Estimating the Derived Demand for Sewage Sludge in Crop Production

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One option for the disposal of sewage sludge is land spreading, including application to private croplands. Land spreading may allow some of the sewage treatment costs to the municipality or county to be offset by farmers' payments for sludge as a crop producing resource. This study investigates the conditions under which a market for sludge will emerge. A linear programming model of a profit maximizing corn for gain farm is formulated and the quantity of sludge available is parametrically varied to trace out marginal productivity curves under various situations. The results for Anne Arundel county, Maryland sludge show a range in value from 0-35 $/ton at application rates from 0-20 tons/acre/year for three years.

The amendments to the Federal Water Pollution Control Act and passage of the Clean Water Act by the U.S. Congress reflect the nation's continuing desire to ensure the cleanliness of our water resources. One result of this commitment is the increased production of sewage sludge as municipalities make the required improvements in effluent quality. It is estimated that the 5.8 million dry tons of sludge generated annually in the U.S. are disposed of by landfilling (43%), incinerating (25%), landspreading (23%), and ocean dumping (9%) (Walker). The water pollution control laws have severely restricted ocean disposal of sludge and have set stringent controls on the discharge of any pollutant into navigable waters. Air quality criteria, high fuel costs, and the resultant ash that must be disposed of restrict the use of incineration, while increasing land values and space limitations often impose high costs on landfill programs. Thus the squeeze of material balance, along with growing demand for environmental quality, forces waste disposal managers to search for alternative measures of disposal.

These factors have increased the interest in landspreading, in which sludge is applied at rates low enough to ensure that environmental damage is minimal and the land is not permanently removed from production, while essential nutrients and organic matter are provided to crops grown in the amended soil. This recycling of resources is explicitly encouraged by the laws enacted and it brings agriculture into the urban waste management picture. Farmers, especially those located near municipalities, are faced with questions concerning the use of sludge on their land. Among these are: should they accept sludge, and if so how much? Should they be paid to allow sludge to be spread on their land, or should they pay for the product? To help answer these questions, the impact of sludge utilization on agricultural returns must be assessed.

Municipalities, in order to make informed decisions about waste disposal options, need to know how much farmers will be willing to pay for sludge, or how much they would have to be paid to accept it. With information about the demand for sludge and about the transportation and application costs, more accurate estimates of the feasibility and net cost of landspreading can be made.

The purpose of this paper is to estimate farmers' demand for sludge. With this demand function, we can answer questions about how much sludge farmers should take, and how much they should pay. The approach of the paper is to develop a linear programming

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model of a representative farm, and through this modelling effort, develop the derived demand for sludge as a factor of production. Sludge provides an alternative to commercial fertilizers as a source of nutrients. This model is applied to growing corn for grain in Anne Arundel county, Maryland.

The economics of landspreading as a means of disposing of sewage sludge has been treated in a variety of different ways. Seitz and Swanson develop the general notion of sludge disposal on agricultural land, and provide a break even analysis of a Chicago disposal—reclamation project. Ott and Forster analyze the least cost method of disposing of sludge for four Ohio communities. Reisner and Christensen study the costs and returns of applying sludge on forage land in Massachusetts. Loftis and Ward develop a dynamic programming model for determining the rate of application of sludge which minimize costs, subject to an environmental quality constraint. Zimmerman and Epp estimate the value of the nitrogen in sewage sludge using a 5 year linear programming model of a representative dairy farm.

The approach of this paper is different from the previous studies in that we derive the demand function for sludge by the agricultural sector. This approach allows us to investigate two different issues. First, under what conditions will markets for municipal sludge develop, and what are the barriers to the development of such markets? Second, does the optimal application of sludge to agricultural land imply a positive price for sludge?

Economics of Waste Disposal

The municipal authority's objective can be viewed as one of minimizing the costs of sludge disposal, given that the methods meet environmental standards. This objective omits other economically reasonable tools, such as higher water rates which influence the sludge production rate. However, it seems a practical goal for the sewage authority. Suppose there are three methods of disposing of sludge: landfilling, incineration, and landspreading. Further, suppose that the landspreading is to occur on farms, homogeneous except with respect to location. Each farm has the same returns from the application of sludge, but farms are located different distances from the sewage authority. Hence higher costs must be incurred to transport sludge to some farms.

The goal of the authority will be to minimize

$$(1) \quad C(x_{1f} X_2, xa) - \sum_{j=i} X[K(x_{3J}) - t_3(x_{3i})]$$

subject to

$$x_j + x_2 + x_3 = x_n$$

$$x_* = \sum_{j=l} X^\wedge$$

where

$X!$ = quantity of waste disposed of by landfilling

x_2 = quantity of waste disposed of by incineration

Xa = quantity of waste disposed of by landspreading

x_{3J} = amount of landspread, jth farm

x — total quantity of waste produced.

$C(Xi,x_2,x_3)$ = total costs to municipal authority of disposing of sludge by various methods including landspreading costs $tj(x_{3i})$ = transportation costs to jth farm for handling x_{3J} units of sludge

$k(x3j)$ = the marginal value of landspreading on the jth farm

$K(Xaj) = \int_0^{x_{3j}} k(x)dx$ = the benefits of landspreading x_{3i} on the jth farm

K(xaj) is simply the area under the marginal value function for landspreading. We are specially interested in computing the functional relationship between k and x_{3i}. The first order conditions for optimizing (1) are

$$d(x) - A = 0, \quad i = 1,2$$
$$C_3 - fj. - A = 0 \quad k(x_{3J})$$
$$- t',(x3,) = 0, \quad j = l,n$$

where $C_t(x)$ « $3C(x)/3xi$, the marginal cost of disposing of sludge by method i, where i = 1,2 and $t'j(x_3j) = dtj(x_3j)/dx_3j$, the marginal cost of transporting another unit of sludge to the jth farm. X is the multiplier associated with the constraint on the total quantity of sludge and ^t is the multiplier on the constraint requiring that the sum of sludge used on all farms be equal to the sludge used for landspreading. At the optimum & is the price charged for sludge. Note that

$$k(x_{3j}) \sim t'jUaj) = M-$$

The only cause for variation in the use of sludge is distance from the market, which is embodied in $t'j(x_{3J})$. We have chosen the criterion of maximizing the community's welfare rather than the sewage authority's revenue.

These conditions reflect our statement of the problem, but they do give us some insight into the formation of markets. For least cost disposal of sludge we require that net marginal costs for each method of disposal be equal:

(2) $$Ci(x) = C_2(x) = C_3(x) - k(x_a) + t'j(x_{3j}) \text{ for all } j.$$

The $k(x_{31})$ — $t'](x_{3j})$ term is the net marginal value of landspreading on the jth farm while C_3 is the marginal cost of preparing sludge for spreading. At the optimum, this term will be equal for all farms. For least cost disposal of sludge, k — t' need not be positive. If the marginal costs associated with landspreading (C_3) are low, then at the optimum the authority can afford to pay farmers to take the sludge. However, if the net marginal value (net of transportation costs) of sludge on farms is positive at the optimum, then a market for sludge exists in the sense that farmers will be willing to pay for the socially optimal level of sludge. Thus the net marginal value function $k(x_3j)$ plays a critical role in community decisions about sludge disposal, and on the institutional structure governing these decisions. In the following section we show how to recover $k(x_{3j})$ using a linear programming model.

A Model of Sludge Use

Sewage sludge consists of the water and solids that are separated from the effluent by the treatment process. The chemical and biological character of the solid portion is the basis for the anticipated benefits and potential hazards from using sludge on food producing land. In addition to essential plant nutrients, organic matter and water, sludges can contain pathogens, toxic heavy metals, pesticides and industrial chemicals (Jelinek and Braude). Heavy metals and certain persistent organic chemicals such as PCB's can enter the food chain from sewage sludge application to farm land if appropriate safeguards are not followed. Nutrient enrichment of surface and groundwater, and the introduction of disease spreading organisms must also be prevented.

Much of the nitrogen and phosphorus content of organic wastes is organic in form and is not readily available for plant uptake until it has been converted to inorganic compounds similar to those in commercial fertilizers. This mineralization of nutrients occurs gradually over time, at a rate governed largely by the level of microbial activity in the soil which in turn is a function of soil conditions such as pH, temperature, moisture, and characteristics of the organic waste (USDA, 1957). The quantities of N, P, and K supplied per unit of sludge per year can be calculated from an estimation of their respective mineralization rates. Table 1 shows the total nutrient content and assumed nutrient availability of a representative sludge under average climatic and soil conditions for the study area.

It is assumed that the only effect of sludge on farm profits is due to the reduction in fertilizer expenditures caused by the nutrients supplied. The study area, Anne Arundel county, Maryland currently has a landspreading program in which the sludge is transported to farms and applied at no charge to the farmer. The farmer does not incur additional tillage costs to control run-off because the sludge is applied by subsurface injection. In fact he may even receive benefits from the tillage provided or from the organic matter added, but these potential effects are not included in the model.

An exponential function from Ibach and Adams, depicting the average crop response to fertilizer for the region which includes the study area was used to extrapolate the yields attained as a result of the various sludge and fertilizer application rates considered in the model. Table 2 represents a simplification of this function, and shows the values used in the model.

While sludge is produced and can be injected in the soil year round, inclement weather and frozen ground limit the quantity that can be applied in winter, and the presence

Table 1. Nutrients supplied by Anne Arundel County Sewage Sludge

Nutrient	Total in Sludge lbs/ton	Lbs/ton available in		
		Year 1	Year 2	Year 3
N	82	27	8	3
P_2O_5	126	63	6	6
K_2O	4	3	0	0

Table 2. Impact of Nutrients on expected yield of corn

Yield (bu/acre)	Nutrients applied (lbs/acre) N	P	K
120	240	175	175
110	150	100	100
100	100	75	75
90	75	60	60

of growing crops, such as field corn, would restrict summer applications. In this model the sludge is injected into the soil in spring prior to seeding. The results, therefore, indicate the demand for applied sludge during the spring.

The criterion that is maximized is the difference between total revenues and the cost of nutrients. Other farm costs are assumed to be independent of sludge rate. Therefore, maximizing this restricted criterion also maximizes profits. Two versions of the model are considered, each covering a three year period.

Each model's objective is to maximize the present value of profits over a three year period, and can be described as follows:

max]T [TR_t - TQ](1 + r)-"-"
I^I.TiiJ t^\

+ ^ DPVjU + r)~^{3}

i=I

where

TR_t = total revenue

$TR_t = p_y h(L, S_t, F_{lt}, F_{2t}, Fat)$

TC_t = X P,F_{lt}
i=I

p_y — p'er bushel price of corn h(L, S_t, $F_{lt)}$ F_2t» F_3t) = annual production of corn in bushels

S_t = tons of sludge applied, year t F_{it} = pounds of fertilizer i used in year t,

i = N,P,K PI = price per pound of fertilizer, i = N,P,K

L = acres of land

DPVi = discounted value of nutrient available after third year i = N,P,K DPVi = Pim(l + r)/(m + r)

m = annual mineralization rate r

r = discount rate

subject to

L ≤ 100 acres; farm has 100 acres for corn production

3
2^ S_t ^ SI; SI = incremental values of sludge
t=i

from 0 to 60 tons per acre.

In the first version, model A, sludge is applied only in the first year. Fertilizer N,P,K can be applied any year in various combinations with different levels of sludge to grow corn in each of 3 years. The second, model B, allows the sludge to be applied in each of the three years. The average Zn content of the Anne Arundel sludge would limit the total amount that could be applied to 60 tons per acre and the amounts that could be applied per year to 20 tons per acre. The LP model chose the optimal allocation of the limited quantity of sludge.

The growing activities in model A include each of the 4 levels of fertilizer shown in Table 2 in each of the 3 years in combination with 9 levels of sludge (from 0 to 10 T/A in 2.5 T/A increments) for a total of 576 activities. Model B, with sludge application permitted in all 3 years, would have 191 million growing activities, but with the restriction that the amount of sludge applied in any year must be greater than or equal to the amount applied in any succeeding year, the number of activities was reduced to 10,560. This follows from the assumption that given constant prices, if it were optimal for a farmer to apply a certain quantity per acre in the first year, then it would not be optimal for him to apply greater than this amount in the following year.

The remaining activities of the linear programming matrix include buying fertilizer, selling corn, and absorbing the value of the N and P that would be left over in the soil at the end of the model's three year period, which we call the reserve value. The present value of this carryover (DPV) was estimated based on the amount and time of sludge application, plant uptake, leaching loss, and mineralization rate of 2% per year. The final set of activities allows the value of this excess N and P to be included in the decision making process. Versions of both models were run with and without the reserve N and P evaluations.

The prices used were as follows: corn at \$2.75/bu; nitrogen at \$.31/lb; phosphate at \$.25/lb; potash at \$.14/lb and were based on those reported in Agricultural Prices, May

1982. Models were run under this set of prices and at discount rates of 5 and 10 percent. The residual values of the excess N and P at 10% discount rate were $.043/lb and $.035/lb, respectively, and at *5%* were $.08/lb and $.065/ lb.

Results

The basic results for some representative models are given in Table 3. Model A evaluates different quantities of sludge applied in the first year. Model B looks at the impact of varying the rate of application over three years. The different cases for Models A and B capture the effects of changing interest rates and changing the reserve value of nutrients. Table 3 shows the shadow prices per additional ton per acre for the different models, different interest rates, and different reserve values for nutrients. The table can be interpreted as follows. Each one of the 751st through the 1000th ton of sludge would increase profits by $10.87. The shadow price in each 250 ton step doesn't change because in the LP model the quantity of sludge available to the farmer was parametrically increased in 250 ton intervals. For model A, the environmental maximum of twenty tons per acre per year due to the Zn content brings the shadow price to zero at that point. The relationships are as we would guess, with the lower discount rate shifting out the derived demand for sludge (A3) and a reduction in the reserve value of nutrients reducing the derived demand for sludge (A2). Though not shown here, results for changing the price of corn are similarly logical.

The shadow price in Model B goes to zero at cumulative application rates of 60 tons per acre, which represents the environmental maximum rate of 20 tons per acre per year. The program increases application rate in increments of 2.5 tons per acre, resulting in many feasible ways to distribute, say 1,000 tons over 100 acres over 3 years. Table 4 shows how various quantities are distributed optimally. For example, when 1,000 tons of sludge are taken by the farm, under Model BI or B2, 500 tons are applied the first year and 250 tons the second and third years. Another feasible scenario for 1,000 tons would be 250 tons the first two years and 500 tons the third year, but clearly with a positive discount rate or with carryover of nutrients this distribution of 1000 tons would not be optimal.

A zero discount rate, no carryover, no environmental restrictions and very long planning horizon would lead to the same application rate each year. It is always feasible, though never optimal, to apply 750 tons in the third year, with none in the first two years.

Implications

These schedules show, given the economic and agronomic relationships assumed, the amounts farmers would be willing to pay for

Table **3.** **Value** of the Marginal **Product** ($/ton)

Discount Rate Excess N,P evaluated Model	.10 Yes AI	.10 No A2	.05 Yes A3	.10 Yes BI	.10 No B2	.05 Yes B3	Sludge (Tons per farm) up to
	$32.46	$29.69	$35.44	$32.46	$29.69	$35.44	250
	25.45	22.67	28.90	25.45	22.67	28.81	500
	10.90	8.13	13.46	13.24	10.04	16.56	750
	10.87	8.09	13.43	11.14	8.13	15.18	1000
	6.22	3.44	8.78	10.90	8.09	13.44	1250
	6.22	3.44	8.78	10.87	7.26	13.44	1500
	6.21	3.44	8.76	9.89 8.27	6.69	12.75	1750
	5.10 0 0	2.32 0 0	7.61 0 0	8.27 5.77	4.72	11.84	2000
	0 0 0 0	0 0 0 0	0 0 0 0	3.91 3.91	4.72 1.92	11.84	2250
	0	0	0	3.67 3.67	.46 -42	9.28	2500
				3.67	.42 .40	6.97	2750
					.38	6.97	3000
						6.51 6.51	3250
						6.51	3500
							6000

Table 4. Three year schedules of optimal sludge applications for a representative 100 acre farm

Model		BI			B2			B3	
Discount ra	te P	.10			.10			.05	
Reserve N,	evaluated	Yes			No			Yes	
Sludge per farm (Tons)	1	Year 2	3	1	Year 2	3	I	Year 2	3
0 125	0.0	0.0 0.0	0.0 0.0	0.0	0.0 0.0	0.0 0.0	0.0	0.0 0.0	0.0 0.0
250	125.0	0.0	0.0 0.0	125 250	0.0 0.0	0.0 0.0	125.0	0.0 0.0	0.0 0.0
375	250.0	0.0	0.0 0.0	375 500	0.0	0.0 0.0	250.0	0.0	0.0 0.0
500	375.0	0.0	0.0	500 500	125.0	0.0 0.0	375.0	125.0	0.0
625	500.0	125.0	125.0	625 750	250.0	0.0 0.0	500.0	250.0	125.0
750	500.0	250.0	250.0	875 1000	250.0	0.0	500.0	250.0	250.0
875	500-0	250-0	250.0	1000	250.0	125.0	500.0	250.0	250.0
1000	500.0	250.0	250.0	1000	250.0	250.0	500.0	250.0	250.0
1125	500-0	250.0	250.0	1000	250.0	250.0	500.0	250.0	250.0
1250	625.0	250.0	250.0	1000	250.0	250.0	625.0	250.0	250.0
1375	750.0	250.0	250.0	1000	250.0	312.5	750.0	250.0	250.0
1500	875.0	250,0	250.0	1000	375.0	375.0	875.0	500.0	250.0
1625	1000.0	375.0	312,5	1000	500.0	500.0	1000.0	750.0	312.0
1750	1000.0	500.0	375.0	1000	562.5	500.0	875.0	750.0	375.0
1875	1000.0	562.0	500.0	1500	625.0	500.0	750.0	750.0	500.0
2000	1000.0	625.0	750.0	2750	750.0	500.0	812.5	750.0	750.0
2250	1000.0	750.0	875.0	2000	1000.0	375.0	875.0	750.0	875.0
2500	1000.0	750.0	1000-0	2000	750.0	250.0	1000.0	875.0 1	1000.0
2750	1000.0	875.0	1166.6	2000	750.0	1000.0	1000.0	000.0	1166.7
3000	1000.0	1000.0	1333.4	2000	1125.0	2000.0	1000.0	1166.7	1333.3
3500	1000.0	1166.7	1666.6		1750.0		1000.0	1333.3	1666.6
4000	1166.7	1333.4	2000.0		2000.0		1166.7	1666.7	2000.0
5000	1333.4	1666.7			2000.0		1333.4	2000.0	
6000	1666.7	2000.0					1666.7		
	2000.0						2000.0		

various levels of sludge. What are the implications of the estimated schedules for the disposal of sludge? To answer this question, we need to use the individual farm schedule to infer the aggregate demand schedule.

In the study area there were about 10,000 acres in corn in 1980 (Maryland Dept. Agr.). Assuming that about half of this land is suitable for sludge application, the equivalent of 50 farms of the representative size assumed in this study would be located in the county. We use model BI as the basis for examining the implied market. In this model, the price of corn is $2.75 per bushel, the interest rate is 10%, the value per pound of reserve Nis $.043 and the value per pound of reserve P is $.035.

First, assume that all transportation costs are zero. With this assumption, we can read from Table 3 the per farm demand at various prices or the price implied by choosing the quantity of sludge to be land applied. For example, if we choose a price of $10.90 per ton the typical farmer would contract for 12.5 tons per acre for a total of 1250 tons over the 3-year period. As shown in Table 4 each farmer will want 750 delivered the first year, and 250 delivered the second and third year. The aggregate demand would be the sum of the usage by all 50 farms, or 37,500, 12,500, and 12,500 for each of the three years. Approximately 11,000 tons of sludge are produced per year in the county.

Assuming transportation costs are zero obviously inflates the demand schedule for sludge. To gain a more realistic picture of the aggregate demand, let us introduce the spatial element in a simplified way. Suppose that half the farms are located ten miles away from the treatment plant, the other half located two miles away. From Hillmer (p. 30) assume that the transport cost per mile is $2 per ton of sludge in which case, farms 10 miles away would have to pay $ 16 per ton more than those nearby. Now what would happen if sludge were offered at $10 per ton? The price to the more distant farms would be $30, inducing them to take 250 tons a piece, while the price to the nearby farms would be $14, at which they would take 500 tons. The stream of annual aggregate demands generated would be 18,750, 0 and 0 tons.

A systematic altering of price and observing aggregate quantities demanded would allow us to determine the aggregate demand schedule for sludge. Then, when combined with information on the relative marginal costs of other methods of waste disposal [Ci, C2, and C_3, in equation 2] one could determine whether a market for sludge might emerge. For example, if Ci = Ci = C_3 then it is clear that sludge should be shipped to farms until the net price to the farmer falls to zero.

Two aspects of the voluntary nature of the contracting are likely to be violated in reality. First the markets outlined above will not function indefinitely over time. In Maryland there are guidelines indicating the cumulative amount of sludge that can be applied to farmland without risk of toxic effects on plants or hazardous accumulation in feed or food crops grown on the land (University of Maryland Agronomy Dept.). The amount may vary from 40 to several hundred tons per acre depending on heavy metal content and soil properties. Second, in some cases there may be local opposition to the disposal of any sludge as a fertilizer supplement. Thus while a consideration of the two party transaction suggests that landspreading may be optimal, the implementation may require dessimination of information not only to farmers but also to the community at large. Here, too, there is a role for extension.

Summary

This paper investigates the circumstances under which a market for sludge will develop. The approach of the paper is to compute the derived demand for sludge as a factor of production of corn in a linear programming framework, where sludge substitutes for purchase of nutrients. The model results shows that under the assumptions made, there is considerable derived demand for sludge, and that even when transportation costs are considered, a voluntary market is not out of the question.

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