Economic and Environmental Evaluation of Dairy Manure Utilization for Year Round Crop Production

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Abstract

The production of excess on-farm manure is placing continuous pressures on dairy producers to meet or exceed standards for environmental regulations while maintaining profitability and competitiveness. Evaluation of the effects of recycling nutrients on the profitability of the whole farm enterprise is important for a dairy operation. The objective of this study was to develop a linear programming model that evaluates the economic performance of a dairy operation considering production and environmental constraints. The main goal was to maximize profits from the dairy enterprise considering milk production, manure production, crop production while maintaining a balance of nutrients in the system. Results from simulation analyses showed greater effects on total farm profits at the more restrictive P-based than N-based manure application rates.

INTRODUCTION

The dairy industry in Georgia as in the United States has shifted towards highly intensive, specialized and localized production systems driven by competitive economic, social and political forces. For more efficient milk production, animals are confined in loafing areas where they deposit large amounts of manure that must be collected, stored and reused to irrigate forage crops in the place of or addition to conventional inorganic fertilizers. As livestock population becomes spatially concentrated (Kellogg et al., 2000), the production of manure nutrients exceeds the assimilative capacity of croplands available for manure application (Lander, Moffitt and Alt, 1998). From water-quality standpoint, environmental concerns center around nutrient runoff from crop fields. As a result, regulators are focusing on the ways to induce confined animal producers to operate in manner to protect the environment while maintaining profitability and competitiveness.

Manure nutrient management decisions have several important dimensions, including the storage and handling practices, rate, timing and method of application, and off-field practices to mitigate pollution. On the farm, the level and/or variability of economic returns to crop and livestock production may be affected by each of these dimensions. Furthermore, federal, state, and local governments have enacted legislation limiting the amount of nitrogen and/or phosphorus that can be applied to a given acreage (USDA/EPA, 1999; U.S. EPA, 2001). These limitations frequently generate additional costs to producers and, therefore, threaten the economic viability of the agricultural sector. Several alternatives are perceived to influence farm nutrient balance and the potential to increase profit and/or reduce pollution. The on-farm constraints include animal feed requirement, forage availability and fertilizer value of manure whereas the environmental constraints represent current and future regulations of land application of manure based on N and P rates.

Researchers around the United States have used economic models to assess the environmental risks as well as the on-farm cost of manure handling with specific emphasis on land application of manure rates to meet the requirements of a nutrient management plan (Ribaudo et al., 2002; Innes, 2000; Fleming, Babcock and Wang, 1998). Other researchers used an optimization framework to predict how a representative farm's return or costs would change under an N and/or P-based restriction on manure applications (Huang and Magleby, 2001; 2001; Huang, Magleby and Somwaru, 2001). Overall, P-based manure disposal policy decreased profits due to an increase in manure disposal costs (Yap et al., 2001).

Most of these studies focused on the balance between manure nutrient and crop uptake and the balance between crop nutrient and animal use. However, few of these models incorporated costs associated with crop and livestock production, feed intake and manure excretion, storage, hauling, and application as well as environmental considerations (Henry et al., 1995; Thompson et al., 1997). The severity of environmental constraints is jointly determined by (1) the total amount of manure that must be disposed of, (2) the total quantity of available cropland, and (3) the level of the constraint itself. At the production unit level these constraints may create opportunities for cost reduction or may entail additional cost because of changes in practices, changes in the structuring of the production facilities and changes in environmental management of manure.

Our research efforts were to develop practical and economical solutions for manure management on dairy farms. The objective of this study was to develop a farm linear programming model used to select cropping systems that match dairy cows' nutritional needs to forage production with manure as primary nutrients source. The main goal was to maximize profits from the dairy enterprise considering milk production, manure production, crops grown for forage and crops grown for sale while maintaining a balance of nutrients in the system.

MATERIALS AND METHODS

Model Description

A whole-farm linear programming model was constructed by incorporating as many factors surrounding dairy nutrient management as possible. The main item of interest was the profit emanating from milk production including crop grown for sale. The model maximized profits by selecting cropping systems based on their feeding value and their ability to meet N, P and K uptake requirements. Within the model the farmer was constrained by land, government regulation, manure storage capacity, feed supply, and nutrient requirements for cattle and crops.

The farmer had access to commercial fertilizer in addition to dairy manure to grow two different rotational forage crops, namely temperate corn-tropical corn-rye/clover (CCR) and temperate corn-bermudagrass-rye/clover (CBR). The farm also had the possibility of producing other crops (corn grain, soybeans, cotton and wheat) for manure application if forage rotation could not assimilate all the manure nutrients. The corn grain crop can produce grain for dairy feed ration or for sale while the cotton crop can produce cottonseed for the dairy ration. The model had the options to choose maximum acreage for crop production and maximum herd size and milk production level. The farm also had the possibility of determining the manure application rate, $\boldsymbol{A_i}$, the amount of $\boldsymbol{j}$ nutrient from commercial fertilizers for crop $\boldsymbol{i}$, $\boldsymbol{F_{ij}}$.

The objective function of the whole farm model is specified in the following mathematical expression:

$$\underset{Ma,Ac}{Maximize}\,p = \left[\sum_t (m_t Milk - LOC_t)cow\right]$$
$$+\left[\sum_i (p_i CRPY_i - CO_i)AC - \sum_i \sum_j (f_j Fer_{ij} ACM_i) - MAC - \sum_i \sum_j (f_j d_{ij} ACRPY_i ACF_i) - rLS\right] \quad (1)$$
$$-\left[\sum_h \sum_t z_{ht} Fed_{ht} + \sum_p \sum_t w_{pt} Min_{pt}\right] - \left[\sum_i \sum_t v_{it} CRPTran_{it} + \sum_t s_t ManTran_t\right]$$

where

m_t = price of milk in season t (t = 1,2,3,4),

LOC_s = livestock management cost,

p_i = price of crop i grown,

$CRPY_i$ = crop i yield,

CO_i = production costs other than plant nutrient and land ownership costs of crop i,

ACM_i = cropping acreages with manure application (can include supplemental nutrients to meet crop requirement),

ACF_i = cropping acreages without manure application,

f_j = cost of the j nutrient of commercial NPK fertilizers,

d_{ij} = pounds of j nutrient needed to produce one unit of i crop,

MAC = manure application cost,

r = land rent ($/acre),

Fed_{ht} = pounds of commodity h fed in period t (determined by dairy ration requirement),

z_{ht} = price ($/unit) of commodity h in period t,

Min_{pt} = amount of concentrated mineral nutrients p purchased in period t,

w_p = cost ($/unit) of concentrated mineral nutrients p purchased

$CRPTran_{it}$ = unit of crop produced for ration transferred from production period to other periods,

v_i = cost ($/unit) of storing forage i per period,

$ManTran$ = tons of manure transferred from period t to $t+1$,

s_t = cost ($/unit) of storing manure per period.

The terms in the first bracket defined net return from milk production and the terms in the second brackets define the net return from the crop production with and without manure applications. The terms in the third bracket represented feed ration cost. The terms in the last bracket represented forage and manure storage costs. Annual operation costs were composed of crop production costs, livestock management costs, purchased feed costs, and forage and manure transferred costs. This objective function was subject to a set of restrictions.

Acreage Restrictions

$$\sum_i (ACM_i + ACF_i) = LAV \qquad (2)$$

where LAV was the total land available including acres leased (LS) by the farm for disposal of supplemental manure.

Crop Rotation Relations

$$\mathrm{CBR}_i = CCR_i \qquad (3)$$

This relation sets crop ***i*** receiving manure nutrients in corn-bermudagrass-rye/clover rotation equal to corn-corn-rye/clover rotation.

Manure Use Restrictions

$$TACM = \sum_u ex_u CC \qquad (4)$$

where ***TACM*** was the total amount of manure applied to cropland; and ex_u was the amount of manure produced annually by one unit of cow capacity; and ***CC*** was the total cow capacity. The manure nutrient constraints ensured that the manure nutrient balance was met. Two constraints (4.1 and 4.2) were included to control the balances for manure and crop nutrients within the nutrient recycling system by allowing for transfers of N from winter to spring and from spring to fall, but force the annual manure balance at the end of the fall/winter growing season.

Annual Nutrient Restrictions

$$\sum_i \sum_j \sum_t (AC_{it} NU_{ji} + NUTRAN_{jt}) = \sum_j \sum_t (Fer_{jt} + MANU_{jt}) \qquad (4.1)$$

where

AC_{it} = acres of crop ***i*** in period ***t***,

NU_{ij} = pounds per acre of nutrient ***j*** taken up by crop ***i***,

$NUTRAN_{jt}$ = pounds of nutrient ***j*** transfer from period ***t*** to ***t + 1***,

$MANU_{jt}$ = pounds of manure nutrient ***j*** available from the farm in period ***t***.

This relation assumes that storage losses were negligible and all nutrients available must be utilized for crop production.

Nutrient Application Restrictions

$$\sum_i \sum_j (F_{ij} + man_j A_i - d_{ij} CRPY_i + masu_{ij}) \geq 0 \quad \text{for } j = N, P, K \qquad (4.2)$$

where $\boldsymbol{masu_{ij}}$ was the amount of surplus manure nutrient ***j*** applied to crop ***i*** but not utilized by the crop and $\boldsymbol{masu_{ij}} > 0$. $\boldsymbol{masu_{ij}}$ was set to zero when nutrient ***j*** is restricted (e.g., $\boldsymbol{masu_i} = 0$ when N was restricted). Surplus manure can occur when the manure application rate was restricted based on one specific nutrient. Restricting the manure application rate for crop based on N would result in a surplus of P from manure because the N:P ratio of the manure maybe greater than the N:P ratio of nutrients utilized by crops.

Per-Acre Nutrient Required by Crops

$$\sum_i \sum_j (F_{ij} + man_j A_i - d_{ij} CRPY_i) \geq 0 \quad \text{for } j = N, P, K \qquad (5)$$

where $\boldsymbol{F_{ij}}$ was the pounds of ***j*** nutrient applied to crop ***i*** and $\boldsymbol{man_j}$ was the pounds of ***j*** nutrient in 1000 gallons of manure; and $\boldsymbol{d_{ij}}$ was the pounds of ***j*** nutrient needed to produce one unit of crop ***i***. This restriction stated that the amount of each nutrient applied per acre from commercial fertilizer and manure must meet the amount needed by the crop. Any excess amount of manure nutrients applied was assumed to have no value to the farm.

Annual Crop Supply Restrictions

$$\sum_i \sum_t AC_{i(t-1)} CRPY_i (1 - CRPS_{i(t-1)}) = \sum_i \sum_g \sum_t (CRPU_{git} + CRPTran_{it}) \qquad (6)$$

where

$\boldsymbol{CRPY_j}$ = per acre yield of crop ***i***,

$\boldsymbol{CRPS_{i(t-1)}}$ = percentage of harvest crop ***i*** sold (Note: only hay can be sold),

$\boldsymbol{CRPU_{git}}$ = pounds of forage ***i*** used by milking cow group **g** in period ***t***,

$\boldsymbol{CRPTran_{it}}$ = transfer of forage ***i*** to period ***t***.

These forage supply constraints ensured that the crop nutrient balance is met. These constraints allowed transfers of forage between seasons assuming no feed loss during harvest and storage of crop ***i*** in period ***t***, but forced an annual crop nutrient balance at the end of the growing cycle.

Feed Ration Restrictions by Milk Production and Period

$$\sum_{i} CRPU_{git}RAT_{qi} + \sum_{h} Fed_{ght}RAT_{qh} + \sum_{k} STOC_{gkt}RAT_{qk} \geq IR_{gqt(mpl)}CON_{gt}DA_{t} \quad (7a)$$

$$\sum_{i=1} CRPU_{git}RAT_{qi} + \sum_{f=1} Fedg_{ght}RAT_{qh} + \sum_{g=1} STOC_{gkt}RAT_{qk} \leq DMI_{gt}FDM_{gq} \quad (7b)$$

where

RAT_{qi} = ration ***q*** associated with crop i, commodity ***h***, or forage on hand ***k***,

$IR_{gqt(mpl)}$ = requirement per cow for ration ***q*** for cow group ***g*** in period ***t***, by milk production level (***mpl***),

CON_{gt} = number of cows in group ***g*** during period ***t***,

DA_{t} = number of days in period ***t***,

DMI_{gt} = total ***DM intake*** for group ***g*** in period ***t***, and

FDM_{gq} = maximum forage dry matter in ration ***q*** from forages.

The first constraint for diet regime forced the amount of a diet component to be greater than the amount required by the cow. The second constraint forced the percentage of a dietary characteristic in a diet to be less than a certain percentage of DMI.

Annual Resource Restrictions

$$\sum_{i=1} AC_{i}Q_{li} = M_{l} \quad (9)$$

where Q_{li} = amount of resource associated with the production of an acre of crop ***i*** (***l*** = land, labor, lagoon, cow, milk production capability, etc.), and M_{l} = maximum or minimum quantity of resource ***l*** available. This resource constraint limited the use of physical and labor resources to be less than the amounts available.

Manure Application Cost

The model estimated the land required for the manure application while minimizing the impacts on environment quality.

$$MA = \sum_{i} ACM_{i}A_{i} \quad (10)$$

where both A_i and ACM_i are decision variables.

Land application of manure includes setting up the machinery and equipment, loading the lagoon and irrigation systems, field travel time, and time spent actually applying in the field. Another question on many producers' minds is how manure application costs increase with hauling distance. However, this question may be more relevant when locating a new facility or purchasing manure than when considering changes in existing facility where manure must be disposed of regardless of the hauling cost. From this standpoint, the cost of transporting manure from storage to the field and then applying it depends on a mileage charge in addition to the base charge for manure application (Fleming, Bacock and Wang, 1998).

Input Factors

The model used specific information to determine optimal nutrient management strategies for dairies. General farm information included number of the dairy cattle, crop acreage availability, labor availability, cost of purchased livestock feed and crop nutrients, storage capacity for manure and feed, and the concentration of nutrients in manure wastewater. The model allowed cows to be fed to produce milk at lower production level than their maximum production level. Default values for available excreted N, P and K were adjusted for crop uptake using commercial fertilizers. Feed nutrients and associated rations were adjusted for milk production. Crop nutrient uptake was determined by expected crop yield and concentration of N, P or K in dry matter.

Livestock inputs encompassed the flow of incurred livestock expenses (feed, veterinary expenses, depreciation on building, machinery and animals, interests on capital stock) including operating costs (electricity, heating fuel, etc.). Crop production costs consisted of annual expenditure on seeds and crop protection and other miscellaneous variable crop costs and fixed costs of machinery ownership. The flow of service emanating from capital stock items such as machinery, buildings and land improvements was measured by summation of all maintenance and running costs, depreciation charges and interest on the capital stock. Finally, all output and input variables defined in value terms were deflated using the appropriate annual price indices.

Data sources

Nutrient concentrations for forages were taken from a study at the dairy research farm in Tifton, Georgia. The study considered temperate corn-bermudagrass-rye/clover and temperate corn-tropical corn-rye/clover as two intensive (triple cropping) forage cropping patterns utilizing manure as plant nutrients source. This experimental data provided information on seed, pesticide, and nutrient inputs, as well as the specific farming operation. Labor required for forage production and livestock management was estimated by calculating the number of hours that were required for each activity. Machinery performance for each field operation and resulting machinery costs were estimated from enterprise budgets developed at the Georgia Branch Experiment Station. Fixed costs included depreciation on tractors, machinery, building and livestock, interest on operating capital and taxes and insurance.

The prices of inputs and outputs are obtained from local fertilizer, pesticide and seed retailers. Chemicals and seed were cost at market prices. Crop prices used were Georgia 2002 farm gate prices. Fertilizer nutrient prices used were $27.03/cwt nitrogen, $6.13/cwt phosphate, and $7.42/cwt potash, using 2002 input prices. Crop production costs including lime application costs averaged from 1997 through 1999 were $371.67/acre for temperate corn, $436.64/acre for tropical corn, $150.69/acre for bermudagrass, and $120.64/acre for rye/clover from 1997 to 1999.

The commodities available for use in dairy rations are those typically available in Georgia. Nutrient requirements for milking cow performance and maintenance were derived from DART ration formulation and adjusted for production level and period. Upper and lower bonds were used for many animal nutrient requirements in balancing the rations.

Alternatively, the dairy operation maintained the same type of operation, and manure storage and application system regardless of manure application restrictions. Milk production was allowed to vary by feeding regimes and cow capacity. Cropped acreages were allowed to change by period to reflect differences in forage needs and manure utilization requirements.

Simulation procedures

This analysis limited itself to the assumption that the dairy operator would utilize all the manure for a year-round forage and crop production in the farm. A baseline scenario and alternative restriction scenarios were subsequently simulated to assess the farm-level impacts. The indicators used to assess the farm-level impacts included (i) net farm profit from dairy operation, (ii) seasonal acres of crop needed with the manure loading restrictions, and (iii) the influence on herd size for given acreage by manure N, P and K loading restriction. The acres cropped depended upon animal nutrient requirements, manure nutrient use and the profitability of non-forage cropping systems utilizing manure and inorganic fertilizers.

The scenarios reported in this paper used fixed land restrictions. In the baseline scenario a maximum of 5 cows per acre was used, but the number of cows and manure application rate were unrestricted and the actual land application of manure was determined. In other words, the number of cows and manure application rates were unrestricted but land available for application was limited. Additional scenarios restricted manure application rate to not exceeding the nitrogen and/or the phosphorus needs of individual crops and acres receiving manure were bounded. This restriction is part of CNMP for the areas where P in soil is low (N-restriction) or high (P-restriction) (NRCS, 2000). In addition to the N and P restriction comparisons, K restrictions were also evaluated even though they are not part of the CNMP programs.

RESULTS AND DISCUSSION

The manure disposal capacity per year was determined by requiring all effluent to be used within a 12-month period but by allowing storage over cropping periods. The impact of manure application policy changes was measured by calculating the differences in returns above variable cost levels between the results of three runs of the model reflecting three alternative policies: N-based, P-based and K-based land application polices. The base run had no restriction on N, P, and K application rates except the number of animal was restricted to 5 cows per acre. The second run represents the management decisions the farmer would be expected to make on applying manure based on N-restriction. This would then allow for manure P and K to be greater than the P and

K needs of crops. The third run represents the management decisions made by the farmer where land application of manure is based on meeting the P needs of the crops. Alternatively, P-restriction does not allow for manure P to exceed the P needs of crops. The fourth run represents a K-based restriction where the manure application rate would not exceed the crop K uptake rate. All runs of the model were based on a representative dairy operation with 600 acres of available cropland. Through comparing the results, it would illustrate what actions the representative farmer would take in order to mitigate the costs of the new regulations.

Model estimates are presented in Table 1. The representative farm returns above variable costs were reduced as a result of the regulation change. Under the N-standard scenario the returns above variable costs were $3691 per acre and the returns above variable costs for the P-based restriction was only $747 per acre compared to $4884 per acre when manure application rate was not restricted. It is useful to estimate the social or environmental benefits as a result of a farmer complying with a nutrient standard policy. The benefits are estimated based on the change in returns above variable costs between the different nutrient standard scenarios relatively to the baseline scenario. For example, the social benefit realized from changing from N-based to P-based manure application was equivalent to $20 per cow. This was mainly a result of an increase in manure disposal costs.

The total farm operation cost was similar for the unrestricted and N-restricted manure management plans. However, the production cost increased over 7% when the manure application rate was based on N or K requirements. The total cost was $12.61 per cwt milk under the N-based scenario compared to $13.64 and $14.13 per cwt milk under the P and K management policy, respectively. This resulted mainly from the fact that there were also wheat and hay crops grown for sale in order to utilize the surplus manure under the more restrictive P and K scenarios. When costs of producing crops for sale were excluded, the farm operation costs was about $12.60 per cwt milk under all manure management policies.

Requiring a P-based nutrient management plan generally increases the cost of manure management because more land is needed to meet the requirements of a P-based plan. Under a P-standard, manure application rates are reduced (relative to an N-standard) such that manure P is not applied in excess of crop uptake requirement. As a result, farms grow hay and wheat for sale in order to utilize the surplus manure. Under a N-based plan, both P and K are over-applied. Potassium may or may not be in excess, depending on the crop. In this study, social benefits for growing additional crops to utilize surplus manure were $15.39 and $60.49 per cow for implementing the P-based and K-based manure management policies, respectively.

Alternatively, the optimal number of milking cows was reduced from 4.4 per acre for the N-restriction policy to only 0.9 cows per acre under the P-restriction plan.

Milk production

Dairy milk production capacity was 60 lbs per cow per day except during the summer period where it was reduced to 50 lbs per day. This was equivalent to 208.4 cwt milk produced per year.

A second set of scenarios were used with the N and P restrictions to show the influence of feeding above herd milk production capacity from lack of knowledge or from insurance and to show to show the influence of using poor quality forage and concentrate ingredients in the ration formulations. In these scenarios using the same quantity of feed input, a 10% reduction in milk production occurred. The model estimates are presented in table 2.

Crop acreage

For each scenario the entire 600 acres were used for crop production. For the N-restriction scenario, a total of 600 acres were grown in spring temperate corn, 600 in summer bermudagrass, and 600 in fall/winter rye/clover. However, the land utilization for cropping in spring, summer and fall/winter periods under the P-restriction was reduced to 366, 0, and 366, respectively. The most significant change came from wheat grown on 233 acres and hay grown on 366 acres for sale under the P-restriction.

Manure utilization

One of the interesting outcomes from the change in manure disposal policies, is the change in manure transfer between production and utilization periods. This includes the timing of when and on what crops it is applied. The most significant from the N- to the P-restriction scenario is that manure is transferred.

CONCLUSION

In this study we present a situation that has economic and environmental formulation. A farm profit maximizing linear programming model is developed which selected most profitable crop production system and purchased nutrients for milk production and land utilization considering a net nutrient balance for the system of zero. The farm model includes dairy ration composition and manure utilization. The objective function maximizes profit from milk and crop production above on-farm costs and environmental restrictions. Size of milking herd and cropland acres are flexible constraints. Diet relationships are modified by period to reflect seasonal changes in requirements and heat stress effects on diet energy levels concentrations. The manure nutrient constraints were developed to allow storage and transfers of manure from one period to another, but force an annual manure-crop nutrient balance. Constraints for animal feed requirements allow transfers of forage between periods as well as buying and/or selling additional feed.

This research presents an analytical framework for jointly determining optimal milk output and evaluating the opportunity to manage manure and crops within a dairy operation. Even though it is presented in the context of dairy management, the model is general enough to be extended to other situations where animal wastes are involved. This model presents an effective strategic planning tool and will allow dairy farmers to formulate their most profitable nutrient management systems.

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Table 1. Estimated profits and costs of dairy and crop production due to change in manure management policies

	No restriction	N-restriction	P-restriction	K-restriction
Dairy and crop operations				
Profit per acre	4884	3691	747	378
Profit per cow	814	841	821	802
Profit per cwt	3.91	4.03	3.94	3.85
Cost per cow	2655	2629	2842	2946
Cost per cwt	12.74	12.61	13.64	14.13
Milk production				
per cow (cwt)	208.4	208.4	208.4	208.4
Milk production excluding cost of growing agronomic crops for sale				
Per cow	NAC[1]	NAC	2633	2606
Per cwt milk	NAC	NAC	12.63	12.51
Number of cows per acre	6	4.4	0.9	0.5
Net income from agronomic crops grown to utilize surplus manure				
Per cow	NAC	NAC	-15.39	-60.49
Per cwt	NAC	NAC	-0.07	-0.29

[1]No agronomic crop was grown for sale under the unrestricted and N-restricted manure application scenarios.

Table 2. Estimated profits and costs of dairy and crop production based on 10% reduction in milk production and manure management policies

	N-restriction	P-restriction
Dairy and crop operations		
Profit per acre	2220	443
Profit per cow	506	497
Profit per cwt	2.70	2.65
Cost per cow	2629	2810
Cost per cwt	14.01	14.98
Milk production		
Milk per cow (cwt)	187.6	187.6
Milk production excluding cost of growing agronomic crops for sale		
Per cow	NAC	2619
Per cwt milk	NAC	13.97
Number of cows per acre	4.4	0.9
Net income from agronomic crops grown to utilize surplus manure		
Per cow	NAC	-17.87
Per cwt	NAC	-0.10

[1]No agronomic crop was grown for sale under the N-restricted manure application scenario.