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Modeling the Use of Sewage Sludge on Pennsylvania Dairy Farms: An Economic Analysis*

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A five-year linear programming farm planning model, permitting the inclusion of nitrogen decay rates, was constructed to include the use of sewage sludge as a primary crop nutrient source. Twenty-two scenarios depicting various operating conditions were examined and maximized net farm incomes compared.

Although only a small percentage difference resulted between the highest and the lowest net revenues over the five-year period, given a variety of operating circumstances, those scenarios including the use of sludge yielded the highest net incomes. Nitrogen application restrictions were at their upper limits when sludge use was included in the optimal solution. The calculation of net present values, for the two sludge contents considered, provided value estimates compatible with the linear programming solutions.

In the United States the traditional means of sludge disposal has been landfilling. This practice required the acquisition of land for the sole purpose of receiving sludge. As the availability of land for sludge disposal became more limited and its cost greater, a more energy and cost efficient means of sludge disposal was sought in the 1970's. Municipal sewage treatment plants handling from one million to 100 million gallons of influent/day are faced with the task of choosing the lowest cost means of influent treatment and disposal of effluent and sludge.¹

Agronomists began experimentation with the application of sewage sludges on crops during the late 1960's. The primary purpose of their experiments was to record and compare crop response to sludge nutrients with crop response to standard commercial fertilizers. In general, agronomists found that sludge application on crops increased yields and conditioned the soil (Kelling et al., 1977; Soon et al., 1978). Farmers are aware of the benefits of

sludge application, but are concerned about the toxic metals contained in sludge, odor problems, the possible inconvenience of receiving municipal sludge, and how sludge use will affect their incomes. Forster et al. (1976), in an economic analysis, concluded that land spreading costs were generally lower than those associated with landfilling and incineration costs. Although larger plants realize economies of size for influent treatment, land application of sludge is not considered cost-effective for large metropolitan plants because of higher transporting costs due to greater distances between the plant and possible application sites. However, Young (1978) also found that, for small and medium sized plants with closer disposal sites, land application of sludge was cost-effective. As a result of these and other cost analyses, many municipalities began to request permission to apply sludge on farmland.

While other studies have demonstrated the engineering and agronomic feasibility of land application of sludge, much remains to be known of the economic value of sludge. The purpose of this study was to examine sludge application on agricultural land from the farmer's perspective, under various operating conditions or scenarios, and to estimate a dollar value of a dry ton of sludge.

External diseconomies, such as odor and

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¹ A treatment plant processing one million gallons of influent per day serves a city of about 10,000 residents (Young, et al., 1977). Therefore, a plant handling 100 million gallons of influent each day would serve a population of about one million persons.

groundwater contamination, are sometimes associated with sludge application. Farmers receive free nutrients from sewage sludge for crop production, and incur no sludge use costs, while neighbors or water supply recipients may either be harmed or required to pay for damages.² Hence, guidelines and regulations for land application of sewage sludge have been devised on local, state, and national levels for the protection of the environment. The issuance of these restrictions is an attempt to minimize the negative externalities associated with the otherwise beneficial use of sewage sludge. Toxic metal contents in the sludge were assumed to be low, and therefore did not impose restricted sludge use. Odor nuisances could not be dealt with in this study, whereas, the inconveniences associated with receiving sludge will be briefly discussed.

Methods

The analysis used in this study involved the comparison of maximized net revenues using linear programming techniques. A 150-acre dairy farm, with a constant herd size of 48 cows and 24 heifers, was modeled for a five-year planning period, for soil and climatic conditions typical of Pennsylvania. The five-year planning horizon permitted the inclusion of residual nitrogen effects, from both sludge and manure, in the model. Residual amounts of inorganic nitrogen are released for several years after the application of manures or sewage sludges. Accounting for the residual amounts of nitrogen in this study was considered important for two reasons. First, cost reduction may be realized because less commercial fertilizer would be needed in years following sludge or manure application. Secondly, nitrogen loading limitations may be set and maintained if all nitrogen in the soil is accounted for.

The general five-year planning model included several variations. Comparisons of net revenue were made of situations involving no sludge application, contracted application of sludge, the purchase of sludge at different prices, and the sale of heifer corral manure.

Discounted and undiscounted net present values were computed for a dry ton of sludge. These values were compared to those indi-

cated by parameterizing the price of a dry ton of sludge in the programming scenarios, and were compared to other available estimates.

For the purposes of this study, it was necessary to assume standardized nitrogen, phosphorus, and potassium contents for the sludge. Similarly, it was necessary to assume proportions of N, P, and K contained in manure. Toxic metal contents in the sludge were neither included in the model nor constrained.

Because the literature has not adequately discussed the effects of sludge use on farming practices, a questionnaire was administered to a sample of municipal sludge program managers and farmers regularly using sludge. The primary purpose of this questionnaire was to determine whether or not normal farm operations must be modified or significantly altered when sludge is applied to cropland and whether or not any significant costs are incurred by farm operators in the agricultural use of sludge.

The results of the survey of municipal sludge program managers and farmers indicated that farm operations are normally unaltered by sludge application. Farmers typically receive sludge upon request and generally incur no additional costs or losses. The municipality or a contracted hauler spreads the sludge in the summer after hay cuttings or spreads and incorporates the sludge in the soil prior to planting. Several farmers reported that no additional disking, chiseling, or plowing was necessary. In fact, the plow layer is broken up when sludge is injected, which may improve production. No excessive weed problems were reported. Hence, it was assumed, in this study, that farm practices were unaltered by sludge use.

The Operational Model

The general farm planning model (Model 1) included only the conventional use of animal manure and chemical fertilizer. A liquid manure handling system was assumed. The slurry (13 percent solids) was assumed to be channeled underground from the dairy barn to a covered manure storage pit with a seven month storage capacity. It was assumed that the slurry was not agitated, and was mechanically pumped into the center of the storage pit from the bottom. The liquid manure would then be applied seasonally (approximately every three to four months) or more often, weather permitting. Nitrogen, phosphorus,

² Assuming transportation and application are provided by the municipality.

and potassium contents in manure were assumed averages for dairy cattle. A difference in nutrient availability was assumed, which depended on storage practices, namely whether the manure and urine are directly pumped into a liquid manure storage pit (dairy manure) or stacked (heifer corral manure).

The second form of the general model (Model 2) assumed that crop nutrients would be obtained from municipal sludge as well as from commercial fertilizer and manure. The nitrogen content of sludge varies to a greater degree than do the phosphorus and potassium contents. Therefore, two different sludge nitrogen levels were used in the analyses. The content information is provided in Table 1. It was assumed that sludge would be subsurface injected or immediately incorporated by disk-ing, if surface applied, except following hay cuttings. The nitrogen decay series used for sludge and manure is .40, .10, .06, .05, .04. The use of a discounting procedure was examined but not applied to sludge, in the model, because discounting the value of nitrogen mineralized in subsequent years did not significantly affect the total value of the sludge.

Model 3 also involves the use of sludge, subject to additional constraints requiring that (1) the amount of sludge applied in the spring may not exceed that applied in the fall by more

than 15 tons for Soil Conservation Service (SCS) Class II land and (2) by more than five tons for SCS Class III land. These constraints simulate conditions which may be placed on recipients of sludge in the future to reduce the amount of sludge storage capacity required by the municipal authority. Fall application of sludge offers a less desirable option from the farmer's perspective, however, than does spring sludge application for the reasons detailed below. Sludge is less valuable when applied in the fall because sludge nutrients mineralize and become available for plant use at a slower rate due to cooler air and soil temperatures. Sludge nutrients are also lost to leaching or fixation as fall and winter snow melts and nutrients are removed to lower soil layers, or held by the organic fraction of the soil. Therefore, 20 percent of sludge and manure nutrients were subtracted to account for leaching or fixation losses between fall application and the next growing season. Nitrogen was assumed to mineralize at a slower initial rate when applied in the fall (.30, .10, .06, .05, .04).

Data

Coefficients for dairy and heifer nutrient requirements, milk yield, bedding requirements,

Table 1. Average Nutrient Contents in Sludges and Manure Used in the Analyses

	Total Nitrogen	First Year Nitrogen Availability	Phosphorus	Potassium
----(pounds/dry ton)----				
9% Nitrogen Sludge (2% solids) ¹	180.00	72.00	35.00 P ₂ O ₅ = 80.50	6.00 K ₂ O = 7.20
4.2% Nitrogen Sludge (6% solids) ²	84.00	34.00	35.00 P ₂ O ₅ = 80.50	6.00 K ₂ O = 7.20
Combined Plant Averages ³ (pounds/dry ton)				
Cd = 0.02 Pb = 0.51				
Cr = 0.20 Ni = 0.09				
Cu = 1.24 Zn = 1.43				
Liquid Dairy Manure (13% solids) ⁴	11.00	4.40	2.00 P ₂ O ₅ = 4.60	8.00 K ₂ O = 9.20
Heifer Corral Manure (20% solids) ⁵	15.60	6.24	2.78 P ₂ O ₅ = 6.40	10.42 K ₂ O = 12.50

¹ Average Sludge from Williamsport Sanitary Authority's Central Plant (Williamsport, PA).

² Average Sludge from Williamsport Sanitary Authority's West Plant (Williamsport, PA).

³ Williamsport Sanitary Authority.

⁴ The Pennsylvania State University Department of Agronomy and The Penn State Farm Management Handbook.

⁵ The Pennsylvania State University Department of Agronomy and The Penn State Farm Management Handbook.

expected net revenues, crop nutrient requirements, harvested yields, production costs, and supply of animal nutrients from crops were obtained from The Penn State Farm Management Handbook (Dum et al. 1981). Crop prices were obtained from the Pennsylvania Crop Reporting Service annual summary.

Sludge content information, including percent dry matter used in this study were drawn from data recorded by two Pennsylvania treatment authorities. Both treatment authorities estimate that approximately 40 percent of the nitrogen is available for plant use the first year.

In addition to free sludge, a range of sludge prices were examined, from \$5.00/dry ton to \$50.00/dry ton. The manure selling price of \$5.00/ton reflects the estimated fertilizer value of the average total nutrients contained in the manure. Fertilizer prices (1979) of N @ \$.20/pound, P_2O_5 @ \$.18/pound, and K_2O @ \$.10/pound, were obtained from The Penn State Farm Management Handbook. These prices are consistent with other prices and cost coefficients used in the study.

Right-hand-side values for nitrogen loading were determined by calculating the nitrogen requirements for each crop rotation and selecting the crop rotation requiring the most nitrogen. The nitrogen requirements for crop rotations considered for Class II and Class III land were calculated in a similar manner. Ten percent excess nitrogen was permitted in the basic analysis. The maximum nitrogen levels were then parameterized to permit the examination of the alternatives of no excess and 20 percent excess nitrogen loading.

Results

Twenty-two variations of the three forms of the general model were analyzed and compared. The primary points of comparison were differences in net revenues (farm income), sludge usage, crop rotation selection and nitrogen loading. Under the conditions assumed for this study it was shown that net revenues were high when sludge was used than when no sludge was applied. The highest net revenue was gained by using nine percent nitrogen sludge and selling heifer manure (as indicated in Table 2). In contrast, the lowest net revenue resulted when no excess nitrogen loading was permitted, necessitating the purchase of more fertilizer to provide complete crop nutrients.

Continuous corn (CCCCC) and corn and alfalfa (CCAAA) rotations for Class II land and the corn and alfalfa rotation (CCAAA) for Class III land were universally optimal for revenue maximization. The acreage devoted to the Class II crop rotations varied insignificantly, and was most greatly affected by nitrogen loading limits.

Sludge typically was not applied as heavily on Class III land as it was on Class II land, where corn demanded large amounts of nitrogen. Annual sludge application remained almost unchanged with sludge prices from \$5.00/dry ton to \$25.00/dry ton. At prices above \$30.00/dry ton, no sludge was used.

The established upper bounds on nitrogen loading rates were generally at their limits if sludge had been used. The upper limits on these constraints were not reached when sludge was not used. This result is reasonable because sludge must be taken "as is," with the fixed proportions of nitrogen, phosphorus, and potassium dependent on the percent dry matter. In order to obtain as much of the other nutrients as possible, sludge will be applied until the nitrogen limits are met.

The need for application of fertilizer nitrogen was often diminished in the fourth and fifth years because nitrogen requirements were partially met by nitrogen mineralized from sludge and manure applied in previous years. Also notable were decreasing amounts of fertilizer nitrogen needed for Class III land and the pasture due solely to residual quantities of nitrogen from manure.

Another point of concern is whether or not the amounts of sludge specified by the optimal programs resulted in excessive application of water to the farmland. The gallons of water/dry ton of sludge were calculated and then converted into acre-inches. A typical annual application of 30 dry tons of sludge on 75 acres would accompany the application of approximately 359,700 gallons (.18 acre-inch) of liquid. Original application rates, for a Model 2 variation, were 15, 23, 30, 37, and 45 dry tons/75 acres in years one through five, respectively. No foreseeable problems would arise as a result of the application of liquid sludge at levels as specified in this study.

The value of sludge as a fertilizer has been studied for a number of years by agronomists. Typically, the sludge's value, from an agronomic perspective, reflects its effect on crop yields and soil condition, and the proportion of sludge nutrients taken up in the plant tissue.

Table 2. Description of All Model Variations and Comparison of Net Revenues

Model Variation Number	Sludge provided at no cost (free)	Heifer corral manure sold @ \$5.00/dry ton	9% total nitrogen sludge used	4.2% total nitrogen sludge used	Liquid dairy manure and heifer corral manure used	No sludge use activity in model	Sludge priced @ \$5.00/dry ton	Sludge priced @ \$10.00/dry ton	Sludge priced @ \$15.00/dry ton	Sludge priced @ \$20.00/dry ton	Sludge priced @ \$25.00/dry ton	Sludge priced @ \$30.00/dry ton	Sludge priced @ \$50.00/dry ton	Spring and fall sludge and manure application	Nitrogen application (10% excess permitted)	Nitrogen application (20% excess permitted)	No excess nitrogen application permitted	Net Revenue for Five Year Planning Horizon
1-1					X	X									X			\$341,431.05
1-2		X			X	X									X			342,206.38
2-1	X		X		X	X									X			346,543.60
2-2	X			X	X	X									X			343,716.59
2-3			X		X	X	X								X			345,762.94
2-4			X		X	X		X							X			344,982.36
2-5			X		X	X			X						X			344,207.05
2-6			X		X	X				X					X			343,467.21
2-7			X		X	X					X				X			342,727.30
2-8			X		X	X						X			X			342,004.23
2-9			X		X	X							X		X			341,431.05
2-10				X	X	X		X							X			342,766.02
2-11				X	X	X				X					X			341,815.51
2-12	X	X	X		X	X									X			347,784.18
3-1	X	X	X		X	X								X	X			343,492.36
3-2	X			X	X	X								X	X			341,747.94
3-3			X		X	X		X						X	X			342,408.53
3-4				X	X	X		X						X	X			341,063.07
3-5			X		X	X				X				X	X			341,384.81
3-6				X	X	X				X				X	X			340,419.05
3-7	X		X		X	X								X		X		346,163.91
3-8	X		X		X	X								X			X	339,814.08

Table 3. Undiscounted and Discounted Net Present Value (NPV) of One Dry Tone of Sludge Based on 9% Nitrogen Content

Year	Column 1 Undiscounted NPV of Sludge		Column 2 Commercial Fertilizer		Column 3 NPV of Sludge Discounted @ Ten Percent	
	Sludge N (pounds)	Cost*	Fertilizer N (pounds)	Cost	Sludge N (pounds)	Cost
1	72.00	0.00	72.00	14.40	72.00	0.00
2	18.00	10.80	72.00	14.40	18.00	11.88
3	10.80	12.24	72.00	14.40	10.80	13.46
4	9.00	12.60	72.00	14.40	9.00	13.86
5	7.20	12.96	72.00	14.40	7.20	14.26
Undiscounted (Column 2-Column 1)			Discounted (Column 2-Column 3)			
			\$14.40			
			3.60			
			2.16			
			1.80			
			1.44			
			\$23.40			
			\$18.54			

Note: The pounds of sludge nitrogen in years two through five are residual amounts of nitrogen being mineralized and becoming available as a crop nutrient.

* Cost of fertilizer to bring total nitrogen to 72 pounds.

Dollar values of sludge have been estimated rarely. However, comparison of these few estimates with the ones derived from this study reaffirmed that the computed net present values, presented in Table 3, are reasonable approximations of sludge value. For instance, Forster, et al. (1976) based their estimates on total nitrogen, phosphorus, and potassium contents, estimating the worth of sludge with 6.4 percent nitrogen to range from \$36.00 to \$49.00 depending on fertilizer prices. Sludge with 3.5 percent nitrogen was estimated to be worth from \$10.00/dry ton to \$15.00/dry ton, given fertilizer prices at the time of the study. Reisner and Christensen (1976) found net farm value/ton of solids to be \$16.64, using a capital budgeting and linear programming framework. Sludge's value is overstated, if calculated solely on the basis of its nutrient content, since its nitrogen is released over time. While phosphorus and potassium are also released over time, relative proportions of phosphorus and potassium in sludge are small, and the impact of their mineralization on sludge's value is insignificant.

The net present value, based on nitrogen mineralization, of a dry ton of nine percent nitrogen sludge was calculated. The results are presented in Table 3. When net present value was discounted at ten percent, only a slight decrease in value resulted, because a significant amount of nitrogen mineralizes in the year of application. The value of a dry ton of

nine percent nitrogen sludge, with low toxic metal content has been estimated to be approximately \$21.00. Similar results were found in Model 2 and Model 3 variations, in which sludge prices were examined. The quantities of sludge used remained the same until the price of sludge exceeded \$25.00/dry ton. The undiscounted net present value of 4.2 percent nitrogen sludge was \$11.00/dry ton, while the discounted net present value was \$10.90/dry ton. Therefore, sludges containing four to five percent total nitrogen would be worth approximately \$11.00/dry ton, possibly more if the other nutrients are considered.

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