OPTIMAL CROP MIX FOR LAND APPLICATION OF MUNICIPAL WASTEWATER

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ABSTRACT

Least cost solutions for a three million gallon a day land application of municipal wastewater system are estimated for three levels of capital cost subsidy: no subsidy, 75 percent, and 85 percent. Irrigation of reed canarygrass is superior of alfalfa, corn, forests, and natural vegetation (weeds). The cost of a full year irrigation of reed canarygrass ranges from $493,000 to $565,000 depending upon the assumed value of reed canarygrass. If the local municipality minimizes its costs while receiving subsidies, inefficiencies result. Total costs to society can increase in excess of 65 percent of the minimum cost solution.

In recent years, there has been increasing interest in controlling water pollution resulting from municipal wastewater discharges. Efforts to control water pollution have focused on the requirements and enforcement procedures of P.L. 92-500, the Federal Water Pollution Control Act Amendments of 1972. Two features of this law which are relevant to this discussion are: (1) the explicit encouragement of wastewater treatment and reuse processes which recycle pollutants to other parts of the environment, particularly land application of municipal wastewater as a method of advanced wastewater treatment; and (2) the provision of federal grants to pay for up to 75 percent of the construction costs of municipal wastewater treatment works including the costs of land which is an integral part of the wastewater treatment process.

A model to minimize the local costs of land application of municipal wastewater, given different capital subsidy rates is used to examine three hypotheses: (1) The minimum cost crop mix for land application includes more than one crop. (2) Restrictions on the land application system significantly raise treatment costs. (3) When local treatment costs, net of federal subsidies, are minimized, socially inefficient treatment options will be selected.

PROBLEM SETTING

No studies are available dealing with cost minimization of land application of municipal wastewater[1]. Bradley (1976) and Young have investigated the costs of land application of wastewater for various single cropping alternatives based on cost data provided by Pound, Crites, and Griffes. These studies do not attempt to develop least cost estimates for land treatment systems but present cost estimates for land application under various scenarios.

The impact of capital subsidies on the selection of wastewater treatment processes has been analyzed in two studies (Marshall and Ruegg, and Rose). These studies investigated the inefficiencies resulting between selection of treatment processes, but did not investigate inefficiencies resulting from subsidies once a treatment process was selected. The selection of a treatment process does not automatically determine the ratio between capital and variable inputs. Thus, inefficiencies can occur when local decision makers attempt to minimize the sum of variable costs and unsubsidized capital costs.

EMPIRICAL ANALYSIS

A linear programming model was developed to minimize the costs of treating 3 million gallon per day (mgd) of wastewater using land application (Bradley, in process). The results are applicable to soil and climatic conditions similar to central Pennsylvania. The model was used to evaluate land application of wastewater with various combinations of crops using cost data from Pound, Crites, and Griffes and unpublished data on crop growth under wastewater irrigation obtained from Drs. L. T. Kardos and W. E. Sopper of The Pennsylvania State University. The latter source includes information on nutrient removal by various crops. The model minimizes treatment costs by selecting the crop subject to a nutrient removal constraint. The cropping activities considered are shown in Table 1. The length of the irrigation season and the application rate for a particular cropping activity are limited by the available data. Neither is permitted to exceed the values reported by Kardos, *et al.* As the application rate and irrigation season increase, treatment costs decrease since fewer acres are irrigated. Conversely net crop revenue tends to increase as more acres are irrigated.[2]

Least cost solutions at three subsidy levels are obtained for four situations discussed below. Additional solutions are computed for two variations in the price of reed canarygrass and for two lengths of irrigation seasons. Annual total costs to society and annual total local costs are minimized for each solution.[3] Inefficiencies due to the subsidies are determined by comparing the total costs to society of the unsubsidized solutions and the solutions which minimize subsidized local costs.

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[1]Land application or treatment of wastewater refers to the controlled discharge of partially treated sewage effluents onto land to remove contaminants from the water. The soil and agricultural crops and forests adsorb and filter nitrates, phosphates, organics, and other elements from the effluent. Land application provides a high level of wastewater treatment comparable to advanced wastewater treatment systems as described by Pound, Crites, and Smith.

[2]For a complete description of the model and data see Bradley (in process).

[3]Annual total costs to society are defined as the sum of amortized construction costs, amortized land costs, and operating costs less crop revenue. Local costs are total costs less subsidies for construction and land purchase.

TABLE 1.

Costs and Return from Land Application of Wastewater

Crop	Application Rate (Inches/Week)	Irrigation Season Days	Crop Yield[a] (Per Acre)	Production Cost[b] Per Acre (Dollars)	Crop Price (Dollars)	Net Crop Revenue Per Acre (Dollars)
Alfalfa silage	1.0	214	8.7 tons	132.0	22.0	58
(60 percent moisture basis)	1.5	214	9.4 tons	132.0	22.0	74
	2.0	214	9.9 tons	132.0	22.0	86
Corn grain	1.0	214	78.2 bu.	118.0	2.2	54
(15.5 percent moisture basis)	1.5	214	79.2 bu.	118.0	2.2	56
	2.0	214	80.1 bu.	118.0	2.2	58
	2.5	214	68.4 bu.	118.0	2.2	33
	3.0	214	56.2 bu.	118.0	2.2	6
Corn silage	1.0	214	16.0 tons	139.0	15.0	101
(70 percent moisture basis)	1.5	214	16.2 tons	139.0	15.0	104
	2.0	214	16.4 tons	139.0	15.0	107
	2.5	214	14.0 tons	139.0	15.0	71
	3.0	214	11.5 tons	139.0	15.0	33
Reed canarygrass silage	1.0	365	7.8 tons	120.0	15.0	-3
(60 percent moisture basis)	2.0	365	11.7 tons	120.0	15.0	54
	2.5	365	13.5 tons	120.0	15.0	82
Natural vegetation[d]	1.0	244	0.0 tons	0.0	0.0	0
	1.5	244	0.0 tons	0.0	0.0	0
	2.0	244	0.0 tons	0.0	0.0	0
	2.5	244	0.0 tons	0.0	0.0	0
	3.0	244	0.0 tons	0.0	0.0	0
Mixed oaks[e]	1.0	365	N/A	0.5	N/A	9
	1.5	365	N/A	0.5	N/A	9
	2.0	365	N/A	0.5	N/A	9
	2.5	365	N/A	0.5	N/A	9
Red Pine[e]	1.0	244	N/A	0.5	N/A	57

[a]Crop yields estimated from unpublished data obtained from Dr. L. T. Kardos, The Pennsylvania State University. The crop yields are estimates of harvestable yields.

[b]Annual production costs for agricultural and silvicultural crops are estimated from Bradley (in process). Irrigation and storage costs are not included in production costs. Production costs refer to cultivation and harvesting costs.

[c]Prices for agricultural crops are prices at the land treatment site. Forage prices are computed using the Peterson method. Base prices for corn and soybean oil meal are assumed to be 2.5 dollars per bushel and 10.0 dollars per 100 pounds, respectively. The 30 cents lower price for corn grain at the site reflects allowances for drying and hauling costs.

[d]Natural vegetation is volunteer growth on uncultivated, unmowed land. There are no production costs or crop revenues.

[e]It is not appropriate (N/A) to think of silvicultural yields and prices on an annual basis since growth rates are assumed to be quadratic. Annualized net forestry revenues are estimated by discounting over the assumed 20 year life of the treatment operation. The stumpage values of timber and pulp used are as follows: 1) 40 dollars per 1000 board feet of oak wood
2) 1.5 dollars per cord of oal pulp;
3) 4 dollars per cord of red pine pulp thinning;
4) 8 dollars per cord of red pine clear cut; and
5) 100 dollars per 1000 board feet of red pine poles.

RESULTS

Minimum cost solutions were determined for four situations (Table 2): 1) a case restricted only by the limits of the available data, 2) a case where the maximum irrigation rate for reed canarygrass is 2 acre inches per week (in/wk), 3) a solution where no reed canarygrass is permitted, and 4) a solution where the irrigation season is restricted to 285 days per year. The latter restriction coincides with the EPA recommended irrigation season for land application systems in central Pennsylvania (Whiting). All solutions are constrained such that nitrate concentrations in the perculant at the 48 inch soil depth are projected to be less than or equal to 10 mg/l.

The unrestricted minimum cost solution calls for irrigating 309 acres of reed canarygrass[4] at a weekly irrigation rate of

[4]The harvested F.O.B. price of reed canarygrass silage is assumed to be $15.00/ton. This value is based on cattle feeding experiments with reed canarygrass at The Pennsylvania State University. The sensitivity of the solution to this price assumption is tested in the following section.

TABLE 2.

Minimum Local Cost Solutions for Four Situations at Three Subsidy Levels for Land Application of Wastewater

Percent Subsidy	Crop	Months Irrigated	Application Rate (in/wk)	Acres Irrigated	Annual Total Local Costs	Annual Total Costs	Difference in Total Costs From Unrestricted Solution
				Unrestricted			
0	RCG[1]	12	2.5	309	$493,000	$493,000	$ –
75	RCG	12	2.5	309	202,000	493,000	–
85	RCG	12	2.5	309	163,000	493,000	–
			Reed canarygrass application rate less than or equal to 2 inches per week				
0	RCG	12	2.0	387	536,000	536,000	43,000
75	RCG	12	2.0	387	221,000	536,000	43,000
85	RCG	12	2.0	307	178,000	556,000	63,000
	C[2]	7	2.0	135			
				No reed canarygrass			
0	ALF[3]	7	2.0	180	731,000	731,000	238,000
	NV[4]	8	3.0	212			
	MOF[5]	12	2.0	68			
75	ALF	7	2.0	189	283,000	733,000	240,000
	NV	8	3.0	222			
	MOF	12	2.5	43			
85	C	7	2.0	660	215,000	876,000	383,000
				285 day irrigation season			
0	RCG	9.33	2.5	396	624,000	624,000	131,000
75	RCG	9.33	2.5	396	237,000	624,000	131,000
85	RCG	9.33	2.5	396	185,000	624,000	131,000

[1]Reed Canarygrass Silage

[2]Corn Silage

[3]Alfalfa Silage

[4]Natural Vegetation (weeds)

[5]Mixed Oak Forest

2.5 in/wk[5] (Table 2). This system costs $493,000 per year. A 75 percent capital subsidy reduces costs to the local municipality to $202,000 per year, a savings of $291,000 per year. With an 85 percent capital subsidy, local costs are $163,000 per year.

Limiting the reed canarygrass application rate to 2 in/wk increases annual total costs to $536,000 per year. The minimum cost solution calls for irrigating 387 acres of reed canarygrass with an application rate of 2 in/wk. With a 75 percent capital subsidy the cost of the local municipality is $221,000 per year. If the local municipality receives an 85 percent capital subsidy and minimizes costs, the crop mix changes to 307 acres of reed canarygrass and 135 acres of corn irrigated at 2 in/wk. Irrigation of corn requires more capital than irrigation of reed canarygrass. Corn has a shorter irrigation season, therefore, its inclusion in the solution requires additional storage and irrigated acreage. However, these higher costs are offset by additional crop revenue which reduces the municipality's unsubsidized costs. The costs to the local municipality are $178,000 per year, while the annual total costs of this system are $556,000, an increase of $20,000 over the minimum cost solution with no subsidy. Replacing 80 acres of reed canarygrass with 135 acres of corn increases total annual capital costs by $25,000, net annual crop revenue by $10,000, and annual non-crop related operating costs by $5,000. Given an 85 percent capital subsidy, the $25,000 increase in total annual capital costs only costs the local municipality $4,000. Thus, the local municipality pays $9,000 to receive $10,000, but the total costs to society are $20,000 higher. Minimization of local costs with an 85 percent subsidy results in higher costs to society.

With the third restriction—no reed canarygrass—total costs are minimized when 180 acres of alfalfa and 68 acres of mixed oak forest are irrigated at 2 in/wk and 212 acres of natural vegetation[6] are irrigated at 3 in/wk. This mix of cropping activities minimizes treatment costs by selecting cropping activities with long irrigation seasons (mixed oak forest) and high application rates (natural vegetation). Alfalfa, which is the best nutrient remover other than reed canarygrass, enters in sufficient acreage so that the nutrient constraint is not exceeded. Annual total costs for this solution are $731,000

[5]This is the highest application rate on reed canarygrass for which information is available from the wastewater irrigation project at The Pennsylvania State University.

[6]Natural vegetation is defined as volunteer growth on uncultivated and unmowed land.

per year.[7] Thus, if reed canarygrass cannot be used for wastewater irrigation, the costs of a wastewater treatment system rise by $238,000 per year, almost a 50 percent increase.

Introducing a capital subsidy into the "no reed canarygrass" restriction changes the optimum crop pattern. With a 75 percent capital subsidy 189 acres of alfalfa are irrigated at 2 in/wk, 222 acres of natural vegetation are irrigated at 3 in/wk, and 43 acres of mixed oak forest are irrigated at 2.5 in/wk. Local costs are $283,000 and the annual total costs for the system are $733,000, an increase of $2,000 above the unsubsidized solution. With an 85 percent capital subsidy, the least cost solution becomes 660 acres of corn irrigated at 2 in/wk. Annual local costs in this case are $215,000, while total costs are $876,000. Capital subsidization again provides an incentive for local municipalities to increase total capital costs in order to obtain more net crop revenue from corn. Increasing the capital subsidy from 75 to 85 percent raises the total cost of the system by $145,000 per year. Elimination of reed canarygrass from the solution with an 85 percent capital subsidy raises costs by $383,000 an increase of 78 percent over the cost of the unrestricted solution.

The Environmental Protection Agency recommends that land application wastewater treatment systems located in central Pennsylvania store their effluent for an 80 day period each winter. With this restriction, the least cost solution is still reed canarygrass irrigated at 2.5 in/wk, but 396 acres rather than 309 acres are needed. Total costs increased to $624,000 per year, an increase of $131,000 per year. The introduction of capital subsidies does not change the optimal crop mix from reed canarygrass for this restriction.

SENSITIVITY TO REED CANARYGRASS PRICE VARIATIONS

The price of reed canarygrass was varied from the $15.00 per ton assumed above to determine the sensitivity of the optimal solution to price changes. Least-cost solutions for two reed canarygrass prices ($6.00 and -$3.00 per ton) and two lengths of irrigation season are presented in Table 3.[8] Negative prices of reed canarygrass occur when the municipality must pay someone to take harvested reed canarygrass from the wastewater treatment site. At $6.00 per ton for reed canarygrass the least cost solution remains irrigation of reed canarygrass with an application rate of 2.5 in/wk. When the price of reed canarygrass falls to -$3.00 per ton, natural vegetation and mixed oak forests are also included in the least-cost solution.

When the price of reed canarygrass falls from $15.00 to $6.00 per ton, the optimal solution remains irrigation of 309 acres of reed canarygrass with a 2.5 in/wk application rate for the entire year. The reduction in the price of reed canarygrass reduces net revenue from the land application system by $37,000 per year raising total local costs with no subsidy to $530,000 per year. Introduction of a 75 percent capital subsidy changes the optimal solution to irrigation of 246 acres of reed canarygrass at 2.5 in/wk and irrigation of 135 acres of corn at 2 in/wk. Annual total local costs are $237,000 and annual total costs are $552,000 per year. Annual total costs are $22,000 greater than when no subsidy is provided. Raising the capital subsidy to 85 percent does not change the optimal solution. Annual total local costs become $195,000 per year with annual total cost remaining at $552,000 per year.

When the price of reed canarygrass falls to -$3.00 per ton with year round irrigation, the least-cost solution includes irrigation of mixed oak forest and reed canarygrass. In this case, 203 acres of reed canarygrass and 106 acres of mixed oak forest are irrigated with an application rate of 2.5 in/wk.[9] Annual total costs are $565,000, which are $72,000 higher than the cost for the unrestricted case in Table 2. When a 75 percent capital subsidy is added, corn enters the solution with reed canarygrass and mixed oak forest. With this case, 159 acres of reed canarygrass and 87 acres of mixed oak forest are irrigated at 2.5 in/wk while 135 acres of corn are irrigated at 2 in/wk. Total annual local costs are $258,000 per year with a total annual cost of $580,000 per year, an increase of $15,000 over the unsubsidized cost solution. With an 85 percent subsidy, 660 acres of corn are irrigated at 2 in/wk. Annual local costs are $215,000 per year while annual total costs rise to $876,000 per year, an increase of $296,000 over the unsubsidized cost solution—$383,000 greater than the cost of the unrestricted solution in Table 2.

Shortening the irrigation season with a $6.00 per ton price for reed canarygrass does not change the optimal crop mix. With no capital subsidy the crop mix remains 396 acres of reed canarygrass irrigated at 2.5 in/wk. Annual total costs are $672,000 per year. The crop mix and application rate are identical to the least-cost solution with the higher price of reed canarygrass ($15.00/ton) and the shorter irrigation season in Table 2. The introduction of a capital subsidy changes the optimal solution. With a 75 percent capital subsidy, 309 acres of reed canarygrass are irrigated at 2.5 in/wk and 145 acres of corn are irrigated at 2.5 in/wk and 145 acres of corn are irrigated at 2 in/wk. Total local costs become $281,000 per year with total annual costs of $694,000 per year, an increase of $22,000 over the unsubsidized solution. Raising the subsidy to 85 percent changes the least-cost solution dramatically. In this case, 660 acres of corn are irrigated at an application rate of 2 in/wk for a total annual local cost of $215,000 per year. Total costs rise to $876,000 an increase of $204,000 over the unsubsidized solution.

When the price of reed canarygrass falls to minus three dollars per ton with the shorter irrigation season, reed canarygrass remains in the unsubsidized solution only. With no subsidy, 174 acres of reed canarygrass and 135 acres of mixed oak forest are irrigated at 2.5 in/wk and 85 acres of natural vegetation are irrigated at 3 in/wk. Annual total local costs are $709,000 per year which is $216,000 higher than the unrestricted solution with the higher reed canarygrass price. The addition of a capital subsidy removes reed canarygrass

[7] Treatment is expensive with this set of crops for two reasons. First, irrigation costs are high because of the large acreage involved. Second, approximately 300 million gallons of storage capacity must be provided to retain wastewater in those months when crops are not irrigated.

[8] A complete sensitivity analysis of the model to variations in the price of reed canarygrass can be found in Bradley (in process). The two prices ($6.00 and -$3.00 per ton) were chosen since they represent changes in the optimal solution.

[9] Mixed oak forest would be irrigated exclusively in this case if it were capable of meeting the 10 mg/l nitrate removal constraint. The mix of reed canarygrass and mixed oak forest irrigation is such that the average nitrate constraint is 10 mg/l. Irrigation of more forest and less reed canarygrass would violate the constraint.

TABLE 3.
Minimum Local Cost Solutions for Two Reed Canarygrass Prices with Two Irrigation Seasons for Land Application of Wastewater

Percent Subsidy	Crop	Months Irrigated	Application Rate (in/wk)	Acres Irrigated	Annual Total Local Costs	Annual Total Costs	Difference in Total Costs From Unrestricted Solution in Table 1
			Year round irrigation with the price of reed canarygrass equal to $6.00 per ton				
0	RCG[1]	12	2.5	309	$530,000	$530,000	$ 37,000
75	RCG	12	2.5	246	237,000	552,000	59,000
	C[2]	7	2.0	135			
85	RCG	12	2.5	246	195,000	552,000	59,000
	C	7	2.0	135			
			Year round irrigation with the price of reed canarygrass equal to -$3.00 per ton				
0	RCG	12	2.5	203	565,000	565,000	72,000
	MOF[3]	12	2.5	106			
75	RCG	12	2.5	159	258,000	580,000	87,000
	C	7	2.0	135			
	MOF	12	2.5	87			
85	C	7	2.0	660	215,000	876,000	383,000
			285 day irrigation season with the price of reed canarygrass equal to $6.00 per ton				
0	RCG	9.33	2.5	396	672,000	672,000	179,000
75	RCG	9.33	2.5	309	281,000	694,000	201,000
	C	7	2.0	145			
85	C	7	2.0	660	215,000	876,000	383,000
			285 day irrigation season with the price of reed canarygrass equal to -$3.00 per ton				
0	RCG	9.33	2.5	174	709,000	709,000	216,000
	NV[4]	8	3.0	85			
	MOF	9.33	2.5	135			
75	C	7	2.0	215	288,000	765,000	272,000
	NV	8	3.0	244			
	MOF	9.33	2.5	17			
85	C	7	2.0	660	215,000	876,000	383,000

[1]Reed Canarygrass Silage
[2]Corn Silage
[3]Mixed Oak Forest
[4]Natural Vegetation

from the optimal solution. With a 75 percent capital subsidy the optimal solution includes 215 acres of corn with a 2 in/wk application rate, 244 acres of natural vegetation with a 3 in/wk application rate and 17 acres of mixed oak forest at 2.5 in/wk. Annual total local costs are $765,000 per year, $56,000 higher than the unrestricted case. With the capital subsidy raised to 85 percent, 660 acres of corn are irrigated with an application rate of 2 in/wk. This is the same solution as the 85 percent capital subsidy solutions for year round irrigation with the price of reed canarygrass equal to $6.00 per ton and the short irrigation season, -$3.00 per ton reed canarygrass options. Annual local costs are again $215,000 per year and annual total costs rise to $876,000 per year which are $167,000 higher than the zero subsidy solution.

CONCLUSIONS

Least-cost cropping solutions for land application of wastewater systems have been discussed. The cost estimates are for a three million gallon per day system located in central Pennsylvania. The analysis shows that irrigation of reed canarygrass is the least-cost solution when no restrictions are placed on the system. The removal of reed canarygrass from consideration raises annual total costs by $238,000 per year, a 48 percent increase in costs. If the length of the irrigation season is restricted to 285 days per year, annual total costs rise by $131,000 per year, a 26 percent increase in costs. Even when the value of reed canarygrass falls so low that one has to pay $3.00 per ton to have it hauled away, some reed canarygrass remains in the least-cost solution due to its nutrient removal capabilities.

When communities are permitted to minimize their local costs within a system of partially subsidized costs, additional costs can be placed on society, and socially inefficient solutions may be chosen. The attractiveness of the socially inefficient solutions to the local municipality increases as the price of reed canarygrass decreases. When the price of reed canarygrass is six dollars per ton with an 85 percent capital subsidy and year round irrigation, minimizing local costs increases total costs by $22,000 per year. If the irrigation season is restricted to 285 days per year and the local community is permitted to minimize its cost, it will choose a system with costs which are 30 percent higher or $204,000 per year than the least-cost system.

Three implications from the analysis are: (1) Reed canarygrass appears to be a superior crop in land treatment systems for the assumptions made; (2) In administering construction subsidies, EPA needs to insure the construction of socially efficient treatment systems: (3) Requiring effluent storage and subsequent land application is expensive. This added expense may be unnecessary since experiments at The Pennsylvania State University have demonstrated that year round irrigation of reed canarygrass is feasible.

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