee almost doubled between 1960 and 1980. This price increase has renewed interest in the substitution of manure for commercial fertilizer. The liquid manure system, developed to capture the value of nutrients found in manure, was the central focus of the research reported in this bulletin.

Dairymen have been reluctant to utilize a liquid manure system because the manure must be diluted with water which adds to the cost of hauling manure to the field. Manure is normally produced at 87.3 percent moisture content. A ton of manure will require the addition of 540 pounds of water to bring it up to the 90 percent moisture content suggested by manure agitator manufacturers as a minimum for efficient agitation.

Dairymen also question whether the additional nutrients saved with a liquid manure system over a conventional system justify the additional cost of the liquid manure system. Henderson (5) estimated the annual cost of handling manure from a 100 milking cow herd at $954 with a conventional system in 1973, but for a liquid manure system the cost was $1,615.

Whether the benefits of a liquid manure system exceed its cost must be decided on a farm by farm basis. Storing manure may preserve the value of manure in two ways. Storage inhibits the breakdown and attendant loss of nutrients which occur when manure is spread daily. If storage is available the manure can be trasferred from the time period in which it is produced to a time period in which it can be most advantageously utilized. The value of manure is affected by the crop to which it is applied. If nutrients applied in excess of crop requirements are

considered valueless, the crop nutrient requirements which most closely correspond to the composition of manure determine the crop to apply the manure to obtain the maximum economic benefit.

The results of this study indicated a positive relationship between the size of the dairy herd and the optimum amount of manure to store. The optimum amount of storage for a 60 milking cow dairy farm was the capacity to handle manure production for about six months. The optimum amount of storage for a 100 milking cow dairy farm, utilizing pasture, was capacity for 8.5 months storage. The optimum amount of storage for a 100 milking cow dairy farm, utilizing a drylot, was nine months capacity. Obviously, the decision to install a liquid manure system must be based upon the value of manure on a particular farm and the cost at which liquid manure system components are available.

The value of manure as a substitute for commercial fertilizer depends heavily on the need to dispose of the manure in a nonpolluting and inexpensive way. At 1980 commercial fertilizer prices, manure was a more expensive source of plant nutrients than commercial fertilizer.

The per acre plant nutrient requirements of 120 pounds N, 80 pounds P_2O_5, and 150 pounds K_2O for corn silage could have been supplied with commercial fertilizer at a cost of $61.61 ($.18/pound for N, $.23/pound for P_2O_5, $.093/pound for K_2O, $7.66 for application). These same nutrient requirements could have been supplied with 7,156 gallons of stored manure at a cost of $91.69 not including the cost of storage.

Any conceivable degradation process, which could have disposed of 7,156 gallons of manure at a cost of less than $30.08 would have represented a less expensive alternative to Tennessee dairymen than the operation of a liquid manure system.

Moisture Content of Manure

Increases in moisture content from 87.3 to 90 percent reduced the quality of manure as a substitute for commercial fertilizer and increased the amount of liquid handled by the system. At an annual cost of $.001 per gallon for manure storage, the total cost for applying commercial fertilizer and operating a liquid manure system on a 60 milking cow (pasture) dairy farm was $11,568.81 when manure was applied at a moisture content of 90 percent; $12,258.60 when applied at a moisture content of 91 percent; and $13,121.26 when applied at a moisture content of 92 percent.

The increase in the optimium manure storage structure size associated with an increase in moisture content was generally less than the increase in manure volume. The nutrients contained in 193,646 gallons of manure at 90 percent moisture content were contained in 242,057 gallons of manure at 92 percent moisture content. At an annual cost of $.001 per gallon for manure storage, a capacity of 193,646 gallons of storage was optimum for the 60 milking cow (pasture) dairy farm when the moisture content was

90 percent; a capacity of 202,653 gallons of storage was optimum when the moisture content was raised to 92 percent. In many instances raising the moisture content of the manure actually lowered the optimum manure storage structure size. In those instances greater cost savings were obtained through reallocation of manure among fields than through increased storage size.

As Produced Manure Chemical Composition

The effect of the as-produced nutrient content of manure on the optimum manure storage structure size was highly dependent upon the opportunity to store manure for subsequent application to corn silage land. Manure with a nutrient composition in the intermediate range had the largest optimum manure storage structure size when the annual cost of manure storage varied from $.035/gallon to $.01/gallon. Manure with the lowest nutrient composition had the smallest optimum size over this range of annual costs because the amount of manure required per acre to meet the plant nutrient requirements of corn silage (13,761 gallons) exceeded the maximum application per acre allowed by the pollution control guideline constraint (11,498 gallons). The optimum size of storage for manure of the highest nutrient composition was in between the other two compositions over this range of annual costs. Due to its high nutrient content, the manure produced, during the time period the corn silage land was open, was adequate to meet the nutrient requirements of the corn silage acreage and no storage was required for this purpose.

The effect of an increase in the as-produced nutrient content of manure on the cost of operating the liquid manure and commercial fertilizer application system was to decrease the cost; the effect of a decrease in nutrient composition was to increase the cost.

Plant Nutrient Loss Rate from Field Applied Manure

In the analysis a 2 percent loss in all plant nutrients was assumed for every month between the month in which manure was applied and the month of March. Results from the study showed little sensitivity to the value assumed for the plant nutrient loss rate over a range from 1.5 percent to 2.5 percent per month. Comparing either extreme to the base rate of 2 percent, the largest cost difference, over the range of annual cost of manure storage evaluated, was $81.00 or 7 percent.

The effect of the plant nutrient loss rate on the optimum manure storage structure size was essentially direct—the larger the plant nutrient loss rate, the larger the optimum manure storage structure size. At an annual cost of $.0005 per gallon for manure storage, the optimum manure storage structure size was 193,646 gallons for a plant nutrient loss rate of 1.5 percent as compared to 279,210 gallons for a plant nutrient loss

rate of 2 percent and 2.5 percent. The total annual cost for manure and fertilizer application for the two storage sizes differed by approximately .2 percent.

Results from previous research have shown a wide variation in the rate of nutrient loss from manure applied to soils. Since a number of relevant variables are unpredictable, especially weather, the results of the study must be interpreted with some caution. If the bulk of plant nutrients for a crop are supplied through manure, soil tests may be necessary to determine the amount of commercial fertilizer supplement needed to supply required nutrients for crop production.

Valuation of Manure

As a consequence of the model formulation utilized, manure was always allocated to corn silage land in preference to alfalfa, hay, or pasture-land—all other things being equal. This ocurred because the ratios of plant nutrients required by corn silage were closer to the ratio assumed for manure than were the ratios of plant nutrients required by the other crops considered.

Manure was allocated to an acre of land up to the point where the most limited nutrient requirement was met. The study accounted zero value to those nutrients supplied by manure in excess of the crops requirement. In the model, commercial fertilizer was available to crops only in a blended form. Consequently, the crops nutrient requirement of each acre of land were met: with manure alone, a blended commercial fertilizer alone, or a combination of manure and the fertilizer blend. With an application of commercial fertilizer alone, nutrient requirements were exactly met. Otherwise one or more nutrients were supplied in excess.

An accounting type of analysis was conducted to see if the linear programming model overstated the cost of meeting crop nutrient requirements by undervaluing manure. The cost of meeting the plant nutrient requirements, of corn silage, with a combination of manure and elemental commercial fertilizer was compared to the cost of meeting the same requirements with a combination of manure and blended commercial fertilizer. The latter combination was utilized in the linear programming model. The costs of meeting the plant nutrient requirement, generated by the two different methods, differed by less than 1 percent.

The closeness in costs obtained with the two methods was accounted for by the requirement to spread all manure produced. Supplementary manure with elemental commercial fertilizer, rather than blended commercial fertilizer, reduced the amount of manure utilized on a given acre of land; but the manure saved had to be applied elsewhere.

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