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I am submitting herewith a dissertation written by Russell Coleman Parker entitled "Size Optimization of Dairy Manure Storage." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Agricultural Economics.

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SIZE OPTIMIZATION OF DAIRY MANURE STORAGE

A Dissertation

Presented for the

Doctor of Philosophy

Degree

The University of Tennessee, Knoxville

Russell Coleman Parker

August 1981

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To Eugene C. Parker

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ABSTRACT

The purpose of this study was to develop a method for determining the size of manure storage structure which would minimize the cost of operating a liquid manure and commercial fertilizer application system on any given dairy farm.

An earthen manure storage structure of 193,646 gallons (6 months storage) was determined to be optimum for a synthetic 60 milking cow dairy farm. An earthen manure storage structure capable of storing manure for 8.5 months (500,000 gallons) was optimum for a synthetic 100 milking cow dairy farm, utilizing pasture. An earthen manure storage structure of 630,000 gallons (9 months storage) was shown to be optimum for a synthetic 100 milking cow dairy farm, utilizing a drylot. Manure storage structures, fabricated from metal or concrete staves, were inferior to structures fabricated from earth on a cost basis as long as manure was maintainable at a moisture content of less than 92 percent in the earthen structure.

The optimum manure storage structure size depended upon a number of factors. The size of and distance to fields utilized for corn silage greatly influenced the optimum amount of manure storage. Increasing the price of commercial fertilizer by 50 percent increased the optimum amount of manure storage on a synthetic 60 milking cow dairy farm from 193,646 gallons to 320,000 gallons.

Injecting manure, rather than surface applying it, normally reduced the optimum amount of manure storage and the cost of operating a liquid manure and commercial fertilizer application system. The cost

of meeting the plant nutrient requirements of an acre of corn silage was reduced from $101.43 with surface application to $77.83 with manure injection.

The linear programming model, utilized in the study, was tested for validity by varying the value assumed for key parameters. The analysis did not uncover any erratic or implausible results; however, model validity was shown to depend upon explicit knowledge of the moisture content of manure prior to land application and upon the nutrient composition of manure as it is produced.

The model showed little sensitivity to the value assumed for the plant nutrient loss rate from field applied manure over a range from 1.5 percent to 2.5 percent per month. Varying the amount of manure input to the liquid manure system and varying the time required for the surface application of manure produced very small changes in the cost of operating the system and in the optimum manure storage structure size.

A hand-held programmable calculator program was developed which is capable of determining the optimum manure storage structure size for any given dairy farm. The calculator program utilized a branch and bound type algorithm and produced results generally comparable to those obtained with the linear programming model.

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CHAPTER I

INTRODUCTION

The proper management of dairy manure is receiving greater emphasis on Tennessee dairy farms than in the past. This emphasis is motivated by a number of factors which do not appear to be transitory. 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 regulation stemming from environmental concerns was passed at the state and federal level. Until recently Tennessee pollution control guidelines required that the yearly production of no more than two mature dairy animals be spread on a single acre of land per year. Dairymen whose land is in close proximity to waterways will likely come under more extensive regulation in the future.

Increased energy costs and labor scarcity also have had an impact on Tennessee dairy waste systems. McCarty (8) determined 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. Poor weather intensifies the conflict between labor requirements of manure management and other more pressing labor requirements during the planting and harvesting seasons. Paralleling the increased cost of fossil fuels, 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 three general types of waste management systems utilized on Tennessee dairy farms are the solid storage/daily haul system, the lagoon system, and the liquid manure system. Each of these systems has evolved to meet a specific need on dairy farms.

In 1980 the solid storage/daily haul system was the most widely utilized system in Tennessee and met the need for a low cost waste disposal system. It 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). However, it is more labor intensive, less flexible with respect to labor, and less capable of meeting strict pollution standards than the lagoon or liquid manure systems. A 1974 Massachusetts study (1) indicated that "given a choice among alternative disposal systems, the daily spreading method of manure disposal proved to be the most economical system." Although the solid storage/daily haul system preserves part of the nutrient value of manure, this goal is secondary to the goal of disposing of dairy manure at minimum cost.

The lagoon system is often the most expensive alternative for Tennessee dairymen. Based upon the 1973 price level and a 100 milking cow herd, Henderson (5) estimated the annual 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, with greater flexibility, than other systems.

Because the liquid manure system is designed primarily to exploit the nutrients found in dairy manure, it is 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.

> Farmers who handled all of their manure in liquid form in free-stall barns usually built a completely new housing and feeding facility for all of their cows. When liquid manure systems were operated with stanchion barns, the system was simply added on without expanding diary cattle housing. When all feeding was done in the barn, the manure was all handled as liquid. If part or all of the feeding was done in the yards, yard manure was either hauled conventionally or scraped into storage trucks whenever it thawed. (6)

Many dairymen, regardless of their existing housing or feeding system, have conventional manure handling equipment which is still operational when they convert to a liquid system. "Some dairymen prefer to build less than a full liquid manure system to gain experience and later install an additional storage structure." (6) Often dairymen build what would otherwise be considered a smaller than optimum storage structure due to the uncertainty of expanding the dairy herd. Although the effects of housing and feeding practices on the operation of a dual liquid/daily haul manure disposal system, the costs associated with removal of manure from the barn and yards to the collection pit, and the disposition of conventional manure handling equipment are important considerations, they were not incorporated in this study. The barn and

yard cleaning operations were excluded from this study to avoid treating each liquid manure system, which utilized a different barn and yard cleaning operation, as a separate system. To do otherwise would have created an impractical number of types of liquid manure systems that differed from one another in marginal ways. The economic analysis of liquid manure systems in this study began at the point where manure entered the storage structure.

Research Objectives and Procedure

There were four principal research objectives in this study:

1. To formulate a linear programming (LP) computer model of a liquid manure and commercial fertilizer application system.

2. To determine the effect of manure storage structure type, commercial fertilizer price, manure injection, field dispersity, and a specific pollution control standard on the optimum manure storage structure size for a given dairy farm.

3. To test the validity of the model with respect to key parameters, stochastic in nature, whose values were specified by assumption.

4. To write an algorithm for a hand-held programmable calculator which produced results equivalent to those obtained with the linear programming model.

The optimum manure storage structure size for a given dairy farm was determined from a simultaneous solution to the following equations:

$$c = f(x,y)$$

$$x = g(c,d)$$

where c = the annual per unit cost of the manure storage structure

x = the size of the manure storage structure

y = the type of manure storage structure (i.e., metal, earthen, or concrete stave)

d = a set of characteristics specific to a given dairy farm (i.e., herd size, acreage, and crop mix)

When variables y and d are fixed the equations can be plotted as in Figure 1. The x-axis represents the size of the manure storage structure in gallons. The c-axis represents the per unit cost of the manure storage structure in mills, which are tenths of 1 cent. The functions depicted are for illustration only. The intersection of the functions indicates that, for this example, the optimum manure storage structure size is 200,000 gallons.[1]

Theoretically, the functions may have no point of intersection or may have multiple points of intersection. In the case of multiple points of intersection, each point of intersection must be examined to determine at which point the combined cost of operating the liquid manure system and the cost of meeting the plant nutrient requirements on the given dairy farm are minimized.

The first equation, $c = f(x,y)$, describes the cost of manure storage as a function of structure size and type. The equation was obtained by fitting a line to cost data obtained from New York dairymen (16). The second equation, $x = g(c,d)$, describes the size of manure

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[1]Throughout this dissertation graphs similar to Figure 1 are displayed. When the objective is to determine an optimum manure storage structure size, both functions, $c = f(x,y)$ and $x = g(c,d)$, are displayed. When the objective is to determine the effect of a parameter such as manure nutrient composition on optimum manure storage structure size, only shifts of the function, $x = g(c,d)$, are displayed.

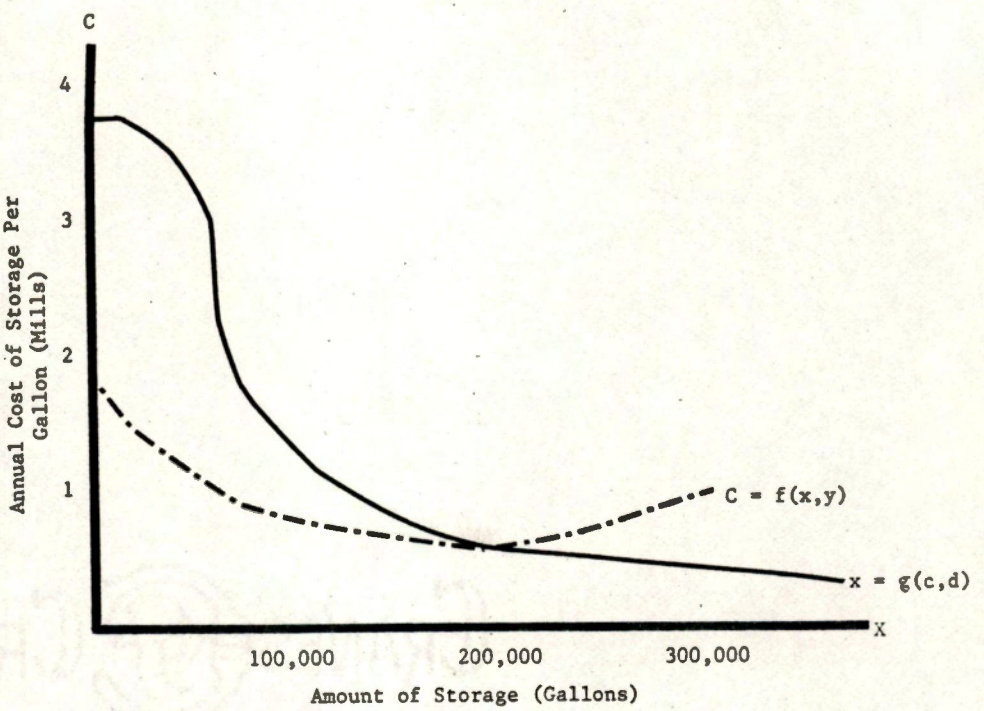


Figure 1. Determination of Optimum Manure Storage Structure Size

storage structure, which minimizes cost,[2] as a function of the cost of manure storage and the characteristics of the given dairy farm. The equation can be obtained by fitting a line to solution points obtained from multiple runs of a linear programming model.

The LP model of a liquid manure and commercial fertilizer application system contained four types of activities: (1) manure application in time period i to acre j of field k; (2) commercial fertilizer application to acre j of field k; (3) manure storage from time period i to time period i + n; and (4) labor required in time period i. Input data for the LP model was obtained from farms synthesized from Tennessee and North Carolina farm planning data. Successive computer runs of the model, with the per unit cost of manure storage incremented each time, provided the data points for fitting equation $x = g(c,d)$.

The LP model was tested for validity by systematically varying selected technical parameters (d) and noting any effect on the function, $x = g(c,d)$ and the cost of operating the liquid manure and commercial fertilizer application system. Erratic or implausible changes in system cost or the function, $x = g(c,d)$, were considered indications of an invalid LP model.

An additional model of a liquid manure and commercial fertilizer application system was formulated utilizing a compact format of input data. The compaction of input data was necessitated by the limited storage capacity of hand-held programmable calculators. The model included a small branch and bound type algorithm which evaluated a

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[2] Includes the cost of operating the liquid manure system and the cost of meeting the plant nutrient requirements of cropped acreage on the given dairy farm.

subset of all possible activities (e.g., manure application in time period i to acre j of field k) and selected the activity which increased system cost the least. Each activity was outputed on a thermal printer as it was selected, reducing the requirement to store the solution within the calculator. Selection continued until all constraints had been met. Solutions obtained with the hand-held calculator were compared to those obtained with the LP model in order to evaluate the accuracy of the hand-held calculator model.

Review of Literature

This review of literature was limited to research completed after 1965 which dealt with the determination of least-cost dairy waste management systems. Three general approaches to determining a least-cost liquid manure system have been used: (1) farm survey and statistical analysis; (2) economic engineering analysis; and (3) computer programming analysis.

Kimball (6) used survey information to study 43 Wisconsin dairy farms in 1970 that utilized liquid manure systems. The effects of the type of housing and the availability of conventional manure handling equipment upon the cost of four liquid manure systems were analyzed. The four systems were: (1) free-stall/all liquid; (2) free-stall/part conventional; (3) stanchion/all liquid; and (4) stanchion/part conventional.

Kimball found that the rank of each system, based on annual operating cost, varied depending upon the cost assumed for labor and the labor intensity of each system. While he did not adjust the cost of each system for the fertilizer value of nutrients preserved, he did

utilize the value of manure as a substitute for commercial fertilizer in determining whether an all liquid or part conventional system was more economical and how large a herd was needed to "pay for" a liquid manure system.

In 1966 Morris (10) used the economic engineering approach in determining a least-cost liquid manure system. Three types of liquid manure systems were considered: (1) below-ground storage; (2) above-ground storage; and (3) lagoon. Information from farm equipment dealers and research reports was utilized to determine the cost of removing manure from the production area, conveying the manure to storage, storing the manure, removing it from storage, and spreading it. Morris valued manure at the cost of an equivalent amount of commercial fertilizer and concluded that "in general the scale and efficiency of the operation and prevention of dilution of the manure determine if the manure can be spread in the fields at a cost equal to or less than the value of the nutrients used by the crop."

Coote (4) modified a large LP model of a dairy farm in 1973 to study dairy waste management. He included predictive equations for erosion and water-borne losses of nitrogen and phosphorus in the modification. These losses were subsequently verified using field data. The model was run in two stages to determine if the economic objectives of manure management were in conflict with the environmental objectives of reduced pollution. The first stage was the identification of farm management policies that maximized net revenue. The second stage imposed hypothetical manure disposal and fertilizer regulations and determined the income-maximizing decisions and environmental effects associated with such regulations. Losses in farm income associated with

the regulations were determined and their effectiveness in controlling environmental pollution was estimated.

The primary variable in Coote's model was a land use activity, e.g., growing crop i on field j. Soil type and crop rotation were explicitly considered. The model was run for a single year and crop acreage was constrained so that each crop within a rotation was represented in equal proportions on each soil.

When crop yield, nutrient requirements, and manure application rate for each activity were considered variable, Coote's model was highly nonlinear. To obtain linearity, a number of assumptions were made. Since the part of nitrogen in manure in organic form is not available to plants until it is mineralized, Coote estimated the mineralization rate for a period long enough for the organic matter fraction of the soil to stabilize. Coote's mineralization figure was based on a soil manure system in equilibrium and assumed that manure unmineralized in the year of application was balanced by mineralized manure remaining from previous applications.

Norstedt (12) utilized a dynamic programming algorithm to schedule the time and determine the rate of manure application to land. Norstedt's dissertation research, completed in 1969, focused on manure storage. The solution for each time period was constrained by storage capacity, the quantity of waste which had been generated, and the land area available for spreading manure. A sensitivity analysis was performed on variables in the model. Both nutrient effectiveness as a function of time and land availability significantly affected the optimum schedule for manure application to land. The cropping program was a critical factor in determining the minimum storage capacity

required. Norstedt suggested that future research should incorporate a labor availability constraint.

In 1977 Safley (16) utilized a third type of computer programming analysis for selection of least-cost manure management systems. Network analysis was used to rank 33 dairy waste management systems according to their net annual cost. Net annual cost for each system was defined as the sum of annual fixed labor and energy cost minus the value of the manurial nutrients produced by the dairy herd. The computer program was designed to provide a waste management service for New York dairymen. Users of the service specified the number of days or storage capacity desired; the type of barn cleaning equipment desired; the size of manure spreader desired; the size of tractors available for manure management activities; the average distance to the field and the time required to get there; the type of road and field conditions; and the associated costs including fuel, fertilizer, and labor.

The Safley model was operated in two stages. The first stage ranked all possible waste management systems and selected a subset as feasible alternatives for the farm in question. The second stage determined the optimum system for the user's farm utilizing a four-period LP model with constraints on land, labor, and manure in each time period. Each time period represented three months.

CHAPTER II

THE LINEAR PROGRAMMING MODEL

The LP model of a liquid manure and commercial fertilizer application system is described in this chapter. An explanation of each part of the model is accompanied by a derivation of its associated cost, time requirement, and contribution to satisfaction of constraints. In a separate section the assumptions and limitations of the LP model are reviewed. The chapter concludes with a discussion of how the LP model was utilized to attain the research objectives of the study.

The LP model of a liquid manure and commercial fertilizer application system was developed in two steps. In the first step cost budgets, technical restrictions, machine specifications, and state regulations were assembled and assumptions were formulated. In the second step, components of the first step were formulated into the following linear function, subject to a finite set of linear inequality constraints.

$$\min z = \sum_{i=1}^{m} \sum_{j=1}^{o} \sum_{k=1}^{p} \alpha_{ijk} u_{ijk} + \sum_{j=1}^{o} \sum_{k=1}^{p} \beta_{jk} v_{jk} + \sum_{i=1}^{m} \phi_i w_i + \sum_{i=1}^{m-1} \sum_{\ell=2}^{m} \psi_{i\ell} x_{i\ell} + \lambda y$$

subject to:

1. $\psi_{i\ell} = 0$ all i and ℓ[3]

2. $\sum_{i=1}^{m-1} x_{i\ell} \pm y$ $\ell=2, 3, \ldots, m$ and $i < \ell$

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[3]Constraint prevents "double counting" of the cost of storing manure.

$$3.\quad \sum_{j=1}^{o}\sum_{k=1}^{p} u_{ijk} - \sum_{\ell=2}^{m} x_{i\ell} = A_i \quad i=1, 2, \ldots, m \text{ and } i < \ell$$

$$4.\quad \sum_{j=1}^{o}\sum_{k=1}^{p} a_{ijk}\, u_{ijk} - w_i \leq B_i \quad i=1, 2, \ldots, m$$

$$5.\quad \sum_{i=1}^{m} b_{ijk}\, u_{ijk} + c_{jk}\, v_{jk} \geq C_{jk} \quad \text{all } j \text{ and } k$$

$$6.\quad \sum_{i=1}^{m} d_{ijk}\, u_{ijk} + e_{jk}\, v_{jk} \geq D_{jk} \quad \text{all } j \text{ and } k$$

$$7.\quad \sum_{i=1}^{m} f_{ijk}\, u_{ijk} + g_{jk}\, v_{jk} \geq E_{jk} \quad \text{all } j \text{ and } k$$

$$8.\quad \sum_{i=1}^{m} u_{ijk} \leq F_{jk} \quad \text{all } j \text{ and } k$$

where z equals total cost

i indexes time periods

j indexes each field

k indexes each acre within each field

u_{ijk} indicates an application of manure (in gallons to acre k of field j in time period i

α_{ijk} equals the cost of an application of manure per gallon to acre k of field j in time period i

v_{jk} indicates an application of commercial fertilizer (per acre requirement) to acre k of field j

β_{jk} equals the cost of an application of commercial fertilizer (per acre requirement) to acre k of field j

w_i indicates a requirement for additional labor in time period i

ϕ_i equals the cost of additional labor in time period i

$x_{i\ell}$ indicates a storage of manure from time period i to time period ℓ

ψ_i equals the cost of storing manure from time period i to time period

y indicates the size of the manure storage structure (in gallons)

λ equals the per unit cost of the manure storage structure

A_i indicates the amount of manure which must be disposed of in time period i (in gallons)

a_{ijk} indicates the amount of time per gallon to apply manure to acre k of field j in time period i

B_i indicates amount of labor normally available for manure application in time period i

b_{ijk} indicates the amount of nitrogen supplied per unit of manure applied to acre k of field j in time period i

c_{jk} indicates the amount of nitrogen supplied per unit of commercial fertilizer applied to acre k of field j

C_{jk} equals the amount of nitrogen required by acre k of field j

d_{ijk} indicates the amount of phosphorus supplied per unit of manure applied to acre k of field j in time period i

e_{jk} indicates the amount of phosphorus supplied per unit of commercial fertilizer applied to acre k of field j

D_{jk} equals the amount of phosphorus required by acre k of field j

f_{ijk} indicates the amount of potassium supplied per unit of manure applied at acre k of field j in time period i

g_{ijk} indicates the amount of potassium supplied per unit of commercial fertilizer applied to acre k of field j

E_{jk} equals the amount of potassium required by acre k of field j

F_{jk} equals the maximum amount of manure which can be applied to acre k of field j according to state pollution control regulations.

Time Required for Manure Application

In order to estimate the time required per gallon of manure application,[4] the following equation was formulated:

$$T = \frac{XA}{V} + 2\ \frac{XP}{V} + \frac{XK}{V} + \frac{XD}{FV} + \frac{XD}{RV} + \frac{.5XE}{FV} + \frac{.5XE}{RV} + \frac{.5XL}{REV} + \frac{.5L}{RE} + \frac{.5XL}{FEV} + \frac{.5L}{FE} + \frac{XL'}{FEV} + \frac{XL'}{REV}$$

where T = time required per gallon of manure application in seconds

X = amount of manure in gallons applied to the field

V = volume of the manure spreader in gallons

A = time in seconds for manure agitation prior to initiation of spreading

P = time in seconds for filling the manure spreader

K = time in seconds for emptying the manure spreader

D = distance in feet from storage to center of nearest field boundary

F = speed of travel to the field in feet per second

R = speed of travel returning from the field in feet per second

E = effective width of the field in feet

L = area of current application in square feet

L' = area previously covered in the field in square feet

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[4] This was the amount of time for which a labor cost was paid and did not necessarily equal clock time.

Given the manure application rate desired for a specific field and the number of acres within the field to which manure has previously been applied, the total amount of time associated with the manure application activity including agitation, loading the manure spreader, application of manure to the fields, and return of the spreader to the storage site was estimated.[5] Due to the variety of terrain, slope, and field conditions existing on Tennessee dairy farms, some idealization of the manure spreading operation was necessary.

E, the effective width of the field, referred to the minimum width of the field from front to back. The term $\frac{XA}{V}$ described the time associated with agitating an amount of manure before beginning to empty the storage structure. The term $\frac{XP}{V}$ described the amount of time required in transferring manure from the storage structure to the liquid manure spreader. The term $\frac{XK}{V}$ described the amount of time required to empty the manure from a liquid spreader onto the field. The term $\frac{XT}{FV}$ described the amount of time required in moving the liquid manure spreader from the storage structure to the center of the effective width of the field. The term $\frac{XT}{RV}$ described the amount of time required in moving the liquid manure spreader from the center of the effective width of the field back to the storage structure. The terms $\frac{.5L}{RE}$, $\frac{.5XL}{REV}$, $\frac{.5L}{FE}$, $\frac{.5XL}{FEV}$, $\frac{.5XE}{FV}$, and $\frac{.5X}{RV}$ described the time consumed while moving within the field prior to and subsequent to actual manure spreading. The terms $\frac{XL'}{FEV}$ and $\frac{XL'}{REV}$ described the time consumed while moving through acres within the field that received an application of manure in a previous

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[5]Since the time required for commercial fertilizer application and manure storage was not constrained, time requirements per unit activity for these operations were not estimated.

time period. The term $\frac{XA}{V}$, reflecting the time consumed while agitating manure prior to the onset of spreading operations, was not multiplied by two because this period of agitation normally required the labor of only one man. The activities associated with the other terms were assumed to require the labor of two men and were therefore multiplied by two.

The clock time required to complete an application of 9,180 gallons of manure to an acre of land is shown in Table 1. Approximately 9,180 gallons of manure were required to meet the plant nutrient requirements of an acre of corn silage, when applied 11 months prior to planting. The time required was inversely related to the size of the liquid manure spreader and directly related to the distance between the manure storage structure and the field. Over the range of distances depicted, a five-fold increase in distance, between the storage structure and the field, increased time required with an 800 gallon spreader 3.28 times and increased time required with a 4,500 gallon spreader 2.38 times.

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 budgets were constructed for each size of equipment. (See Tables 2 and 3.)

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

TABLE 1. Time Required to Apply 9180 Gallons of Manure to an Acre of Land by Size of Manure Spreader and Distance to the Field [1]

Distance to Field (ft.)	Time for 800 Gallon Spreader (min.)	Time for 1625 Gallon Spreader (min.)	Time for 2222 Gallon Spreader (min.)	Time for 3265 Gallon Spreader (min.)	Time for 4500 Gallon Spreader (min.)
2000	160	90	72	56	47
4000	251	135	105	78	63
6000	343	180	138	101	79
8000	434	225	171	123	96
10,000	525	270	203	146	112

[1]The field was assumed to have a minimum width of 2000 feet; speed of travel to the field was assumed to be 5.86 fps and the speed of return travel was assumed to be 14.67 fps; for all spreader sizes a 1950 gpm filling rate, a 520 gpm emptying rate, and a 3250 gpm rate of agitation were assumed.

TABLE 2. Determination of User Cost per Gallon of Manure for Liquid Manure Handling Equipment Based Upon Manure Production From a 60 Milking Cow Dairy Farm and 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
1625 Gal. Spreader	5,100	6	850.00	637.50	191.25	1,678.75	.003728
2222 Gal. Spreader	8,827	6	1,471.77	1,103.38	331.01	2,905.56	.006452
3264 Gal. Spreader	10,688	6	1,781.33	1,336.00	400.80	3,518.13	.007812
4500 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.

TABLE 3. 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 ($)	Estimated Hours of Use Annually (Hrs.)	Diesel Fuel Consumption Rate (gpm)	Fuel/Oil[1] Filter Cost ($)	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	498	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 Ft. Fert. Spreader	1,213	60	-	-	202	182	46	6.66

[1]Fuel price of $.87 plus 15% 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.

1. The annual cost of the liquid manure spreader.

2. The annual cost of the manure agitation pump.

3. The cost of labor.

4. The cost per unit time for the tractor utilized in manure agitation.

5. The cost per unit time of an additional tractor utilized for land application.

The cost was calculated as follows:

1. Items 1 and 2 (above) were divided by the total number of gallons of manure handled by the system during a year.

2. Item 3 was calculated from an estimate of the labor time required per gallon of manure application.

3. Item 4 was multiplied by an estimate of the agitation time required per gallon of manure application.

4. Item 5 was multiplied by an estimate of the land application time required per gallon of manure application.

5. The above conversions were summed.

The technique for determining the cost of surface-applying manure with an 800 gallon liquid manure spreader can be illustrated with the following values:

1. An annual cost of an 800 gallon liquid manure spreader, retailing for $3,800.00, of $1,250.83.

2. An annual cost of a 60 horsepower (hp) manure agitation pump, retailing for $3,766.00, or $1,459.83.

3. A labor cost of $3.00 per hour.

4. A cost of tractor manure agitation time of $8.75 per hour.

5. A cost of tractor land application time of $8.75 per hour.

6. A labor time requirement of 27.75 minutes per manure spreader load.

7. An agitation time requirement of 14 minutes per manure spreader load.

8. A land application time requirement of 13.75 minutes per manure spreader load.

9. A total of 450,338 gallons of manure handled by the system.

With the above values, the cost of surface-applying manure per gallon, with an 800 gallon liquid manure spreader, was determined to be: (1,250.83/450,338) (1,459.83/450,338) + (27.75/60) (3/800) + (14/60) (8.75/800) + (13.75/60) (8.75/800) = $ .0128

The technique for determining the cost of surface-applying manure with a 4,500 gallon liquid manure spreader can be illustrated with the following values:

1. An annual cost of a 4,500 gallon liquid manure spreader, retailing for $13,940.00, of $4,588.58.

2. An annual cost of a 60 hp manure agitation pump, retailing for $3,766.00, of $1,459.83.

3. A labor cost of $3.00 per hour.

4. A cost of tractor manure agitation time of $8.75 per hour.

5. A cost of tractor land application time of $17.58 per hour.

6. A labor time requirement of 46.94 minutes per manure spreader load.

7. An agitation time requirement of 24.16 minutes per manure spreader load.

8. A land application time requirement of 22.78 minutes per manure spreader load.

9. A total of 450,338 gallons of manure handled by the system.

With the above values, the cost of surface-applying manure per gallon, with a 4,500 gallon liquid manure spreader, was determined to be: (4,588.58/450,338) + (1,459.33/450,338) + (46.94/60) (3/4,500) + (24.16/60) (8.75/4,500) + (22.78/60) (17.58/4,500) = $ .0162

Cost of Commercial Fertilizer Application

The cost of commercial fertilizer application was estimated for corn silage, alfalfa, timothy hay, permanent pasture, and summer pasture uisng standard fertilizer recommendations. The estimated cost of commercial fertilizer for corn silage is shown in Table 4. Using the cost estimation technique, as shown in Table 4, 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.[6]

Cost of Manure Storage

The cost of manure storage was determined from 1978 cost data on manure storage purchase prices reported by Safley (16). This cost data is listed by storage structure size and type in Table 5. Notice that for 149,600 gallons of storage, the cost of a concrete stave structure was approximately 17.5 times the cost of an earthen storage structure. On many farms, the soil structure precludes earthen storage structures.

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[6] Alfalfa required 10 pounds N, 90 pounds P_2O_5, 180 pounds K_2O. Timothy hay required 30 pounds N, 90 pounds P_2O_5, 90 pounds K_2O. Permanent pasture required 30 pounds N, 90 pounds P_2O_5, 90 pounds K_2O. Summer pasture required 120 pounds N, 60 pounds P_2O_5, 60 pounds K_2O.

TABLE 4. Estimated Cost for Meeting the Plant Nutrient Requirements of an Acre of Corn Silage with Commercial Fertilizer

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

TABLE 5. 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 from an unpublished dissertation by Safley (16).

[2]Asterisk indicates no observation. The respective size and type were not encountered during the survey.

Per unit storage costs diminished with increasing storage structure size for all types of structures. At approximately 300,000 gallons 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 for each type and size of structure are depicted in Table 6. 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.

Nitrogen Supplied by Manure

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. Three pathways of nitrogen loss were evaluated for this period of time: volatilization, leaching, and run-off.

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.

Nitrogen leaching loss is often assumed to be a residual, i.e., the difference between the amount of nitrogen applied per unit area and the amount of nitrogen contained in the harvested crop per unit area. This assumption best describes leaching loss during the time between the beginning of nutrient uptake by the crop and the harvesting of the crop. This loss occurs whether the source of nitrogen is commercial

TABLE 6. Estimated Annual Cost of Manure Storage per Gallon by Size and Type of Structure, 1978[1]

Size of 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 price obtained from an unpublished dissertation by L. M. Safley (16).

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

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

[4]Asterisk indicates no observation for the respective size and type.

fertilizer or manure. Leaching of nitrogen from field-applied manure between the time of application and the time when commercial fertilizer would otherwise be applied was assumed equal to nitrogen input to the soil from rainfall (see Buckman and Brady, 1965, p. 430).

Nitrogen runoff loss is caused by the same soil-water dynamics which account for soil erosion. A loss of 2 percent of the nitrogen, remaining after allowing for volatilization loss, 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 (7).

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

Unless otherwise stipulated, the nitrogen, phosphorus, and potassium content of manure as produced was assumed to be .0426, .0076, and .0280 pounds/gallon, respectively, approximately the values reported by the Midwest Plan Service (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, reducing 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 as-produced phosphorus content of dairy manure was divided by .44 to acquire the P_2O_5 equivalency. The as-produced potassium content of dairy manure 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.

Phosphorus and Potassium Supplied by Manure

The phosphorus and potassium 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. Only one pathway of nutrient loss was assumed to apply to phosphorus and potassium.

Phosphorus runoff loss of 2 percent of the phosphorus present in fresh manure was assumed to occur for every month between the month in which the manure was applied and the month in which commercial fertilizer would otherwise have been applied. A runoff loss of 2 percent per month was also assumed for potassium (7).

Plant Nutrients Supplied by Commercial Fertilizer

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 since it was not applied until the onset of plant nutrient uptake.

Plant nutrient uptake and application of commercial fertilizer were assumed to occur in March. In meeting the plant nutrient requirements of cropped acreage, the LP model allowed the joint application of manure and commercial fertilizer to the same land.

Right-Hand Side

The right-hand side of constraints in the linear programming model depended upon information concerning the number of fields on a dairy farm, the cropping system on the farm, the NPK requirement of each crop/field combination, the amount of labor available for manure management during each time period, the cost of this labor, the stock of dairy animals on the farm, and the applicable pollution standard. In this study, the necessary information was synthesized from farm planning manuals (14, 19) to reflect a cross section of dairy operations in Tennessee. The manner in which this data was synthesized is described in the next chapter.

Assumptions and Limitations of Model

The LP model developed for this study was based on the following additional assumptions and limitations:

1. 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 manurial nutrients not available were balanced by residual nutrients from previous applications of manure which became available during the year.

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

3. An outdated pollution control guideline, which required that manure from no more than two mature dairy animals be spread on a single acre of land, was incorporated as a constraint in the model.

4. Each liquid manure spreader, regardless of size, was assumed to have a 1,950 gpm filling rate and a 520 gpm emptying rate; manure spreading was assumed to be completed in a direction normal to the longest field dimension; the speed of the manure application and the width of application were assumed to be consistent with the equation formulated to estimate the amount of time required for applying manure.

5. The material 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 unless necessary to attain a 90 percent moisture content prior to emptying the storage structure.

6. Manure agitation was assumed to be at a rate of 3,250 gpm; the time required for agitating manure, prior to beginning land spreading operations, was determined by dividing the amount of manure to be spread by 3,250; the size of the power unit required for agitation was assumed to be 60 PTOHP.

7. 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 of 87.3 percent as produced and of 90 percent as spread; in drylot 100 percent of the manure produced by milking animals was retained by the liquid manure system; on pasture the amount of manure retained varied by month according to the amount of animal confinement; the amount of manure retained from that produced by dry stock and young stock varied according to the amount of animal confinement.

8. Commercial fertilizer was assumed to be applied in March; nitrogen volatilization was assumed to be 50 percent for surface-applied manure; the plant nutrient loss rate (via runoff) was 2 percent

per month for each nutrient; it was assumed that no loss of plant nutrients occurred while manure was in storage.

9. Time utilized in hooking up, servicing, and repairing manure spreading equipment was not included in the model.

10. 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 percent prior to agitation and spreading.

11. Manure was not permitted to be allocated to fields containing crops until after the crop was harvested except for permanent pasture; runoff of manure, itself, was assumed to occur in negligible quantities; slope and other variables not specifically addressed were assumed to affect the loss of nutrients from field applied manure in negligible amounts.

Utilization of the Model

The optimum manure storage structure size for a given dairy farm was determined from a simultaneous solution to the following equations:

$c = f(x,y)$, the manure storage cost equation

$x = y(c,d)$, the manure storage size equation

where c = the annual per unit cost of the manure storage structure

x = the size of the manure storage structure

y = the type of manure storage structure (i.e., metal, earthen, concrete stave)

d = a set of characteristics specific to a given dairy farm (i.e., herd size, acreage, and crop mix)

The size equation [x = g(c,d)] was obtained by fitting a line to solution points obtained from parametric programming of the linear model. The cost equation [c = f(x,y)] was obtained by fitting a line to cost data originally obtained from New York dairymen (16).

The effect of manure storage structure type on the optimum structure size for a given dairy farm was determined by fixing the size equation and plotting a cost equation for each type of structure. The different simultaneous solutions obtained indicated the effect of storage type on optimum storage size.

The effect of commercial fertilizer price on the optimum manure storage structure size was determined by fixing the cost equation and plotting a separate size equation for each increase in commercial fertilizer price. The different cost equations were obtained by varying the cost of commercial fertilizer (β_{jk}) in the linear programming model.

The effect of the opportunity cost of labor on the optimum manure storage structure size was indicated by shifts in the cost equation. These shifts were obtained by inputing different costs for additional labor (ϕ_i) into the linear programming model.

The LP model was also utilized to determine the effect of labor wage rate on the optimum liquid manure spreader size for each of three synthetic Tennessee dairy farms described in the next chapter. For any given labor wage rate and type of dairy farm, there will be one spreader size with which the manure produced on the farm can be spread on farm fields at least cost. The relationshp between the labor wage rate on a farm and the size of spreader considered optimum for that farm was examined at four labor wage rates: 3, 4, 5, and 6 dollars per hour.

The effect of other variables such as the nutrient loss rate, manure retention rate, manure chemical composition, and time required for manure application on the optimum manure storage structure size were determined indirectly during the validation of the linear programming model itself. The LP model was tested for validity by systematically varying selected technical parameters (a_{ijk}, b_{ijk}, d_{ijk}, f_{ijk}) and noting any effect on the size function [$x = g(c,d)$] and the cost of operating the liquid manure and commercial fertilizer application system. Erratic or implausible changes in the system cost or the size function were considered indications of an invalid LP model.

CHAPTER III

APPLICATION OF MODEL TO SYNTHETIC DAIRY FARMS

An application of the linear programming model to three Grade A dairy farms is described in this chapter. The farms were synthesized to represent a range of viable Grade A dairy farms in Tennessee.

A 60 milking cow dairy farm, utilizing pasture, a 100 milking cow dairy farm, utilizing pasture, and a 100 milking cow dairy farm, utilizing a drylot system, were synthesized.

The herd composition of each farm was assumed to follow a pattern suggested by the Midwest Plan Service (MWPS). The ratio of milking cows to dry cows to heifers to calves to newborn calves was specified as 10/2/5/3/2. Herds were assumed to be Holstein animals. Manure production was assumed to be a function of animal weight. MWPS suggested that an average 1,000 pound dairy animal will produce 9.9 gallons of manure per day at a moisture content of 87.3 percent (9).

The percent confinement was utilized to estimate the monthly volume of manure input to the liquid manure system on each farm. A North Carolina planning guide (19) suggested the following percent confinement for dairy farms utilizing pasture: 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.

The amount of cropland on each farm was inferred from feed requirements of dairy budgets listed in a Tennessee farm planning guide (14). The requirements listed for a dairy farm, utilizing pasture,

with an average yearly milk production level of 13,000 pounds were:

1. 7.5 tons of corn silage per milk cow.
2. 2 tons of corn silage per heifer.
3. 1 ton of alfalfa per milk cow.
4. 1 ton of grass/clover per heifer.
5. .75 acre of permanent pasture per milk cow.
6. 1.5 acres of permanent pasture per animal unit of replacement stock.
7. .5 acre of summer pasture per milk cow.

The requirements listed for a dairy farm, utilizing a drylot, with an average yearly milk production level of 15,000 pounds were:

1. 12 tons of corn silage per milk cow.
2. 2 tons of corn silage per hiefer.
3. 1 ton of alfalfa per milk cow.
4. 1 ton of grass/clover per heifer.
5. 1.5 acres of permanent pasture per animal unit of replacement stock.

The productivity of cropland on each farm was inferred from crop budgets listed in the Tennessee farm planning guide (14):

1. Corn silage was produced at a rate of 15 tons per acre[7] when fertilized at the rate of 120 pounds N, 80 pounds P_2O_5, and 150 pounds K_2O per acre.

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[7]Not all land on Tennessee dairy farms will support these production levels. Fertilizer levels specified are what the crop requires for yields at the level specified.

2. Alfalfa was produced at a rate of 3.5 tons per acre[8] when fertilized at the rate of 15 pounds N, 90 pounds P_2O_5, and 180 pounds K_2O per acre.

3. Red clover/timothy hay was produced at the rate of 2.5 tons per acre[9] when fertilized at the rate of 30 pounds N, 90 pounds P_2O_5, and 90 pounds K_2O per acre.

4. Ladino fescue for permanent pasture was produced at a fertilizer rate of 30 pounds N, 90 pounds P_2O_5, and 90 pounds K_2O.

5. Summer pasture was produced at a fertilizer rate of 120 pounds N, 60 pounds P_2O_5, and 60 pounds K_2O.

Based upon the above feed requirements and land productivity, it was assumed that a 60 milking cow herd on pasture required 40 acres of corn silage, 21 acres of alfalfa, 12 acres of clover/timothy hay, 79 acres of permanent pasture, and 30 acres of summer pasture. A 100 milking cow herd on pasture required 67 acres of corn silage, 35 acres of alfalfa, 20 acres of clover/timothy hay, 132 acres of permanent pasture and 50 acres of summer pasture. A 100 milking cow herd on drylot required 87 acres of corn silage, 35 acres of alfalfa, 20 acres of clover/timothy hay, and 85 acres of permanent pasture.

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.

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[8] Ibid.

[9] Ibid.

The pollution constraint for each synthetic farm was assumed to be 11,498 gallons of manure per acre of cropland. The constraint was calculated by multiplying the assumed daily manure production of a mature dairy animal,[10] 12.4 gallons per day (gpd), by 365 days and increasing this figure by approximately 27 percent to reflect the increase in moisture content from 87.3 percent to 90 percent and multiplying this figure by 2.

The cost of commercial fertilizer application on the synthetic farm was calculated to be $61.66 per acre of corn silage; $47.85 per acre of alfalfa; $42.16 per acre of timothy hay; $42.16 per acre of permanent pasture; and $48.66 per acre of summer pasture. These costs were calculated using the plant nutrient requirements shown earlier and assumed a price of $.18/pound of N; $.23/pound of P_2O_5; and $.093/pound of K_2O.

The field dispersity was assumed to be equivalent on each of the synthetic farms. All fields were assumed to have a minimum width of 2,000 feet[11] and to be located 1,910 feet from the manure storage structure. Speed of travel to each field was assumed to be 5.86 feet per second (fps) and the speed of return travel was assumed to be 14.67 fps.

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[10]Mature dairy animals were assumed to weigh an average of 1,250 pounds.

[11]The cost of surface-applying manure reflects the minimum width of the field to which it is applied. As the width of a field increases, greater amounts of time are consumed in transit. As the width of a field decreases, greater amounts of time are consumed in turning. For an application of 9,180 gallons of manure per acre to a 20-acre field, the estimated cost of application was $2,436.63 if the field had a 2,000 foot width; $2,411.23 if the field had a 1,500 foot width; $2,396.41 if the field had a 1,000 foot width; and $2,423.87 if the field had a 500 foot width.

The monthly manure retention in gallons for each synthetic farm is listed in Table 7. Manure retention is defined as the amount of manure which is collected during barn and lot cleaning operations and input to the storage structure. The January manure retention for the 60 milking herd synthetic farm was calculated as follows:

1. The herd was composed of 60 milking cows, 16 dry cows, 30 heifers, 18 calves, and 12 newborn calves.

2. Manure production was assumed to be a function of animal weight.

3. Each milking cow was assumed to weigh 1,250 pounds, each dry cow 1,000 pounds, each heifer 800 pounds, each calf 300 pounds and each newborn calf 100 pounds.

4. A milking cow was assumed to produced 15.75 gallons of manure daily at 90 percent moisture content.

5. At 90 percent moisture dry cows produced 12.57 gallons daily, heifers produced 10.03 gallons daily, calves produced 3.81 gallons daily, and newborn calves produced 1.27 gallons daily.

6. The herd produced 1,480.56 gallons of manure daily at 90 percent moisture content.

7. The monthly manure retention for January was calculated by multiplying the daily herd production of manure (1,480.56 gallons) by the percent confinement for January (100 percent) by 365 (days) and dividing the entire product by 12, yielding an estimate of 45,034 gallons.

The manure nutrient composition assumed for manure production on all synthetic farms is listed on Table 8. Each entry shows the amount of elemental commercial fertilizer which could have been replaced

TABLE 7. Amount of Manure Retained by Liquid Manure Systems on Three Synthetic Tennessee Dairy Farms by Month

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/ Dry-Lot 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

TABLE 8. 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	.0239
NOV	.0155	.0125	.0245
DEC	.0158	.0128	.0250

[1]Assumes commercial fertilizer is replaced in the month of March, nitrogen in manure is subject to a 50% volatilization loss; and all elements are lost at a rate of 2% for each month between application and the month of March.

by a gallon of manure if it had been applied during the month indicated at the beginning of each row.

Optimum Manure Storage Structure Size

Application of the LP model to the three synthetic dairy farms showed that the optimum manure storage structure size was dependent upon a number of factors. Two of the more important factors were the size of the farm and the type of storage structure.

Dairy farms which plant large acreages of field crops have a greater requirement for commercial fertilizer than dairy farms planting small acreages. Since commercial fertilizer utilization on synthetic dairy farms was dependent upon the size of acreage planted, the value of manure as a substitute for commercial fertilizer was likewise dependent upon the size of acreage planted. The dependency extended to stored manure as well. On synthetic farms where stored manure had a higher value, larger manure storage structures were justified.

The relationship between farm size and optimum manure storage structure size is shown in Figure 2. A size equation [size = g(storage cost, farm parameters)] was plotted for each size of synthetic farm. A single cost equation [cost = f(storage size, storage type)] was plotted to represent the cost of earthen manure storage structures. The optimum manure storage structure size for each synthetic farm was determined from the intersection of the cost equation with the respective size equation.

Based upon 1978 prices, utilizing an earthen storage structure, the optimum amount of storage for the synthetic 60 milking cow dairy farm was 193,646 gallons or approximately 6 months storage. The

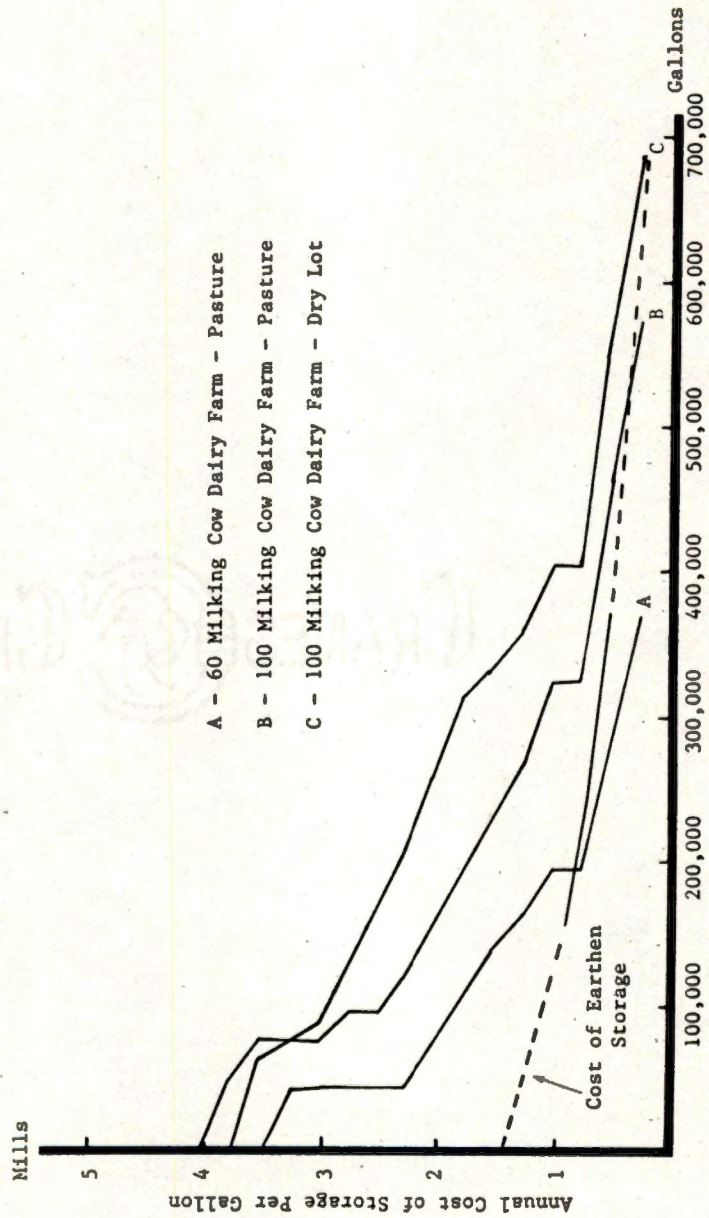


Figure 2. Amount of Storage Which Minimizes the Cost of Operating a Liquid Manure System and the Cost of Meeting the Plant Nutrient Requirements of Cropped Acreage by Type of Farm and Cost of Storage

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 synthetic 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 was explained by the fact that stored manure on the larger farms had a gerater value as a substitute for commercial fertilizer than it did on the smaller farms and by the fact that the annual cost of manure storage per gallon was a decreasing function of the storage structure size.

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 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 synthetic 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 for part of 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 2, 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, installation of the smallest size commercially available would minimize the cost of operating the liquid manure and commercial fertilizer application system. Larger metal or cement stave structures were justified on a cost basis when the cost of labor in a given time period was extremely high and the storage structure could have facilitated the transfer of the manure spreading labor requirement to a time period when labor was less costly. Even in these circumstances costs could have been further reduced by construction of an earthen storage structure, if permitted, since the fixed cost of the earthen structure was less than that of either the metal or concrete stave structures.

Effect of Fertilizer Price on Optimum Manure Storage

This study utilized a commercial fertilizer price of $.18/pound for N, $.23/pound for P_2O_5 and $.093/pound for K_2O in determining the optimum manure storage structure size for a given dairy farm. When

these prices were increased in isolation from the price of other inputs such as labor, fuel, or liquid manure system equipment, the optimum manure storage structure size for a given dairy farm increased.

This increase in optimum structure size is shown in Figure 3. A separate size equation [x=g(c,d)] was plotted for each commercial fertilizer price level. A single cost equation [c=f(x,y)] 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 runs of the linear programming model utilizing input data from the synthetic 60 milking cow dairy farm and assuming the utilization of a 2,222 gallon liquid manure spreader.

Based upon 1978 prices for an earthen storage structure, the otpimum amount of storage for a 60 milking cow dairy farm is 193,646 gallons (6 months storage) at the fertilizer prices stated above; 260,000 gallons (7.5 months storage) with a 10 percent or 25 percent increase in fertilizer prices; and 320,000 gallons (9 months storage) with a 50 percent increase in fertilizer price. It is unlikely that fertilizer prices will increase in isolation from other input prices. Coinciding increases in the price of labor, fuel, or liquid manure system equipment would tend to decrease the stated estimates.

Each size equation in Figure 3 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. The nutrient preservation capacity of the manure storage structure was

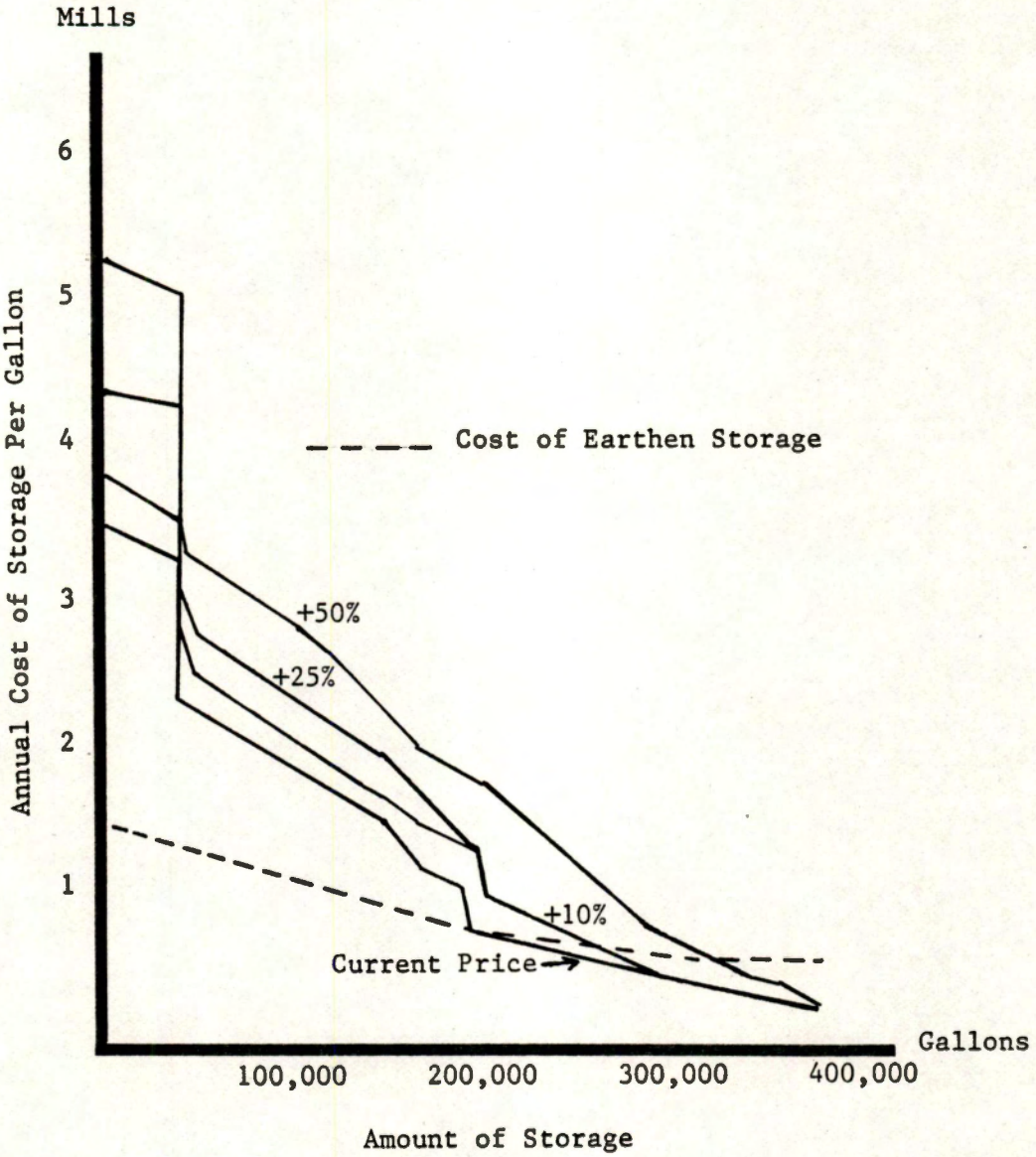


Figure 3. Effect of 10, 25, 50 Percent Commercial Fertilizer Price Increase on Optimum Storage Size for a 60 Milking Cow Dairy Farm.

maximized by loading it with manure produced in April--since this manure would otherwise have experienced the longest time period between application and nutrient uptake and thereby have experienced the greatest plant nutrient loss.

Each size equation in Figure 3 is a plot of solutions obtained from the linear programming model. The parallel segment corresponds to a range over which the optimum manure storage structure size was not sensitive to the cost of the structure itself. Each successively higher point on the parallel segment of the size equations indicates a higher annual cost of manure storage. This increase in the annual cost of the storage structure caused an increase in the cost of operating the liquid manure and commercial fertilizer application system. However, a greater increase would have occurred if the size of the storage structure had been made in response to the increase in the annual cost of the structure.

Effect of the Opportunity Cost of Labor

When labor is utilized for manure management, it is unavailable for use in other productive activities. While the wage rate paid to labor may be equal in manure management and the other productive activities, the financial return to each activity might be quite different. In the following analysis, the effect of the opportunity cost of labor on the optimum manure storage structure size for a given dairy farm is estimated. The analysis seeks to determine whether considerations of the opportunity cost of labor justify a more capital intensive structure than would be justified without such considerations.

An estimate of the total monthly labor requirement[12] for a 60 milking cow dairy farm, utilizing a daily haul manure management system, was obtained from a North Carolina dairy farm planning guide (19). It was assumed that labor had been allocated among the time periods to maximize profit and that the labor distribution was equivalent to what would be observed on a similarly sized Tennessee dairy farm. It was also assumed that the relative amount of labor required in a given time period was a reflection of the opportunity cost of labor in that time period. The opportunity cost of labor for the time period with the lowest labor requirement (July) was set at the assumed typical labor wage rate for Tennessee dairy farms of $3.00/hour. The opportunity cost of labor in other time periods was assumed to be higher and was estimated as the ratio of labor utilized in that time period (L) to the labor required in the least demanding time period (L'), multiplied by $3.00. This ratio could be simply the quotient of the labor requirements or to achieve a wider variation in opportunity cost values, it could be the quotient of the labor requirements to some power.

Table 9 shows the monthly opportunity cost of labor generated from the quotient of the labor requirement of the time period listed in column one and the July labor requirement $\frac{L}{L'}$ to the power of 0, 1, 4, and 10. For example, the opportunity cost of labor in March, when assumed to be a function of the ratio of labor requirements to the fourth power, was obtained by evaluating the expression, $(383/333)^4 \times 3$.

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[12]The estimated total monthly labor requirement was 408 hours for January, 383 hours for February, 383 hours for March, 416 hours for April, 413 hours for May, 354 hours for June, 333 hours for July, 431 hours for August, 452 hours for September, 397 hours for October, 415 hours for November, and 408 hours for December.

TABLE 9. Opportunity Cost of Labor Generated from the Ratio of Labor Required in the Given Month (L) to Labor Required in July (L') by Exponent and Month.

Month	Labor Cost Derived from $3\left(\frac{L}{L'}\right)^0$ ($/hr.)	Labor Cost Derived from $3\left(\frac{L}{L'}\right)^1$ ($/hr.)	Labor Cost Derived from $3\left(\frac{L}{L'}\right)^4$ ($/hr.)	Labor Cost Derived from $3\left(\frac{L}{L'}\right)^{10}$ ($/hr.)[1]
JAN	3.00	3.68	6.76	22.87
FEB	3.00	3.45	5.24	12.15
MAR	3.00	3.45	5.24	12.15
APR	3.00	3.75	7.31	27.77
MAY	3.00	3.72	7.10	25.83
JUN	3.00	3.19	3.83	5.52
JUL	3.00	3.00	3.00	3.00
AUG	3.00	3.88	8.42	39.57
SEP	3.00	4.07	10.18	63.68
OCT	3.00	3.58	6.06	17.40
NOV	3.00	3.74	7.24	27.11
DEC	3.00	3.68	6.76	22.87

[1]Levels of opportunity cost of these magnitudes are quite often obtained in optimizing farm plans estimated using linear programming techniques.

The effect of the opportunity cost of labor on the optimum manure storage structure size for a 60 milking cow farm, utilizing a 2,222 gallon spreader, is depicted in Figure 4. Four size equations were plotted; one for each power to which the labor ratio was raised. A cost equation for a storage structure fabricated from metal and a cost equation for a storage structure fabricated from concrete staves were also plotted. Only one intersection was observed. The cost equation for a metal structure intersects the size equation, generated from the labor ratio to the tenth power, at approximately 60,000 gallons or approximately 1.7 months of storage.

The lack of any other intersections indicated that the annual cost of metal and concrete stave manure storage structures normally exceeded the price at which cost savings could have been realized. A labor wage rate differential of $51.53 per hour was required before the cost of a 60,000 gallon metallic manure storage structure could be justified. This differential was attained when the opportunity cost of labor in March reached $12.15/hour and the opportunity cost of labor in September reached $63.68/hour.

Effect of Labor Wage Rate on the Optimum Manure Spreader Size

The relationship between the size of the liquid manure spreader utilized and the cost of operating a liquid manure and commercial fertilizer application system on the three synthetic farms is shown in Figures 5, 6, and 7. Spreaders with capacities of 800, 1,625, 2,222, 3,265, and 4,500 gallons were budgeted. Labor wage rates of 3, 4, 5, and 6 dollars per hour were considered. A separate computer run was made for each farm/spreader size/labor wage rate combination.

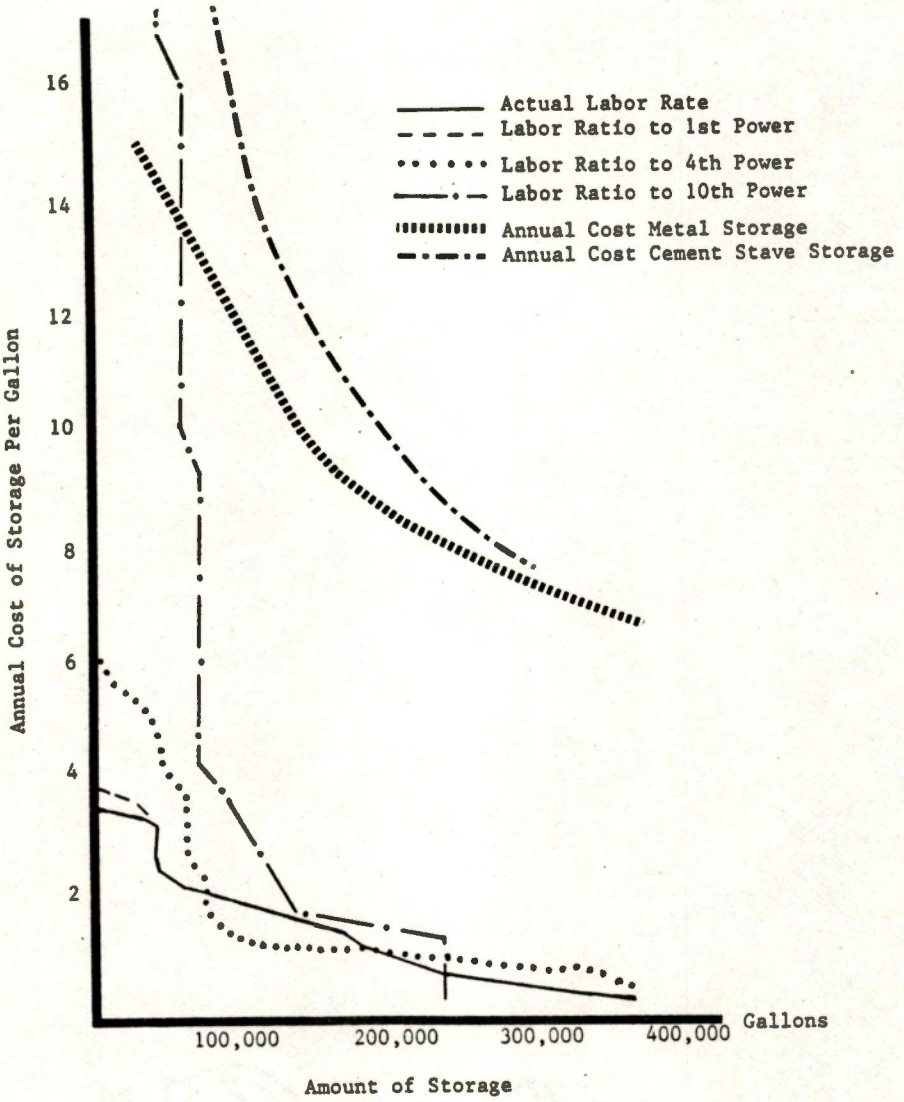


Figure 4. Effect of the Opportunity Cost of Labor on the Size and Type of Manure Storage Structure Minimizing the Cost of Operating a Liquid Manure System on a 60 Milking Cow (Pasture) Dairy Farm

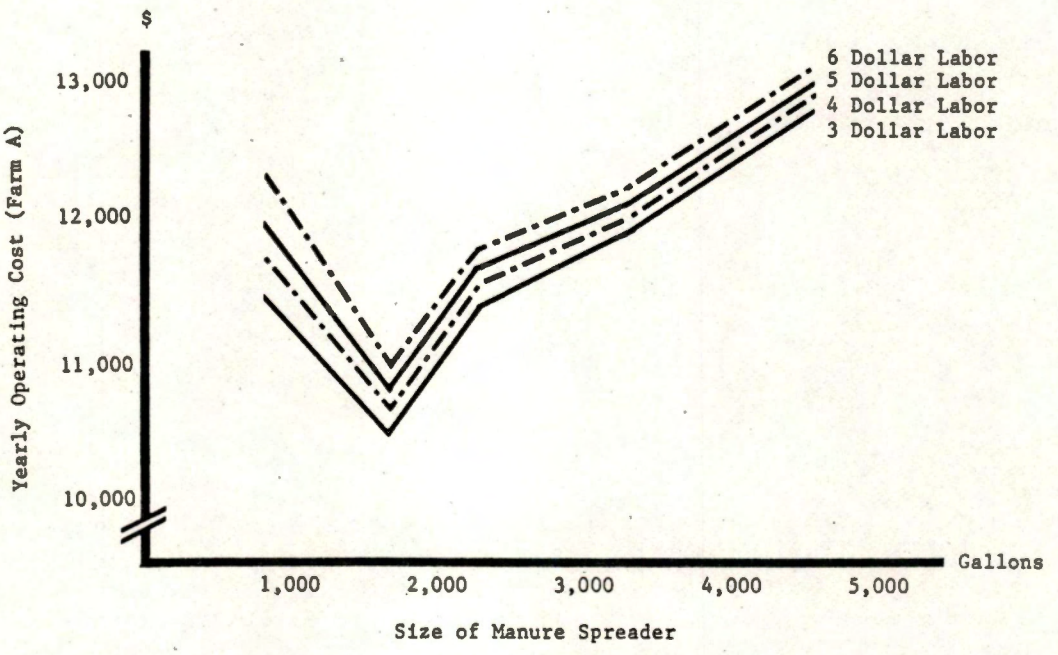


Figure 5. Cost of Operating a Liquid Manure System and Meeting Plant Nutrient Requirements of Cropped Acreage on a 60 Milking Cow Dairy Farm (Pasture) According to Labor Wage Rate Paid and Size of Liquid Manure Spreader Utilized

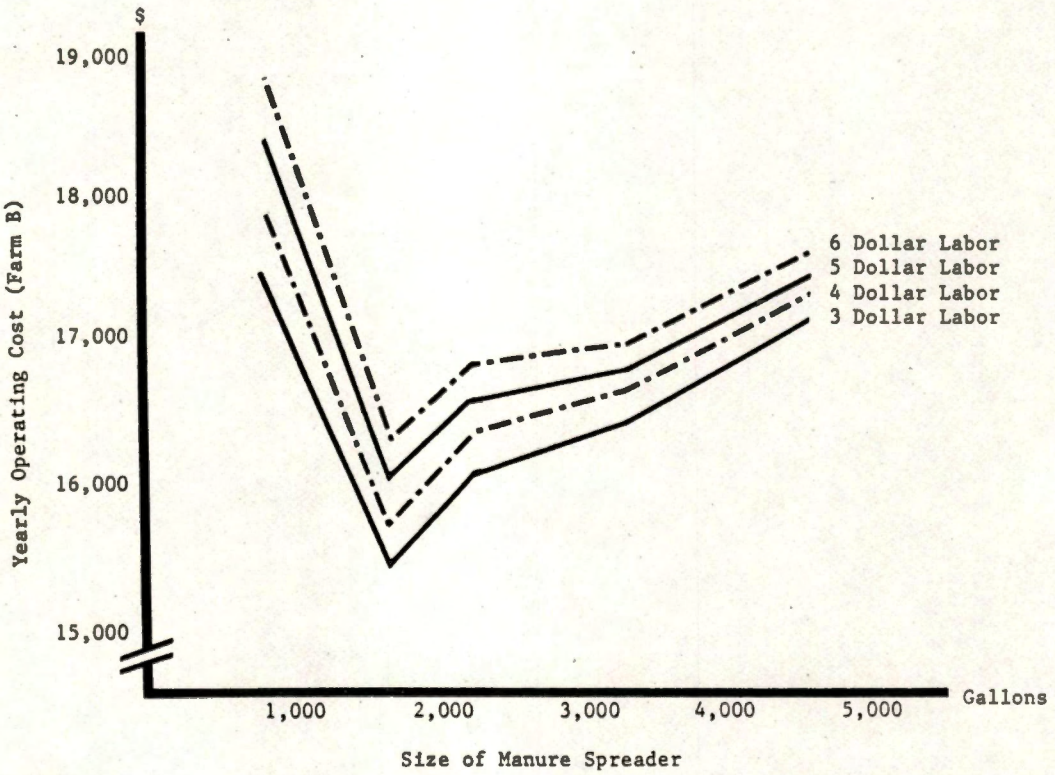


Figure 6. Cost of Operating a Liquid Manure System and Meeting Plant Nutrient Requirements of Cropped Acreage on a 100 Milking Cow Dairy Farm (Pasture) According to Labor Wage Rate Paid and Size of Liquid Manure Spreader Utilized

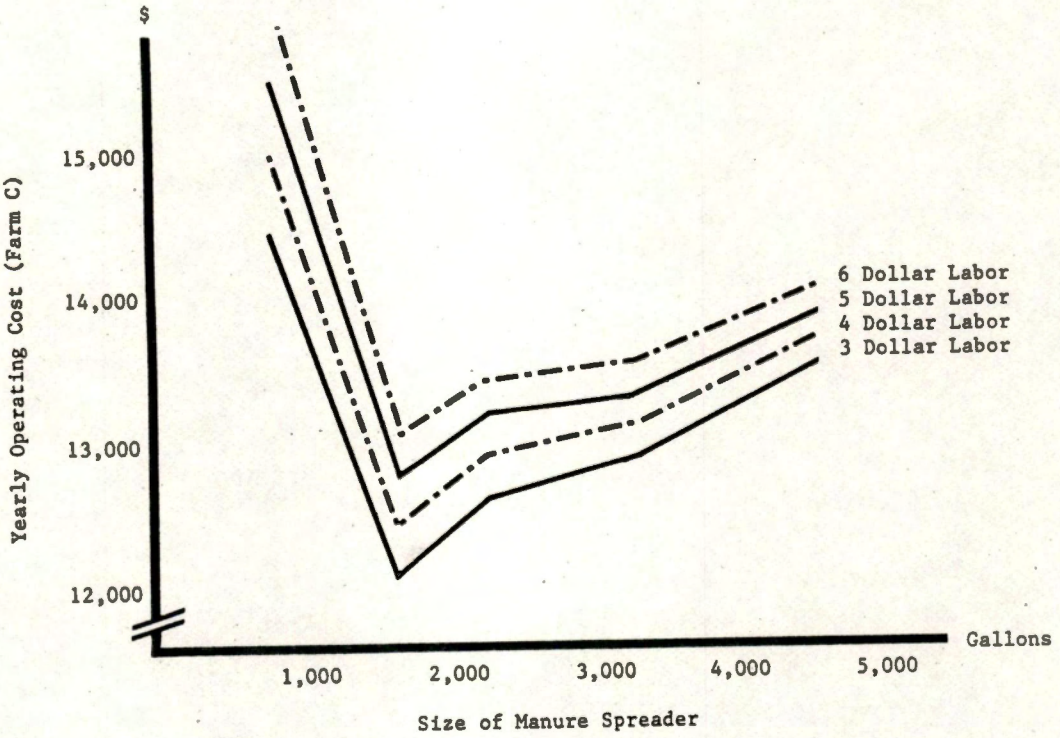


Figure 7. Cost of Operating a Liquid Manure System and Meeting Plant Nutrient Requirements of Cropped Acreage on a 100 Milking Cow Dairy Farm (Dry Lot) According to Labor Wage Rate Paid and Size of Liquid Manure Spreader Utilized

The results for a 60 milking cow dairy farm are shown in Figure 5. When a 1,625 gallon spreader was utilized and the labor wage rate was $3.00/hour, the yearly operating cost was approximately $10,500. Approximately $5,239 of this amount was the cost of commercial fertilizer including application. The cost of commercial fertilizer was constant for every spreader size/labor wage rate combination shown in Figure 5 because the allocation of manure was constant for each combination.[13]

The results for a 100 milking cow dairy farm, utilizing pasture, are shown in Figure 6. When a 1,625 gallon spreader was utilized and the labor wage rate was $3.00/hour, the yearly operating cost was approximately $15,500. Approximately $8,696 of this amount was the cost of commercial fertilizer including application. A constant level of 571,249 gallons of manure storage was incorporated in all results reported in Figure 6.

The results for a 100 milking cow dairy farm, utilizing drylot, are shown in Figure 7. When a 1,625 gallon spreader was utilized and the labor wage rate was $3.00/hour the yearly operating cost was approximately $12,100. Approximately $4,676 of this amount was the cost of commercial fertilizer including application. A constant level of

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[13]The allocation of manure on a given farm (application of manure to acre k of field j in time period i) remained constant unless the size of the storage structure changed. In order to minimize interaction between storage size and liquid manure spreader size, the annual cost of manure storage was set at a price level below which manure storage is normally available, $.00025 per gallon. A constant level of 373,778 gallons of manure storage was incorporated in all results reported in Figure 4.

686,761 gallons of manure storage was incorporated in all results reported in Figure 7.

The acquisition of a large liquid manure spreader may be motivated by the scarcity of labor in a certain time period or by the level of the wage rate for labor that is available in the time period. As indicated in Table 1 on page 18, the time required to spread a given amount of manure is inversely related to the size of the liquid manure spreader utilized. Increasing the size of the manure storage structure is another way of dealing with seasonal labor scarcity or with seasonally high labor wage rates. This analysis sought to determine the relationship between the labor wage rate and the optimum manure spreader size when the labor supply was adequate in all time periods and no seasonal variation in the labor wage rate existed.

For all farms and labor wage rates considered, use of the 1,625 gallon liquid manure spreader resulted in the lowest yearly operating cost. The yearly operating cost included all the expenses associated with meeting the nutrient requirements of the cropped acreage. Labor was included as one of the inputs for calculating operating cost. As the labor wage rate increased, the cost advantage of the 1,625 gallon spreader diminished. This can be inferred by comparing the slope between solution points for the 1,625 and 4,500 gallon spreaders at a labor wage rate of $3.00/hour to the slope between the same two spreader size solution points at a labor wage rate of $6.00/hour. This slope decreases with increases in the labor wage rate. At a very high labor wage rate, use of the 1,625 gallon spreader would not result in the lowest yearly operating cost.

CHAPTER IV

MODEL VALIDATION

To validate any kind of model means to prove that the model is a true representation of some existing system and that inferences based on the model are applicable to the existing system. Since there are various degrees by which any model can fail to describe a system, validation techniques often appraise the degree of confidence which can be placed in a model rather than outrightly accepting or rejecting the model.

Validation techniques vary in their requirement for empirical data. Techniques with small empirical data requirements will demonstrate the invalidity of a model without the expense and time associated with validation techniques requiring greater amounts of empirical data. Often these preliminary techniques will identify what specific empirical data needs to be obtained if more elaborate validation techniques are to be used.

Sensitivity analysis, which has a low requirement for empirical data, was the model validation technique utilized in this study.[14] The analysis was focused on model parameters whose assumed values lacked reliability, because the actual values of the parameters were stochastic and related to variables, exogenous to the model. Model parameters

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[14]The linear programming algorithm, itself, provided an initial test of model validity. When a feasible solution was found, the logical consistency of the constraints in the model was demonstrated. When an optimum solution was found, boundedness of the problem was demonstrated; therefore, the model could not produce nonsensical results such as negative manure storage structure size.

which lacked reliability included:

1. The moisture content of manure prior to land application.
2. The as-produced manure chemical composition.
3. The plant nutrient loss rate from field-applied manure.
4. The manure production and retention rate.
5. The time required for surface application of manure.

Sensitivity analysis of the linear programming model with respect to the above parameters was carried out by systematically varying the parameters (a_{ijk}, b_{ijk}, d_{ijk}, f_{ijk}), noting any effect on the size equation [x=g(c,d)] and on the cost of operating the liquid manure and commercial fertilizer application system (objective function value).

Had alterations in a parameter value produced large changes in system cost or optimum manure storage structure size, model validity would have been shown to depend upon explicit knowledge of the parameter value involved. Had alterations in a parameter value produced small changes in system cost or optimum storage structure size, the model would have been valid even for those farms on which the exact value of the parameter involved was unknown. Had alterations in a parameter value produced erratic or implausible changes in system cost or optimum structure size, an incorrect specification of the functional relationship between the parameter involved and other model variables would have been indicated.

Systematic changes in the values, assumed for the model parameters, produced no erratic or implausible effects on the size equation [x=g(c,d)] or on the cost of operating the system. However, the validity of the linear programming model was shown to depend upon

explicit knowledge of the moisture content of manure prior to land application and of the nutrient composition of manure as it was produced.

Moisture Content of Manure

The LP model assumed that all dairy farmers would increase the moisture content of manure from 87.3 percent, as it was produced, to 90 percent prior to land application. A 90 percent moisture content was 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. These increases in moisture content uniformly increased the cost of operating the liquid manure and commercial fertilizer application system. At an annual cost of 1 mill ($.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. 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. This analysis indicated that the LP model was sensitive to the parameter value assumed for the moisture content of manure as it was applied to the fields whether the increase in moisture content was purposeful to facilitate agitation or unintended rainfall or lot runoff.

Increases in moisture content shifted the size equation [x=g(c,d)] as shown in Figure 8. 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 was caused 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 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 manure 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.

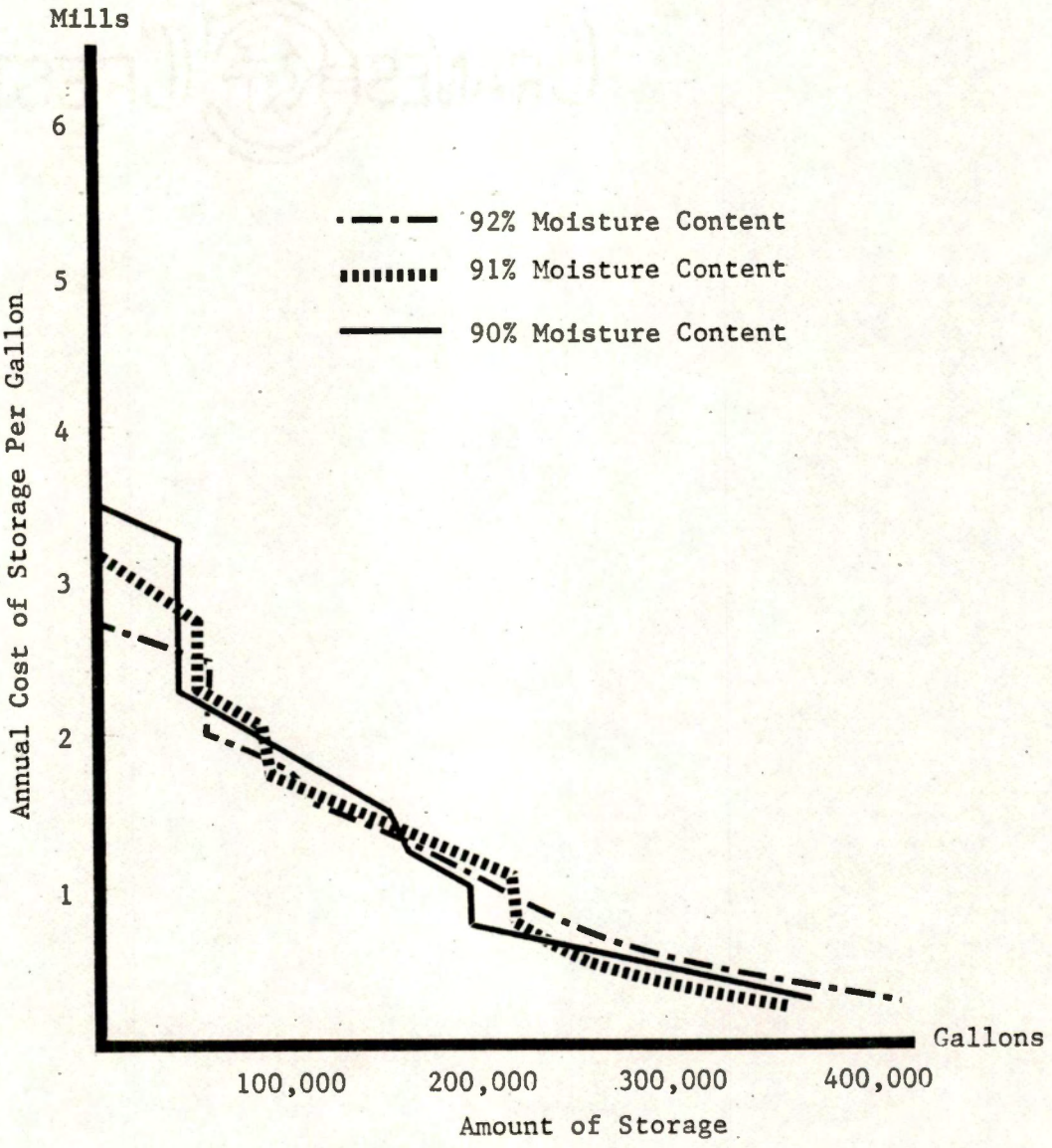


Figure 8. Amount of Storage Which Minimizes the Cost of Operating a Liquid Manure System and the Cost of Meeting the Plant Nutrient Requirements of Cropped Acreage on a 60-Milking Cow Dairy Farm According to the Final Manure Moisture Content and the Annual Cost of Manure Storage

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 storage structures constructed from metal were superior to 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 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. The LP model assumed that the nutrient content of manure as produced on synthetic 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, the operating cost of the system decreased from $11,568.81 to $9,742.59, at an annual cost for manure storage of 1 mill/gallon. When the assumed nutrient content was decreased to .0340 pounds N/gallon, .0075 pounds P/gallon, and .0144 pounds K/gallon,[15] the operating cost of the system

[15]Research literature (16) suggested that the N content of fresh dairy manure ranges from .0340 pounds/gallon to .0467 pounds/gallon. The P content ranges from .0075 pounds/gallon to .0166 pounds/gallon. The K

increased from $11,568.81 to $12,363.56, at 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.

Increasing and decreasing the as-produced nutrient content of manure shifted the size equation [x=g(c,d)] as shown in Figure 9. At an annual cost of .75 mill/gallon of manure storage, lowering the as-produced nutrient composition of manure[16] shifted the size equation from 193,646 gallons to 162,122 gallons. At an annual cost of .75 mill/gallon of manure storage, raising the as-produced nutrient composition of manure[17] shifted the size equation from 193,646 gallons to 234,176 gallons.

The shifts in the size equation were not uniform over the entire range of manure storage costs. The size equation was shifted down when the as-produced nutrient composition of manure[18] was raised and the annual cost of manure storage was greater than 1 mill/gallon. Costs greater than 1 mill/gallon for manure storage are justified mainly by the opportunity to store manure for subsequent application to corn silage land. When the as-produced nutrient composition of manure was

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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. According to the linear programming formulation utilized the value of manure as a substitute for commercial fertilizer is partially a function of the ratio of the nutrients contained in the manure.

[16]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.

[17]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.

[18]Ibid.

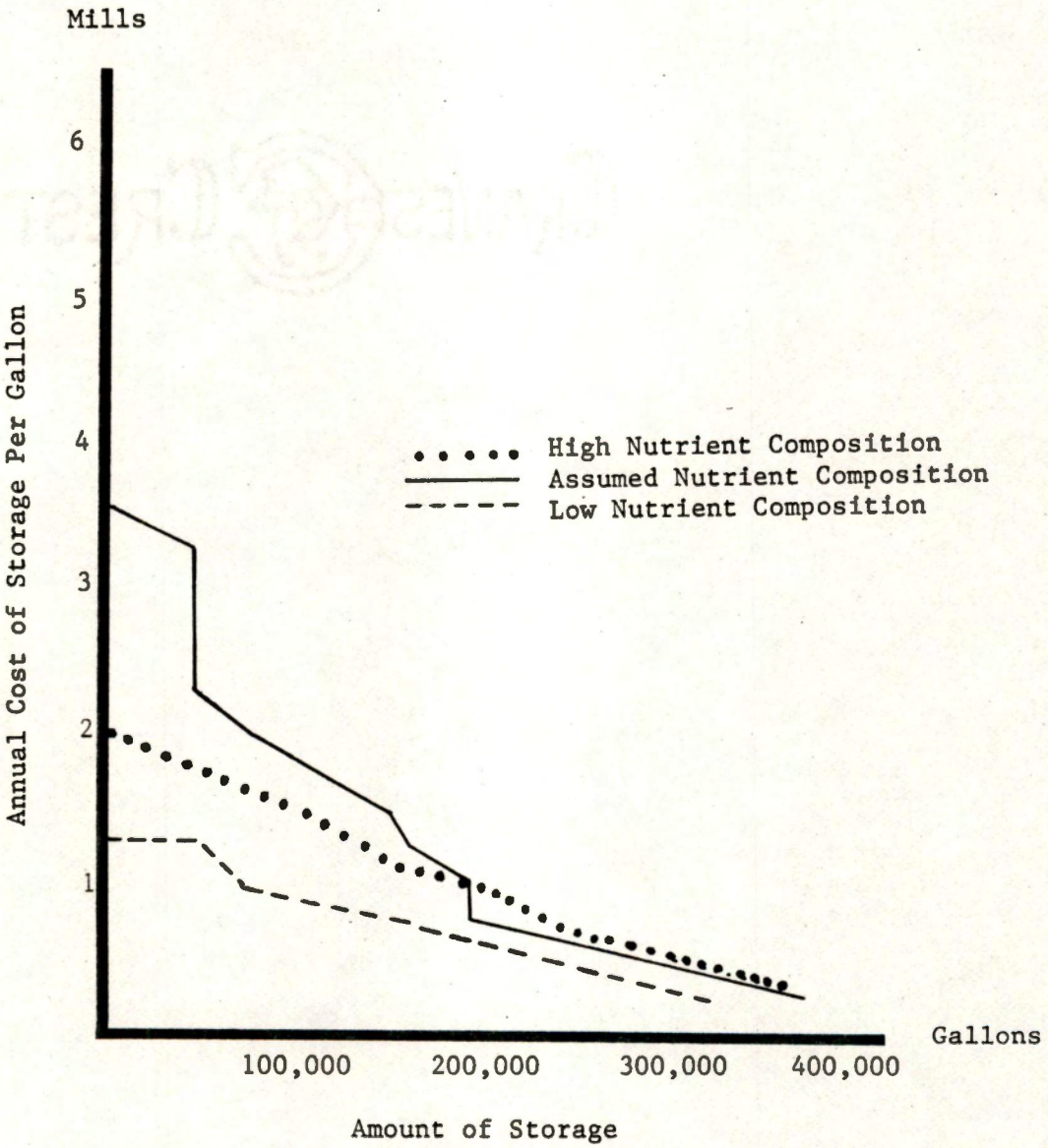


Figure 9. Amount of Storage Which Minimizes the Cost of Meeting the Plant Nutrient Requirements of Cropped Acreage on a 60 Milking Cow Dairy Farm According to the Initial Nutrient Composition of Manure and the Annual Cost of Manure Storage

raised[19] in the LP model, enough nutrients were produced during the time the corn silage land was open (October to March) to meet the corn silage land's nutrient requirements, making storage for subsequent application to corn silage land unnecessary.[20]

At costs less than 1 mill/gallon for manure storage, shifts in the size equation were in the expected directions. Increasing the as-produced nutrient composition[21] shifted the size equation up; decreasing the as-produced nutrient composition[22] shifted the size equation down. The cost of operating the liquid manure and commercial fertilizer application system was minimized by replacing as much commercial fertilizer 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 high 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.

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[19] Ibid.

[20] According to this logic, 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 unnecessary to store manure for that purpose.

[21] See footnote 17.

[22] See footnote 16.

Plant Nutrient Loss Rate from Field-Applied Manure

Nutrient loss from field-applied manure has shown great variation from year to year, often correlated with 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 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 [x=g(c,d)] as shown in Figure 10. Shifts, although occasionally large,[23] 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.

Manure Production and Retention Rate

The manure production rate assumed in the LP model was 9.9 gallons per day per animal unit (1,000 pound dairy animal). Safley reported examples of manure production rates which ranged from 8.536

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[23]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 279,210 gallons to 193,646 gallons. The cost difference represented by the two storage sizes was $20.98 or .2 percent.

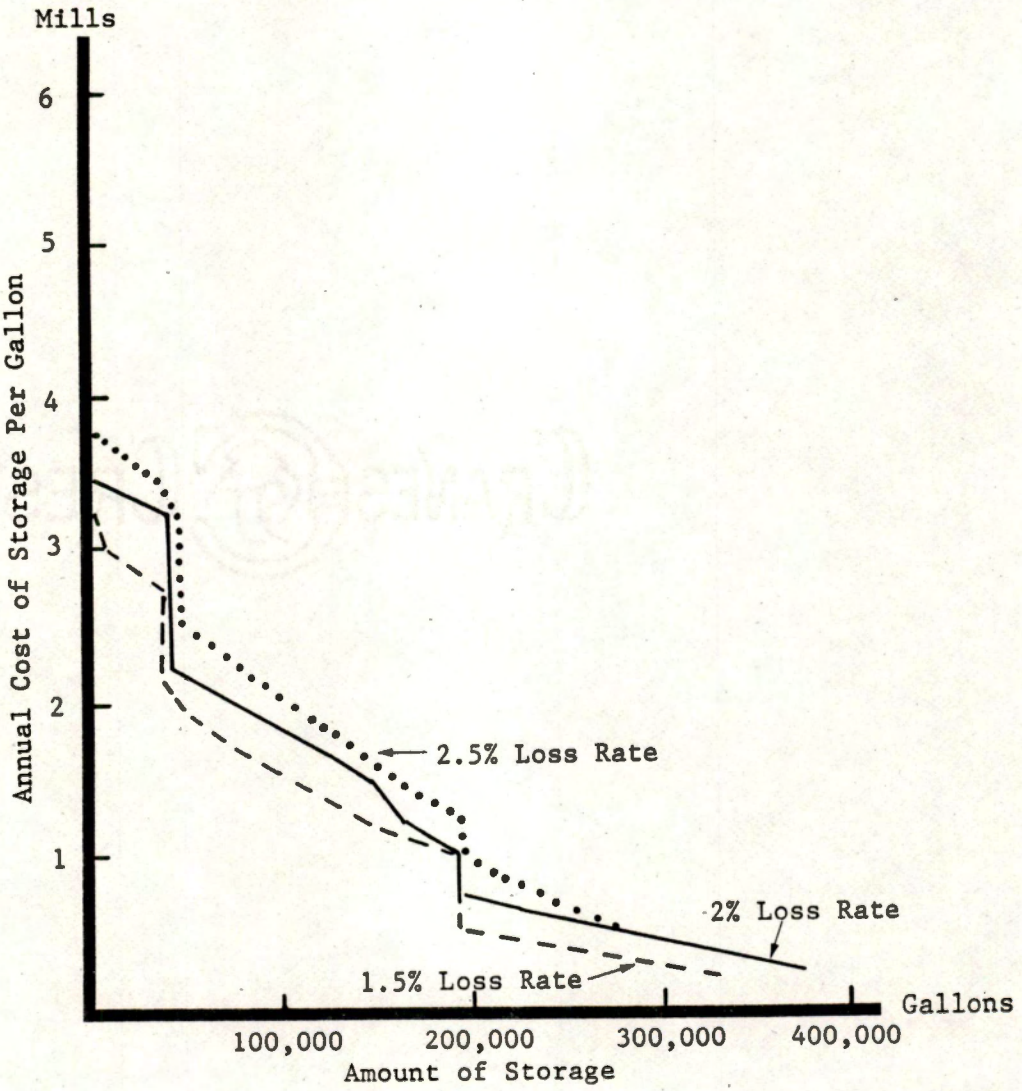


Figure 10. Amount of Storage Which Minimizes the Cost of Operating a Liquid Manure System and the Cost of Meeting the Plant Nutrient Requirements of Cropped Acreage on a 60 Milking Cow Dairy Farm According to the Plant Nutrient Loss Rate and the Annual Cost of Manure Storage

gallons/day/animal unit to 10.866 gallons/day/animal unit (16).[24] The manure retention rate assumed in the LP model, when applied to a dairy farm utilizing pasture, was: 100 percent in November, December, and January; 90 percent in October, February, March, and April; 70 percent in May, July, August, and September; and 60 percent in June.

Since alteration of either the manure production rate or the manure retention rate produced an alteration in the amount of manure input to the liquid manure system, the sensitivity of the LP model to the parameter value assumed for the manure production rate and the parameter value assumed for the manure retention rate were examined jointly. The analysis utilized two computer runs. The first run incorporated a 5 percent increase in retention over the assumed rate for months in which the assumed rate was not 100 percent. The second run incorporated a 5 percent decrease in retention under the assumed rate for months in which the assumed rate was not 100 percent.

Since manure was a more expensive source of plant nutrients than commercial fertilizer,[25] increases in the amount of manure input to the system increased the cost of operating the liquid manure and commercial fertilizer application system and vice versa. However, the LP model was shown to be insensitive to the parameter values chosen for the manure retention rate and the manure production rate when their cumulative

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[24]Production rates assume a manure density of 8.2828 pounds/gallon.

[25]Meeting the plant nutrient requirements (120 pounds N, 80 pounds P_2O_5, and 150 pounds K_2O per acre) of corn silage with commercial fertilizer cost $61.61 ($.18/pound for N, $.23/pound for P_2O_5, $.093/pound for K_2O, and $7.66 for application). Meeting these same nutrient requirements required 7,156 gallons of stored manure at a cost of $91.69, not including the cost of storage.

effect on the amount of manure input to the system ranged between plus 5 percent and minus 5 percent.

At an annual cost of 1 mill/gallon for manure storage, the cost of operating the liquid manure and commercial fertilizer application system was $11,679.91 with a 5 percent increase in the manure retention rate, $11,568.81 with the originally assumed manure retention rate, and $11,457.75 with a 5 percent decrease in the manure retention rate. Over the range of manure storage costs evaluated, the maximum alteration in the system cost caused by changing the manure retention rate was 0.96 percent.

Altering the manure retention rate shifted the size equation [x=g(c,d)] as shown in Figure 11. At an annual cost of 1 mill/gallon for manure storage, increasing the manure retention rate by 5 percent shifted the size equation from 193,646 gallons to 203,328 gallons. At the same cost for manure storage, decreasing the manure retention rate by 5 percent shifted the size equation from 193,646 gallons to 183,965 gallons.

The shifts in the size equation were not uniform over the entire range of manure storage costs. At costs greater than 1.75 mills/gallon of manure storage, decreasing the manure retention rate shifted the size equation up. At this level of cost, the location of the size equation was determined by how the plant nutrient requirements of corn silage land were met. When the manure retention rate was decreased by 5 percent, the amount of nutrients produced during the time the corn silage land was open (October to March), was insufficient to meet the corn silage land's nutrient requirements. Consequently, the amount of manure

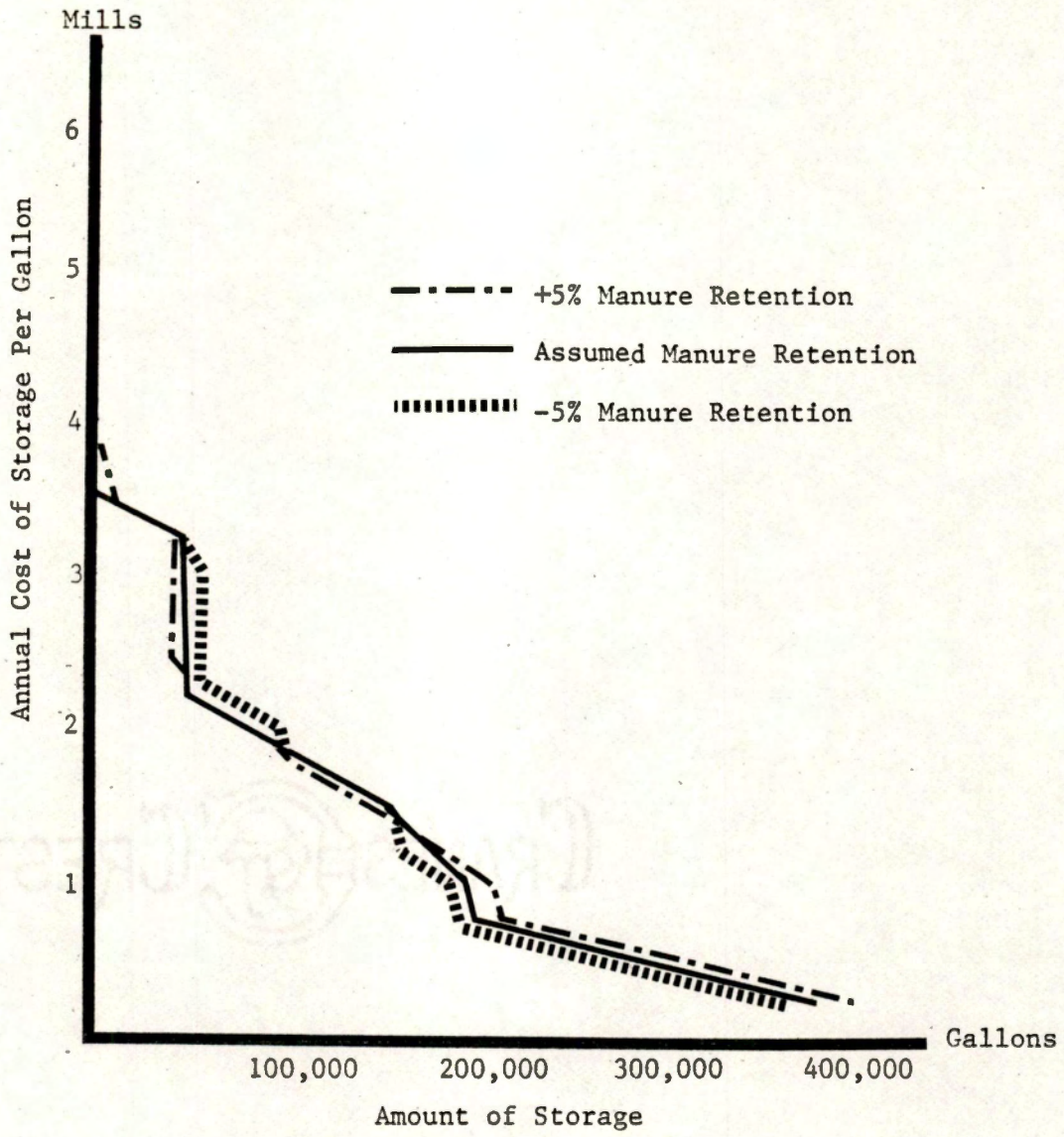


Figure 11. Amount of Storage Which Minimizes the Cost of Operating a Liquid Manure System and the Cost of Meeting the Plant Nutrient Requirements of Cropped Acreage on a 60 Milking Cow Dairy Farm According to the Manure Retention Rate and the Annual Cost of Manure Storage

which had to be stored for subsequent application to corn silage land was increased accounting for the upward shift.

Increasing the manure retention rate, at these cost levels, had the opposite effect. The size equation was shifted down since even more manure became available during the October to March period. At costs less than 1.75 mills/gallon for manure storage, shifts in the size equation were in the expected directions.

Time Required for the Surface Application of Liquid Manure

The time required for the surface application of liquid manure was central to estimating the cost of operating the liquid manure and commercial fertilizer application system. Since the equation utilized to estimate the time required for application disregarded such factors as terrain, slope, and field conditions, it was important to evaluate the sensitivity of the LP model to variations in the estimates provided by the equation.[26]

In Table 10 the base LP model solutions for the 60 milking cow (pasture) dairy farm are compared with solutions obtained for labor requirements 10 percent below and 10 percent above the base level. Optimum manure storage levels for each labor requirement level were obtained at 10 manure storage cost levels, ranging from .25 mill/gallon to 2.5 mills/gallon. The annual cost levels used are shown in column 1 of Table 10. The optimum amount of storage activity in solution for each cost of storage level and labor requirement level is shown in

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[26]Base labor requirements for different size spreaders and distances to fields were shown in Table 1 on page 18.

TABLE 10. Optimum Amounts of Storage and Objective Function Values for a 60 Milking Cow Synthetic Farm for Three Levels of the Time Required for the Surface Application of Manure

Annual Cost of Manure Storage ($)	Storage Amt. for Time Est. Less 10% (gal.)	Obj. Function Value for Est. Less 10% ($)	Storage Amt. For Time Est. (gal.)	Obj. Function Value for Time Est. ($)	Storage Amt. For Time Est. Plus 10% (gal.)	Obj. Function Value for Est. Plus 10% ($)
.00025	369,278	11,218	369,278	11,384	369,278	11,550
.00050	279,210	11,297	279,210	11,462	279,210	11,628
.00075	193,646	11,355	193,646	11,520	193,646	11,686
.00100	193,646	11,403	193,646	11,569	193,646	11,734
.00125	162,122	11,450	162,122	11,616	162,122	11,780
.00150	143,391	11,489	143,391	11,654	130,598	11,819
.00175	109,553	11,521	109,553	11,685	109,559	11,850
.00200	75,721	11,544	75,721	11,709	77,332	11,874
.00225	41,889	11,561	41,889	11,726	58,533	11,892
.00250	41,889	11,571	41,889	11,737	41,889	11,903

columns 2, 4, and 6. The objective function value[27] for each cost of storage level and labor requirement level is shown in columns 3, 5, and 7.

The LP model was shown to be insensitive to the values chosen for the time required for the surface application of manure within plus 10 percent and minus 10 percent of the original time estimates. The largest change in the optimum manure storage structure size, produced by an alteration in the time estimate, was 16,644 gallons at an annual cost of manure storage equal to 2.25 mills/gallon. The changes in the cost of operating the liquid manure and commercial fertilizer application system, produced by an alteration in the time estimate, were consistently on the order of $200 or roughly 1.7 percent.

Plant Nutrient Loss from Manure During Storage

The LP model assumed that no nutrient loss took place between the point in time when manure was placed in the storage and the point in time when it was removed from storage. Research has demonstrated that plant nutrient losses from manure do occur during storage (16).

The most compelling reason for assuming no nutrient loss during storage was to avoid modeling the parameters which control this loss: mean temperature, pH of stored manure, duration of storage and whether manure is top- or bottom-loaded. In addition it was not clear that a mechanism for estimating loss could be easily incorporated into the linear programming structure of the model.

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[27] The combined cost of manure disposal and supplying required plant nutrients for crops grown.

The validity of applying the model to Tennessee dairy farms, in spite of the no storage loss assumption, was based upon the knowledge that storage loss would be essentially limited to nitrogen volatilization loss which would occur between manure production and plant uptake of nutrients; it did not matter whether the nitrogen loss took place on the barn floor prior to scraping, took place in the storage structure, or took place on fields prior to plant uptake of nutrients.[28]

The LP model may not be valid for Tennessee dairy farms on which the cumulative effect of better barn cleaning operations, better storage, manure injection, and quick uptake of nutrients reduce the volatilization loss of nitrogen to less than 50 percent.

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 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.

Manure was allocated to an acre of land up to the point where the most limiting nutrient requirement was met. The LP model placed no value on 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 requirements

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[28]The average N loss from fermented manure between spreading and incorporation has been estimated at 20 percent after six hours, 25 percent after 24 hours, and 45 percent after 96 hours (18).

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. Supplementing manure with elemental commercial fertilizer, rather than blended commercial fertilizer, reduced the amount of manure utilized on a given acre of land; but the remaining manure had to be applied elsewhere.

The nutrient requirements for an acre of corn silage were assumed to be 120 pounds N, 80 pounds P_2O_5, and 150 pounds K_2O. The content of manure, after allowing for N volatilization loss, was assumed to be .01677 pounds N/gallon, .01358 pounds P_2O_5/gallon, and .0266 pounds K_2O/gallon. Consequently, 7,156 gallons of manure were required to meet the N requirement; 5,891 gallons of manure were required to meet the P_2O_5 requirement; and 5,635 gallons were required to meet the K_2O requirement.

The linear programming model produced a cost of $153.30 for meeting the plant nutrient requirements of two acres of corn silage. The first acre's nutrient requirements were fulfilled with 7,156 gallons of manure at a cost of $91.69 (7,156 x $.0128). The second acre's nutrient requirements were fulfilled with blended commercial fertilizer at a cost of $61.61.

Had elemental commercial fertilizer been utilized, two additional fertilizer/manure allocations would have been possible. The P_2O_5 and K_2O requirements of the first acre could have been met with 5,891 gallons of manure at a cost of $75.48 (5,891 x $.0128). Meeting the N requirements of the first acre would have required the application of 21.3 pounds of elemental N fertilizer at a cost of $3.83 (21.3 x $.18) plus $7.66 for application. The balance of the manure (7,196 - 5,891) would have been applied to the second acre at a cost of $16.21 (1,305 x $.0128). The cost of meeting the balance of the second acre's nutrient requirements would have been $17.78 for N, $14.45 for P_2O_5, $10.85 for K_2O, and $7.66 for application. This yielded a total cost of $153.92 for the two acres.

Another possible allocation was the application of 5,635 gallons of manure to the first acre, meeting only the requirement for K_2O. This allocation would have cost $85.25 for the first acre and $68.03 for the second acre. The total cost of $153.28 was slightly less than that obtained with the linear programming model ($153.30).

CHAPTER V

MANURE INJECTION

Many innovations have been developed to increase the efficiency of a liquid manure and commercial fertilizer application system. Some innovations reduced the amount of labor required to operate a system; other innovations increased the amount of commercial fertilizer replaced by manure. During this study the effects of one major innovation, manure injection, on the cost of operating a liquid manure and commercial fertilizer application system were analyzed. The results of this analysis are discussed in this chapter.

The analysis of manure injection was essentially a cost comparison of fertilizing corn silage with injected manure and of fertilizing corn silage with surface-applied manure. The total cost per acre for injection ($77.83) was lower than the total cost per acre for surface application ($101.43). However, the per gallon cost of injecting manure ($.0132) was higher than the per gallon cost of surface-applying manure ($.0128).

The higher application cost per gallon associated with manure injection was mainly due to the increased horsepower required to pull the manure injector through the soil. The power required for surface application of manure was 22.73 hp in sandy soil and 22.15 hp in clay soil. The power required for manure injection, with one injector, was 39.42 hp in sandy soil and 44.29 hp in clay soil.

In spite of the higher per gallon cost of manure injection, the per acre cost of manure injection was less than that of surface

application because injection reduced the amount of manure which had to be applied. The amount of manure applied was a function of the rate at which plant nutrients in manure were lost prior to the onset of plant nutrient uptake.

The plant nutrient requirements of corn silage utilized in the analysis was 120 pounds N, 80 pounds P_2O_5, and 150 pounds K_2O per acre. The amount of manure, at 90 percent moisture content, required to meet these requirements is shown in Table 11 according to the percentage of nutrient loss. For instance, if corn silage had been fertilized with manure, which had experienced a 10 percent loss of nutrients, 6,547 gallons would have been required.[29]

The plant nutrient loss percentage, utilized for manure injection in the analysis, was 5 percent. The pathways of nutrient loss were volatilization and runoff. The nutrient loss from runoff, when manure was injected, was assumed to be zero.[30] The loss of nitrogen via volatilization was assumed to be 5 percent. The 5 percent assumption was optimistic since 10 percent or more of the N present in manure may volatilize while it remains on the barn floor prior to cleaning operations. There is also the potential for volatilization loss of N while manure is in storage. According to the 5 percent loss rate for N and 0 percent loss rate for other nutrients assumed in the analysis, 5,891 gallons of

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[29]This manure requirement was consistent with the requirement contained in the linear programming model. Manure was applied until the limiting nutrient requirement, in this case P_2O_5, was met.

[30]Ross, et. al., found that injection of manure into the soil essentially eliminated any pollutant yield in the runoff from test plots as compared to surface application (15).

TABLE 11. Amount of 90% Moisture Content Manure Required to Meet the Plant Nutrient Requirements of an Acre of Corn Silage According to the Nutrient Loss Percentage

Percent of Nutrient Loss (%)	N Content of Manure (#/gallon)	Amount of Manure to Meet N Requirement (gallon)	P_2O_5 Content of Manure (#/gallon)	Amount of Manure to Meet P_2O_5 Requirement (gallon)	K_2O Content of Manure (#/gallon)	Amount of Manure to Meet K_2O Requirement (gallon)
0	.03355	3,577	.01358	5,891	.02662	5,635
5	.03187	3,765	.01290	6,202	.02529	5,931
10	.03019	3,974	.01222	6,547	.02396	6,260
15	.02852	4,208	.01154	6,932	.02263	6,628
20	.02684	4,471	.01086	7,366	.02130	7,042
25	.02516	4,769	.01019	7,851	.01997	7,511
30	.02348	5,111	.00951	8,412	.01863	8,052
35	.02181	5,502	.00883	9,060	.01730	8,671
40	.02013	5,961	.00815	9,816	.01597	9,393
45	.01845	6,504	.00747	10,710	.01464	10,246
50	.01677	7,156	.00679	11,782	.01331	11,270

manure were required to meet the plant nutrient requirements of an acre of corn silage.[31]

The plant nutrient loss percentage, utilized for the surface application of manure in the analysis, was 55 percent for N, 10 percent for P_2O_5, and 10 percent for K_2O. The loss of nutrients from surface-applied manure depended upon how long the period was between manure application and the onset of plant nutrient uptake. Manure was assumed to be applied in October, with the initiation of plant nutrient uptake occurring the following March. The 55 percent loss of N was composed of an assumed 50 percent volatilization loss and 5 percent runoff loss. A loss of 2 percent of the N, remaining in manure after volatilization, for each month between October (surface application) and March (plant nutrient uptake) was assumed. Accordingly 7,916 gallons of surface-applied manure were required to meet the N requirement of corn silage.

The nutrient loss of P_2O_5 and K_2O from surface-applied manure was composed entirely of runoff loss. A loss of 2 percent of P_2O_5 and K_2O for each month between October and March was assumed. Accordingly, 6,520 gallons of surface-applied manure were required to meet the P_2O_5 requirement of corn silage; 6,234 gallons of surface-applied manure were required to meet the K_2O requirement of corn silage. In order to meet all corn silage nutrient reuqirements, 7,916 gallons of surface-applied manure were required as compared to 5,891 gallons of injected manure.

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[31]Notice that the loss rate of N must reach 40 percent before a greater amount of manure is required. Assumptions of N loss at any value between 5 percent and 40 percent, to account for greater loss in storage or greater loss on barn floors prior to cleaning, would not have altered the analysis since 5,891 gallons of manure would have been required regardless.

The cost of meeting the plant nutrient requirements of an acre of corn silage[32] with injected manure was composed of the following items:

1. Annual cost of liquid spreader--$16.36
2. Annual cost of agitation unit --$19.09
3. Annual cost of injector unit --$ 2.18
4. Labor charge --$10.23
5. Tractor charge for agitation --$15.04
6. Tractor charge for injection --$14.93

The total per acre cost for injection was $77.83. On a clay soil the cost increased to $77.88. Utilizing two injectors increased the per acre cost to $79.95 for a sandy soil and $80.02 for a clay soil.

The cost of meeting the plant nutrient requirements of an acre of corn silage with surface-applied manure was composed of the following items:

1. Annual cost of liquid spreader--$21.99
2. Annual cost of agitation unit --$25.65
3. Labor charge --$13.74
4. Tractor charge for agitation --$20.20
5. Tractor charge for surface application --$19.85

The total per acre cost for surface application was $101.43. On a clay soil the cost increased to $101.38.

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[32]An 800 gallon liquid manure spreader with one injector was utilized. Corn silage was assumed to be grown on a sandy soil.

If a manure injection activity had been included in the LP model, the optimum manure storage structure size would have been reduced in every instance where manure was stored for subsequent application to corn silage acreage. Injection of manure increases the number of acres which can be fertilized with the manure produced between October and March. The study assumed 256,692 gallons of manure were produced between October and March on the synthetic 60 milking cow dairy farm. If surface-applied, 256,692 gallons of manure would have been sufficient for approximately 34 acres of corn silage. If injected, 256,692 gallons of manure would have been sufficient for approximately 44 acres of corn silage.

In the analysis manure had its greatest value as a substitute for commercial fertilizer when applied to corn silage. The 60 milking cow dairy farm was assumed to grow 40 acres of corn silage. Since the amount of manure produced between October and March, when the corn silage land was open, was insufficient to meet the total plant nutrient requirements of the corn silage acreage, manure was stored to meet the deficit. Had injection equipment been utilized on the farm, the amount of manure storage could have been reduced to 42,077 gallons or approximately one month's storage.

Manure injection may not be an alternative on certain types of land with heavy sod or in certain time periods due to the presence of standing crops. In these situations possession of manure injection equipment may not reduce the size of manure storage structure required.

CHAPTER VI

THE PROGRAMMABLE CALCULATOR MODEL

This chapter describes programming efforts to duplicate the results obtained with the linear programming model on a hand-held programmable calculator. The calculator utilized was a Texas Instruments Model 59. The primary obstacles encountered in developing a suitable model would have been similar if another calculator of comparable size had been utilized.

The greatest obstacle in developing the programmable calculator model was the small storage capacity of the calculator and the necessity of trading off memory (storage) for executable steps. The TI-59 can be operated with as few as 160 executable steps with 100 storage locations or as many as 960 steps with 0 storage locations.

In order to select the best ratio of executable steps to storage locations, it was necessary to determine which pieces of information were requisite to the model and to determine how this information could be fitted into the smallest possible number of storage locations. An additional objective was to structure the information in an expandable fashion so that if more storage locations become available through modification of the calculator, the structure of additional information would be totally compatible with the existing structure of information.

Input data for the model required 70 storage locations, restricting the size of the algorithm to 399 executable steps. The input data, utilized in optimizing the liquid manure and commercial fertilizer application system on the synthetic 60 milking cow dairy farm, is shown

in Table 12. The first group of 10 storage locations constitutes an internal directory of the location of certain bits of information and allows the algorithm to access specific information at any time. The next five groups of ten storage locations contain information on the five fields (crops) grown on the synthetic 60 milking cow dairy farm--one group of ten storage locations for each field (crop). Information such as commercial fertilizer application rates, size of the field, and the time/cost associated with manure spreading was included for each field. Up to a maximum of five fields may be modeled with the existing storage capacity of the calculator. If, however, more storage becomes available, due to modification of the calculator, the algorithm could handle additional fields providing each field is described with a group of ten storage locations structured in the same manner as the existing five groups. The last group of ten storage locations contained information including the production of manure, labor availability, and plant nutrient loss on a per time period basis. In the version used twelve time periods were modeled. With greater storage capacity a larger number of time periods could be programmed.

Coupling a thermal printer to the TI-59 was an important mechanism in reducing the number of storage locations necessary to duplicate the results of the linear programming model. As each result was determined by the algorithm, it was printed on thermal paper eliminating the need to provide additional storage locations for output data.

The algorithm utilized in the programmable calculator model could be described as a branch and bound type algorithm. Given a finite number of choices, i.e., application of as-produced manure to field i during time period j in amount k or application of stored manure to

TABLE 12. TI-59 Input Data for 60 Milking Cow Dairy Farm (Pasture)

Storage Location Number	Storage Content	Description of Storage Content
00	6	Counter for Do-Loop
01	1	Directory for indirect addressing
02	2	Directory for indirect addressing
03	3	Directory for indirect addressing
04	4	Directory for indirect addressing
05	5	Directory for indirect addressing
06	6	Directory for indirect addressing
07	7	Directory for indirect addressing
08	8	Directory for indirect addressing
09	0	Source of manure application activity output
10	0	Source of manure application activity output
11	61.66	Cost of applying commercial fertilizer to Field A
12	40	Number of acres in Field A
13	.0131092723	Cost per gallon of applying manure to Field A
14	.0000170672	Cost increment of manure application for Field A
15	.939191021	Time required in applying manure to Field A
16	.0046817157	Time increment of manure application for Field A
17	120	Pounds/acre of N required by Field A
18	.1	Availability of Field A in current time period
19	.01677	N in pounds supplied per gallon of manure
20	0	Not used
21	47.85	Cost of applying commercial fertilizer to Field B
22	20	Number of acres in Field B
23	.0131092723	Cost per gallon of applying manure to Field B
24	.0000170672	Cost increment of manure application for Field B
25	.939191021	Time required in applying manure to Field B
26	.0046817157	Time increment of manure application for Field B
27	113.387	Pounds/acre of N required by Field B
28	.1	Availability of Field B in current time period
29	.003	Annual cost of manure storage per gallon
30	0	Not used
31	42.16	Cost of applying commercial fertilizer to Field C
32	15	Number of acres in Field C
33	.0131092723	Cost per gallon of applying manure to Field C
34	.0000170672	Cost increment of manure application for Field C
35	.939191021	Time required in applying manure to Field C
36	.0046817157	Time increment of manure application for Field C
37	111.2	Pounds/acre of N required for Field C
38	.1	Availability of Field C in current time period
39	150,000	Time in seconds available for manure application in time period
40	40,530	Manure in gallons available for application in time period
41	42.16	Cost of applying commercial fertilizer to Field D

TABLE 12 (continued)

Storage Location Number	Storage Content	Description of Storage Content
42	80	Number of acres in Field D
43	.0131092723	Cost per gallon of applying manure to Field D
44	.0000170672	Cost increment of manure application for Field D
45	.939191021	Time required in applying manure to Field D
46	.0046817157	Time increment of manure application for Field D
47	111.2	Pounds/acre of N required by Field D
48	.1	Availability of Field D in current time period
49	0	Not used
50	0	Not used
51	48.66	Cost of applying commercial fertilizer to Field E
52	30	Number of acres in Field E
53	.0131092723	Cost per gallon of applying manure to Field E
54	.0000170672	Cost increment of manure application for Field E
55	.939191021	Time required in applying manure to Field E
56	.0046817157	Time increment of manure application for Field E
57	120	Pounds/acre of N required by Field E
58	.1	Availability of Field E in current time period
59	9999	Source of manure storage activity output
60	9999	Source of manure storage activity output
61	45,488.89	Seed for generating monthly production of manure
62	.8999999999	Multiplied times seed to determine manure production
63	.6969695969	Multiplied times seed to determine manure production
64	150,000	Seed for generating time available per time period
65	.9999999999	Multiplied times seed to determine time availability
66	.01677	Seed for generating N supply per gallon of manure
67	.9896949290	Multiplied times seed to determine N content
68	.8987858382	Multiplied times seed to determine N content
69	0	Source of manure storage size output

field i during time period j in amount k, it was known beforehand that certain sets of choices would dominate other sets of choices. For instance, the closest acreage to the storage structure would be allocated manure in preference to acreage further distant from the storage--all other things being equal. Only the dominant set of choices needed to be examined. With five fields (crops) modeled, the algorithm considered an application of manure to the first acre of each field with either as-produced or stored manure. This constituted 10 choices, each with its associated cost. The algorithm compared each of the 10 choices and selected the one which was least expensive. This choice was immediately output to the thermal printer, indicating whether manure was to be stored or applied as produced as well as the amount of manure and field of application. To avoid the computational problems of manure allocations to fractions of an acre, each allocation was specified on an acre basis. The algorithm utilized is shown in Table 13.

A number of techniques were considered for evaluating how well the results obtained with the programmable calculator model duplicated the results obtained with the LP model. Some confidence region could have been placed around the LP model solution. The programmable calculator model would have been considered adequate if the calculator solution had fallen within the specified confidence region. However, since linear programming solutions have no statistical basis, any established confidence region would be strictly subjective and highly arbitrary.
A second test of the adequacy of the programmable calculator model was its ability to mirror the solutions of the LP model throughout the range of relevant parameters, e.g., cost of storage, rate of manure production,

Table 13. TI59 Branch and Bound Manure Storage Size Optimization Algorithum

Executable Step Number	Step	Description of Executable Steps
000	76 LBL	
001	11 A	
002	97 DSZ	
003	00 00	
004	00 00	
005	08 08	
006	61 GTO	
007	13 C	
008	01 1	
009	32 X:T	
010	01 1	Increment Directory
011	00 0	
012	71 SBR	
013	03 03	
014	59 59	
015	73 RC*	Determine Field Availabilty
016	08 08	
017	65 ×	
018	01 1	
019	00 0	
020	95 =	
021	59 INT	
022	22 INV	
023	67 EQ	
024	12 B	
025	43 RCL	Is New Manure Spreading Activity Less Expensive ?
026	09 09	
027	32 X:T	
028	73 RC*	
029	03 03	
030	75 -	
031	53 (	
032	73 RC*	
033	01 01	
034	55 ÷	
035	53 (	
036	73 RC*	
037	07 07	
038	55 ÷	
039	43 RCL	
040	19 19	
041	54)	
042	54)	
043	95 =	
044	77 GE	No
045	12 B	
046	42 STO	Yes
047	09 09	
048	43 RCL	
049	03 03	
050	42 STO	
051	10 10	
052	76 LBL	
053	12 B	Is New Manure Storage Activity Less Expensive ?
054	43 RCL	
055	59 59	
056	32 X:T	
057	73 RC*	
058	03 03	
059	75 -	
060	53 (	
061	73 RC*	
062	01 01	
063	55 ÷	
064	53 (	
065	73 RC*	
066	07 07	
067	55 ÷	
068	43 RCL	
069	66 66	
070	54)	
071	54)	
072	95 =	
073	85 +	
074	43 RCL	
075	29 29	
076	95 =	
077	77 GE	No
078	11 A	Yes
079	42 STO	
080	59 59	
081	43 RCL	
082	03 03	
083	42 STO	
084	60 60	
085	61 GTO	
086	11 A	
087	76 LBL	
088	13 C	
089	71 SBR	Reset Directory
090	03 03	
091	38 38	

TABLE 13 (continued)

Executable Step Number	Step	Description of Executable Steps
092	43 RCL	Is
093	09 09	Storage or
094	32 X:T	Spreading
095	43 RCL	Activity
096	59 59	Less
097	77 GE	Expensive
098	01 01	?
099	25 25	
100	43 RCL	
101	60 60	Set
102	71 SBR	Directory
103	03 03	to
104	76 76	Storage
105	71 SBR	Activity
106	03 03	
107	59 59	
108	73 RC*	
109	07 07	
110	55 ÷	Output
111	43 RCL	Manure
112	66 66	Storage
113	95 =	Activty
114	42 STO	
115	59 59	
116	99 PRT	
117	44 SUM	
118	69 69	
119	94 +/-	
120	44 SUM	
121	40 40	
122	61 GTO	
123	01 01	
124	67 67	
125	43 RCL	
126	10 10	
127	71 SBR	Set
128	03 03	Directory
129	76 76	to
130	71 SBR	Spreading
131	03 03	Activity
132	59 59	
133	43 RCL	
134	03 03	
135	55 ÷	
136	01 1	
137	00 0	
138	95 =	

Executable Step Number	Step	Description of Executable Steps
139	59 INT	Designate
140	85 +	Field to
141	01 1	Receive
142	02 2	Manure
143	95 =	Application
144	69 OP	
145	04 04	
146	73 RC*	
147	07 07	
148	55 ÷	
149	43 RCL	
150	19 19	
151	95 =	Output
152	42 STO	Manure
153	09 09	Spreading
154	69 OP	Activity
155	06 06	
156	69 OP	
157	00 00	
158	94 +/-	
159	44 SUM	Decrement Acreage
160	40 40	Availability
161	65 ×	
162	73 RC*	
163	05 05	
164	95 =	
165	44 SUM	Decrement Labor
166	39 39	Availability
167	73 RC*	
168	04 04	
169	74 SM*	Increment
170	03 03	Cost of Manure
171	73 RC*	Spreading
172	06 06	
173	74 SM*	Increment
174	05 05	Time Required
175	01 1	
176	94 +/-	
177	74 SM*	
178	02 02	
179	76 LBL	
180	14 D	
181	00 0	
182	32 X:T	
183	73 RC*	Is Acreage
184	02 02	Exhausted
185	22 INV	?

TABLE 13 (continued)

Executable Step Number	Step	Description of Executable Steps
186	67 EQ	
187	01 01	
188	93 93	
189	09 9	
190	09 9	
191	72 ST*	
192	03 03	
193	71 SBR	
194	03 03	
195	38 38	
196	43 RCL	
197	06 06	
198	42 STO	
199	00 00	
200	01 1	
201	94 +/-	
202	32 X:T	
203	43 RCL	Manure Exhausted ?
204	40 40	
205	69 OP	
206	10 10	
207	67 EQ	
208	16 A'	
209	43 RCL	Labor Exhausted ?
210	39 39	
211	69 OP	
212	10 10	
213	67 EQ	
214	16 A'	
215	61 GTO	
216	11 A	
217	76 LBL	
218	16 A'	
219	43 RCL	Place Remaining Manure in Storage due to Exhaustion of Labor Resource
220	40 40	
221	69 OP	
222	10 10	
223	68 NOP	
224	67 EQ	
225	02 02	
226	32 32	
227	43 RCL	
228	40 40	
229	99 PRT	
230	44 SUM	
231	69 69	
232	97 DSZ	
233	00 00	
234	02 02	
235	39 39	
236	61 GTO	
237	02 02	
238	50 50	
239	01 1	
240	00 0	
241	71 SBR	
242	03 03	
243	59 59	
244	71 SBR	
245	03 03	
246	48 48	
247	61 GTO	
248	02 02	
249	32 32	
250	71 SBR	
251	03 03	
252	38 38	
253	00 0	
254	32 X:T	
255	43 RCL	
256	48 48	
257	22 INV	
258	67 EQ	
259	02 02	
260	62 62	
261	91 R/S	Halt Program Execution for Data Input
262	98 ADV	
263	43 RCL	
264	62 62	
265	22 INV	
266	67 EQ	
267	02 02	
268	73 73	
269	43 RCL	
270	63 63	
271	42 STO	
272	62 62	
273	43 RCL	
274	67 67	
275	22 INV	
276	67 EQ	
277	02 02	
278	83 83	
279	43 RCL	

TABLE 13 (continued)

Executable Step Number	Step		Description of Executable Steps
280	68	68	
281	42	STO	
282	67	67	
283	43	RCL	
284	62	62	
285	71	SBR	
286	03	03	
287	87	87	
288	65	×	
289	43	RCL	
290	61	61	
291	95	=	
292	44	SUM	Update
293	40	40	Manure
294	43	RCL	Availability
295	62	62	
296	65	×	
297	01	1	
298	00	0	
299	00	0	
300	95	=	
301	22	INV	
302	59	INT	
303	42	STO	
304	62	62	
305	43	RCL	
306	64	64	
307	42	STO	Update
308	39	39	Labor
309	43	RCL	Availability
310	67	67	
311	71	SBR	
312	03	03	
313	87	87	
314	65	×	
315	43	RCL	
316	66	66	
317	95	=	
318	42	STO	Update
319	19	19	Nitrogen C
320	43	RCL	Content
321	67	67	
322	65	×	
323	01	1	
324	00	0	
325	00	0	
326	95	=	

Executable Step Number	Step		Description of Executable Steps
327	22	INV	
328	59	INT	
329	42	STO	
330	67	67	
331	43	RCL	
332	06	06	
333	42	STO	
334	00	00	
335	61	GTO	
336	11	A	
337	68	NOP	
338	43	RCL	Subroutine for Resetting Directory
339	08	08	
340	71	SBR	
341	03	03	
342	76	76	
343	94	+/-	
344	71	SBR	
345	03	03	
346	59	59	
347	92	RTN	
348	73	RC*	Subroutine for Updating Field Availability
349	08	08	
350	65	×	
351	01	1	
352	00	0	
353	95	=	
354	22	INV	
355	59	INT	
356	72	ST*	
357	08	08	
358	92	RTN	
359	44	SUM	Subroutine for Incrementing Directory Addresses
360	01	01	
361	44	SUM	
362	02	02	
363	44	SUM	
364	03	03	
365	44	SUM	
366	04	04	
367	44	SUM	
368	05	05	
369	44	SUM	
370	06	06	
371	44	SUM	
372	07	07	
373	44	SUM	

TABLE 13 (continued)

Executable Step Number	Step		Description of Executable Steps
374	08	08	
375	92	RTN	
376	24	CE	Subroutine for Determining Value Necessary For Resetting Directory
377	55	÷	
378	01	1	
379	00	0	
380	95	=	
381	59	INT	
382	65	×	
383	01	1	
384	00	0	
385	95	=	
386	92	RTN	
387	24	CE	Subroutine Used in Updating Resource Availability
388	65	×	
389	01	1	
390	00	0	
391	00	0	
392	95	=	
393	59	INT	
394	55	÷	
395	01	1	
396	00	0	
397	00	0	
398	95	=	
399	92	RTN	

and plant nutrient loss rate. This latter test was deemed appropriate for evaluation of the programmable calculator model.

Results obtained with the LP model and with the programmable calculator model are compared in Table 14. The comparisons were made under four different sets of assumptions to determine if both models are equally sensitive to key parameters.

The first two rows of Table 14 compare the results obtained when the standard assumptions of manure production, manure composition, and method of spreading, etc., were utilized.[33] The input data for both models was obtained from the synthetic 60 milking cow dairy farm. Field A represents the corn silage acreage. Field B represents the alfalfa acreage. Field C represents the timothy hay acreage. Field D represents the permanent pasture acreage. Field E represents the summer pasture acreage. The objective function value is the total cost of operating the liquid manure and commercial fertilizer application system for one year. Under standard assumptions, the allocation of manure in the two model solutions differed by a single acre. The total cost differed by $37.00. The difference in storage activity for the two solutions was due to the requirement of complete acre allocations of manure in the programmable calculator model.

Comparison of the results obtained when the standard assumptions were altered with respect to the plant nutrient loss rate, the as-produced nutrient composition of manure, and the manure moisture content are also shown in Table 14. The correspondence for each pair of

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[33] See pages 30 and 31 for a discussion of the standard assumptions.

TABLE 14. Comparison of Model Solutions Obtained with a Linear Programming Algorithm and a Branch and Bound (TI-59) Algorithm According to the Assumption Incorporated in the Computer Run

Algorithm Type	Assumption for Optimization of 60 Milking Cow Farm	Objective Function Value ($)	Storage Activity in Solution (gallon)	Acres of Manure Application Activity Field					Acres of Commercial Application Activity Field				
				A	B	C	D	E	A	B	C	D	E
Branch and Bound	Standard Assumption	11,795	35,778	40	0	0	20	0	0	20	15	60	30
Linear Programming	Standard Assumption	11,758	41,889	40	0	0	19	0	0	20	15	61	30
Branch and Bound	1.5% Plant Nutrient Loss Rate	11,725	14,311	37	0	0	24	0	3	20	15	56	30
Linear Programming	1.5% Plant Nutrient Loss Rate	11,687	5,513	35	0	0	25	0	5	20	15	55	30
Branch and Bound	Low Manure Nutrient Composition	12,455	94,007	3	0	15	43	0	37	20	0	37	30
Linear Programming	Low Manure Nutrient Composition	12,364	72,054	4	0	15	40	0	36	20	0	40	30
Branch and Bound	91% Manure Moisture Content	12,440	23,841	38	0	0	21	0	2	20	15	59	30
Linear Programming	91% Manure Moisture Content	12,439	40,121	39	0	0	20	0	1	20	15	60	30

[1]Utilizes an annual cost of storage of $.001 per gallon; all other runs use $.003/gal.

solutions on the basis of manure application activity, commercial fertilizer application activity, and total cost was quite close.

Some divergence in the solutions obtained with respect to manure storage activity occurred due to the greater flexibility of the LP model. The LP model permitted solutions which combined applications of manure and commercial fertilizer to the same acre of land. In the programmable calculator model nutrient requirements could be supplied either by manure or by commercial fertilizer, but not by a combination of the two.

The second comparison in Table 14 contains a storage activity of 14,311 gallons, obtained from the LP model, and of 5,513 gallons, obtained from the programmable calculator model. This divergence appeared large in the context of percentage. The LP model solution was 160 percent higher than the programmable calculator model solution. However, on an allocation basis, the divergence represented under two acres assuming 7,000 gallons of manure per acre were required. On a month's storage basis, the divergence represented less than one week. The annual cost of the two storage activities differed by less than $27.00. Some of the value of manure as a substitute for commercial fertilizer was forfeited in the programmable calculator model solution.

The comparisons made in Table 14 suggest that algorithms can be developed for programmable calculators which to a large degree substitute for algorithms requiring large computers. While algorithms for hand-held calculators may be less flexible and require more computing time than larger computer algorithms, they provide greater accessibility to users and are sufficiently accurate for use by both the analyst and the decision-maker.

CHAPTER VII

SUMMARY AND CONCLUSIONS

The purpose of this research was to develop a method for determining the size of manure storage structure 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. A LP model of a liquid manure and commercial fertilizer application system was utilized to determine which variables have a significant effect upon the optimum manure storage structure size. The model contained four types of activities: (1) manure application in time period i to acre j of field k; (2) commercial fertilizer application to acre j of field k; (3) manure storage from time period i to time period i + n; and (4) labor required in time period i. The model also incorporated a set of constraints which corresponded to labor availability, manure availability, nitrogen requirements, phosphorus requirements, potassium requirements, pollution regulation, and manure storage.

A synthetic 60 milking cow dairy farm utilizing pasture, a synthetic 100 milking cow dairy farm utilizing pasture, and a synthetic 100 milking cow dairy farm utilizing drylot were constructed from Tennessee and North Carolina farm planning guides. Each synthetic farm provided a separate data base for the LP model, indicating crops grown, crop acreage, crop plant nutrient requirements, and the amount of manure input to the liquid manure system. Additional cost and time requirement

data was supplied from machinery budgets and an equation designed to estimate the time required for the application of liquid manure to land.

The principal technical assumptions of the LP model were: that manure, as it was produced, contained .0426 pound N/gallon, .0076 pound P/gallon, and .028 pound K/gallon; that 50 percent of the N content of manure was lost due to volatilization between production and plant uptake; that N, P, and K were lost from field-applied manure at a rate of 2 percent for each month between the month of application and the month in which plant uptake of nutrients began (March) and; that manure was maintained at 90 percent moisture content while in storage regardless of the type of storage structure.

Analysis of Model Solutions

As a consequence of the model formulation utilized, increasing the size of the manure storage structure on a given dairy farm up to a certain point increased the fixed cost of the liquid manure system and decreased the cost of meeting the plant nutrient requirements of the cropped acreage. When the larger structure facilitated shifting the job of spreading manure from a time period with a high labor wage rate to a time period with a lower wage rate, the variable cost of operating the liquid manure system was reduced as well. The linear programming algorithm incremented the size of the manure storage structure until the net effect of the last size increment on cost was zero or positive. The size of manure storage structure estimated in this fashion was considered optimum for the farm in question and depended in part upon the factors discussed in the following sections.

Type of Manure Storage Structure

The optimum manure storage structure size for a dairy farm was found to be inversely related to the annual cost of the storage structure. Based upon 1978 prices and utilizing an earthen storage structure, the optimum amount of storage for a 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 9 months storage. The positive relationship exhibited between optimum storage structure size (in months) and farm size was explained by the fact that stored manure on the larger farms had a greater value as a substitute for commercial fertilizer than it did on the smaller farm and that the annual cost of manure storage per gallon was a decreasing function of the storage structure size.

This study indicated that except when a very high value was placed on labor (in critical labor periods), only earthen manure storage structures would be inexpensive enough to justify storage. On each farm the increase in the fixed cost of the liquid manure system associated with a metal or concrete structure of any size dominated the corresonding decrease in the cost of meeting the plant nutrient requirements of the cropped acreage. An increase in the size of a metal storage structure on a 60 milking cow dairy farm did not produce a net reduction in cost until labor was valued at $63.68/hour in September, while labor in March was valued at $12.15/hour. With this labor wage rate differential,

the optimum size of a metal storage structure was 60,000 gallons or approximately 1.7 months.

Commercial Fertilizer Price

This study utilized a commercial fertilizer price of $.18/pound for N, $.23/pound for P_2O_5, and $.093/pound for K_2O in determining the optimum manure storage structure size for a given dairy farm. When these prices were increased in isolation from the prices of other inputs such as labor, fuel, or liquid manure system equipment, the optimum storage structure size for a given dairy farm increased.

Based upon 1978 prices for an earthen storage structure, the optimum amount of storage for a 60 milking cow dairy farm was 193,696 gallons (six months storage) at the fertilizer prices stated above; 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 prices.

Even though increases in manure storage reduced the cost of meeting the plant nutrient requirements of crops grown in dairy farms, stored manure was a more expensive source of nutrients than was commercial fertilizer. The plant nutrient reuqirements of 120 pounds N, 80 pounds P_2O_5, and 150 pounds K_2O per acre 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.

Manure Injection

A manure injection activity was not incorporated in the LP model. However, a comparison was made between the cost of meeting the plant nutrient requirements of an acre of corn silage with stored manure (assuming a 50 percent N volatilization loss) and the cost of meeting the requirements with manure injected during the time period in which it was produced (assuming a 5 percent N volatilization loss).

Although the cost per gallon of injecting manure was higher than the cost per gallon of surface applying it (due to increased horsepower requirements), the total cost per acre for injection ($77.83) was lower than the total cost per acre for surface application of stored manure ($101.43). The cost difference was a reflection of the differing amounts of manure required. With the 5 percent N loss assumed for injection, P was the limiting nutrient and 5,891 gallons of manure were required to meet the nutrient requirements of corn silage. With the 50 percent N loss assumed for surface application, N was the limiting nutrient and 7,156 gallons of manure were required. Had a cost for storage been added to the per acre cost of surface application, the cost difference would have been greater.

In the above example, the utilization of manure injection equipment reduced the size of storage structure required to operate the liquid manure system at least cost. In effect manure was stored in the

ground rather than in an expensive storage structure. Use of the injection system spread the amount of time required for application more evenly over all time periods. Use of manure storage and subsequent surface application greatly increased the labor required in the time period just prior to planting (March).

Manure injection may not be an alternative on certain types of land with heavy sod or in certain time periods due to the presence of standing crops. In these situations possession of manure injection equipment may not reduce the size of manure storage structure required.

Field Dispersity

The effect of field dispersity upon the optimum manure storage structure size for a given dairy farm was indirect. The distance to each field, containing a specific crop, affected the allocation of manure between crops. The allocation of manure between crops affected the optimum manure storage structure size.

As a consequence of the model formulation utilized, manure was always allocated to corn silage land in preference to alfalfa, hay, or pastureland--all other things being equal. This 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.

Manure was allocated to an acre of land up to the point where the most limiting nutrient requirement was met. The LP model placed no value on those nutrients supplied by manure in excess of the crops' requirement. Using this method of valuation manure storage was justified for retaining manure produced during the months when corn silage

land was not available due to standing crops and increased the size of manure storage structure considered optimum. On a given dairy farm the distance to land devoted to corn silage could have been great enough that a less costly alternative would have been to apply manure at the time it was produced to crops located closer to the barns, reducing the amount of storage required.

Pollution Control Standard

A recently discarded Tennessee pollution control guideline was incorporated in the LP model in order 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 a given dairy farm. The guideline requiring that the yearly production of no more than two mature dairy animals be applied to a single acre of land, was incopo-rated 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 pre-condition 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 on all synthetic farms. During this period an amount of manure equivalent to the yearly produc-tion 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 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 pound/gallon for N, .0075 pound/gallon for P, and .0144 pound/gallon for K. This composition was a combination of the lowest empirically observed value for each element reported in publications reviewed during the course of this study.

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.

Analysis has suggested that compliance with the recently rescended manure land application guideline would have affected Tennessee dairy farms characterized by limited land availability, manure of a very low quality, and/or manure storage availability at costs exceeding any realizable benefits from preserving the fertilizer value of manure.

Model Validation

Model validation in this study was limited to a sensitivity analysis of those parameters whose assumed values, although empirically

based, were not as reliable as other parameters, such as fertilizer price, and whose actual values vary from farm to farm.

The sensitivity analysis was intended to test the validity of the model in three respects. Had alterations in a parameter value produced large changes in system cost or optimum manure storage structure size, model validity would have been shown to depend upon explicit knowledge of the parameter value involved. Had alterations in a parameter value produced small changes in system cost or optimum size, the model would have been valid even for those farms on which the exact value of the parameter involved was unknown. Had alterations in a parameter value produced erratic or implausible changes in system cost or optimum size, an incorrect specification of the functional relationship between the parameter involved and other model variables would have been indicated.

Alterations in parameter values produced no erratic or implausible effects but revealed that the validity of the model depended upon explicit knowledge of the moisture content of manure prior to land application and the nutrient composition of manure as it is produced.

Moisture Content of Manure

The LP model assumed that all dairy farms would increase the moisture content of manure from 87.3 percent, as it was produced, to 90 percent prior to land application. A 90 percent moisture content was 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. 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 optimum 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, 193,646 gallons of storage were optimum for the 60 milking cow (pasture) dairy farm when the moisture content was 90 percent; 202,653 gallons of storage were optimum when the moisture content was raised to 92 percent. In many instances, greater cost savings were obtained through reallocation of manure among fields than through increased storage size.

If a metal 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. The total annual system cost with an earthen manure storage structure was $13,121--assuming manure was maintained at 92 percent moisture content. This comparison of costs indicated that storage structures constructed from metal were superior to earthen manure storage structures which maintained manure at moisture contents higher than 92 percent.

AS-Produced Manure Chemical Composition

The LP model assumed that the nutrient content of manure as produced on synthetic dairy farms was .0426 pound N/gallon, .0076 pound P/gallon, and .028 pound K/gallon. This composition approximated the values suggested by the Midwest Planning Service (3). At an annual cost of $.001/gallon for manure storage, the annual cost of operating the liquid manure and commercial fertilizer application system on a 60 milking cow (pasture) dairy farm was $11,568.81 with the above manure chemical content and the optimum manure storage structure size was 193,646 gallons.

Research literature suggested that the N content of fresh dairy manure ranges from .0340 pound/gallon to .0467 pound/gallon; the P content of fresh dairy manure ranges from .0075 pound/gallon to .0166 pound/gallon; and the K content of fresh dairy manure ranges from .0144 pound/gallon to .0331 pound/gallon. When the as-produced content of manure was reduced to a combination of the lowest empirical estimates for each nutrient, optimum storage was 72,054 gallons for the 60 milking cow (pasture) dairy farm with an associated cost of $12,363.56. When the as-produced content of manure was increased to a combination of the highest empirical estimates for each nutrient, 193,646 gallons of storage were optimum with an associate cost of $9,742.59. These effects were the result of a combined change in manure quality and the ratio of plant nutrients in the manure.

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 medium nutrient composition 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 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 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 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 stochastic in nature, especially weather, the results of the deterministic LP model must be interpreted with some caution. If the bulk of plant nutrients for a crop are supplied through manure, a soil test should be conducted in the spring so that a supplement of commercial fertilizer can be applied if necessary.

Manure Production and Retention Rate

Since alterations in either manure production or manure retention produce an alteration in the amount of manure input to the liquid manure system, their effects on the optimum manure storage structure size for a 60 milking cow (pasture) dairy farm were examined jointly. The analysis utilized two computer runs. The first run incorporated a 5 percent increase in retention over the originally assumed rate for months in which the assumed rate was not 100 percent. The second run incorporated a 5 percent decrease in retention under the originally assumed rate for months in which the assumed rate was not 100 percent.

Since manure was a more expensive source of plant nutrients than commercial fertilizer, increases in the amount of manure input to the system increased the cost of operating the liquid manure and commercial

fertilizer application system and vice versa. Increases in the amount of manure input to the system decreased (or maintained) the optimum manure storage structure size for the farm when the opportunity to store manure for subsequent application to corn silage acreage existed. Increases in the amount of manure input to the system increased the optimum size when the plant nutrient requirements of corn silage land were satiated. The exact opposite effect on optimum storage size occurred when the amount of manure input to the system was decreased.

The model was shown to be insensitive to the parameter values chosen for manure retention and manure production when their cumulative effect on the amount of manure input to the system ranged between plus 5 percent and minus 5 percent. Over the range of manure storage costs evaluated, the maximum alteration in the system cost caused by changing the manure retention rate was .96 percent. The maximum alteration in the optimum manure storage structure size caused by changing the manure retention rate was 5 percent.

Time Required for the Surface Application of Liquid Manure

The time required for the surface application of liquid manure was central to estimating the cost of operating the liquid manure and commercial fertilizer application system. Since the equation utilized to estimate the time required for application disregarded such factors as terrain, slope, and field conditions, it was important to evaluate the sensitivity of the LP model to variations in the estimates provided by the equation. The optimum size of manure storage structure did not appear to be sensitive to the estimate of time utilized. The largest divergence produced by a 5 percent variation in time required was

16,644 gallons of storage at an annual cost of manure storage equal to $.00225/gallon. Divergences in the cost of operating the system to variation in time required for field application were consistently on the order of $200 or roughly 1.7 percent.

Programmable Calculator Algorithm

An attempt was made to determine the feasibility of reformulating the linear programming storage optimization model so that similar solutions could be obtained with a hand-held programmable calculator. The resulting model utilized a branch and bound type algorithm of 399 steps and a compact format of input data requiring 69 memory locations.

The overall correspondence between results obtained from the LP model and the hand-held calculator model was quite good. When the models were run under standard parameter values, the allocation of manure differed by a single acre; the difference in the cost of operating the system obtained from each model was $37.00.

When parameter values for plant nutrient loss rate, manure composition, and manure moisture content were altered, correspondence on the basis of manure application activity, commercial fertilizer application activity, and system operating cost was quite close. There was some divergence in the solutions obtained with respect to the optimum manure storage structure size. This divergence was related to the greater flexibility of the linear programming algorithm. The linear programming algorithm permitted a solution in which an acre of land received both an application of manure and an application of comemrcial fertilizer; the branch and bound type algorithm did not permit such a solution.

Although the study demonstrated the feasibility of reformulating mathematical models for solution on hand-held calculators, the branch and bound type model as formulated was not suitable for a dairyman's or technician's use. A number of suggestions were made for improving the model for general use.

Further Research

Some research efforts in waste management have ignored the value of manure as a substitute for commercial fertilizer altogether. Other efforts have revealed a variety of methods for determining the value of manure as a substitute for commercial fertilizer. In the present study manure was allocated to an acre of land up to the point where the most limiting nutrient requirement was met. The LP model placed no value on these nutrients supplied by manure in excess of the crops' requirement.

In some instances, the nutrients supplied in excess of the stipulated commercial fertilizer application rate would likely have had additional value as a result of increased crop yield. In other instances, the nutrients supplied in excess could have had a neutral or negative effect upon yield. Further research is necessary to determine the effect of different manure valuation methods on what constitutes an optimum liquid manure management system.

In the LP model commercial fertilizer was available to crops only in a blended form. Consequently, the crop nutrient requirements 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. Modification of the model to supply commercial fertilizer on an elemental basis may reduce the amount of excess nutrients supplied by manure and may alter the operation, size, and cost of the optimum liquid manure system for a given dairy farm. The principal difficulty in formulating commercial fertilizer application on an elemental basis is determining how to put the costs associated with applying fertilizer (labor, tractor charge, fertilizer spreader charge) on a per element basis.

Certain innovations in a liquid manure system increase the preservation of a particular nutrient in manure. Manure injection by limiting volatilization greatly increases the amount of nitrogen that can be supplied by manure. In the LP model manure was normally applied to the point where the most limiting nutrient requirement was met. Unless the particular nutrient whose availability is increased through innovation is also the most limiting nutrient, the additional nutrient amount will be considered excess (of no value) by the model. Incorporation of commercial fertilizer application in the model on an elemental basis would facilitate the economic evaluation of liquid manure system innovations which affect a particular nutrient in manure rather than all nutrients collectively.

This study assumed that the value of manure as a substitute for commercial fertilizer applied only to fertilizer which would be applied in some future time period. However, manure substitutes for commercial fertilizer on pasture at the time it is applied provided plant nutrient uptake is ongoing. Manure which is side-dressed on emerging corn and other row crops likewise has an immediate fertilizer replacement value. The incorporation of these considerations into the LP model would make

the model more widely applicable. The model could then be utilized to determine the effect of side-dressing manure and applying manure to pasture for immediate plant uptake on the optimum manure storage structure size for a given dairy farm.

The optimality of incorporating a manure storage structure built of metal or concrete staves in a given liquid manure system was shown to be highly dependent upon the value of labor in different time periods. Additional data is needed to properly specify the value of labor utilized in manure management in each time period on various types of Tennessee dairy farms. Additional data is also needed on the maximum amount of labor available for manure management in each time period. Incorporating these considerations in a model would further clarify the effect of labor value and availability on the optimum manure storage structure size for a given dairy farm.

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