Resources, Conservation and Recycling 17 (1996) 97–107

resources, conservation and recycling

Returns to municipalities from integrating crop production with wastewater disposal[1]

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Received 27 September 1995; revision received 3 January 1996; accepted 10 February 1996

Abstract

Land application of wastewater provides an alternative for wastewater deposition which can be both environmentally sound and economically viable. Effluent from the wastewater system of the city of Lubbock, Texas, USA was used for crop irrigation as a study case. A dynamic optimization model was developed to determine the optimal cropping system that would utilize all the effluent supplied, remove all hazardous materials from the effluent, and maximize crop net revenues. The results indicate that the optimal crop composition contains alfalfa, wheat-corn, wheat-grain sorghum, and cotton. The study also reveals that increases of cropland area and effluent volume could increase municipal revenues.

Keywords: Wastewater; Land application; Crop irrigation; Dynamic optimisation model; Crop composition

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1. Introduction

Municipal and industrial wastewater treatment facilities are often planned with little regard for potential (a) monetary benefits to offset investment and operating costs or (b) degradation of the environment due to dumping of the after-treatment waste. As urban populations grow governments are implementing laws on the activities that

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[1] Publication T-1-414, College of Agricultural Sciences and Natural Resources, Texas Tech University.

0921-3449/96/$15.00
PII 0921-3449(96)01106-8

present potential damage to the environment. As a result, municipalities are struggling with increased environmental regulations and budget constraints. The goal of most municipalities is to meet regulations in a cost effective manner [1].

One method of wastewater treatment is land application. Land application is defined as 'the controlled application of wastewater onto the land surface to achieve a designed degree of treatment through the natural physical, chemical, and biological process within the plant-soil-water matrix' [2]. Land application consumes relatively little energy and labor, but requires more land area as compared to traditional mechanical and chemical treatments.

A cost analysis of land application systems by Anheuser-Busch breweries revealed that land application systems had less than one half the capital investment required of a mechanical system with the same capacity, and maintenance costs were 60% lower [3]. The land application approach also appears to be environmentally sound, according to a survey conducted by the Environmental Protection Agency (EPA) of 100 facilities using land treatments for both municipal and industrial wastewater [4].

Benham-Blair et al. [5] studied the long-term effects of wastewater treatment. Their results showed that after 17 years of border strip flood irrigation, all parameters were within the allowable limits and the site could be used for further treatment. Iskandar [6] argued that with proper design and management, land treatment systems can give equal or better quality effluent treatment at a lower cost. In 1986, there were over 3000 land application projects throughout the USA [7].

A major problem in wastewater management is that cities produce municipal and industrial wastewater that is considered to be a hazardous material. The larger the population of a city, the larger the volume of wastewater. For traditional wastewater treatment methods, this implies a high cost of treatment with no return to investment and/or operating costs. Land application of wastewater provides an alternative means of displacing the wastes, while also providing potential water and nutrient resources for plant growth. In addition, it can generate revenues to help recover some of the investment and operating costs.

Land application of wastewater in agricultural production in the USA must meet EPA standards [8]. EPA regulations may specify maximum application rate of the effluent, maximum concentration of the effluent constituents, effluent pretreatment, exclusion of some crops, and other constraints, depending on local conditions. These factors underscore the importance of evaluating land application and the need to balance the system between economic returns and environmental concerns.

Where land application of wastewater is a viable alternative, an optimal enviro-economic solution is composed of a cropping pattern that: (a) utilizes the disposed effluent; (b) consumes all the chemical materials in the effluent; (c) meets all other environmental regulations; (d) satisfies the municipality's physical and financial constraints; and (e) produces the highest revenues among all the potentially feasible crops for the site.

The overall objective of this study was to determine the optimal cropping pattern to maximize net returns from municipal wastewater use in crop production, while meeting environmental standards, using the city of Lubbock, Texas, USA as the case study. The specific objectives were to: (1) identify the water and land characteristics for the area studied; (2) determine the optimal cropping patterns that maximize net returns to wastewater use, subject to technical and environmental constraints; and (3) compare the optimal cropping patterns under different cropland availability and effluent supply levels.

2. Methods and procedures

2.1. Study area and data preparation

Lubbock County is in the center of the Southern High Plains region of the USA (Fig. 1). The total area of the county is 231 465 ha. Most of the county is nearly level to being a gently undulating plain, interrupted by numerous enclosed depressions (playa lakes). Soils range from loam to clay. Average annual precipitation is 46.7 cm. Most of the rainfall occurs during the warm season, April through October.

The city of Lubbock, the major city of the county, has been utilizing land application of a secondary treated sewage effluent on its own farm since the early 1930s. The data obtained from the city farm was used as a case study for this research. In 1937, approximately 3.78 million liters of a secondary treated sewage effluent were applied daily to 80 ha of land. By 1992, the city farm had been increased to approximately 2430 ha, of which 1944 were under cultivation. In addition, the city constructed a storage reservoir on the farm site with a maximum capacity of 1558 million liters of effluent.

The site has been studied previously; in particular, Borrelli and Fedler [2] recommended a cropping pattern for the city farm which utilized the nitrogen available in the effluent. They recommended a combination of 75% of the area in corn-wheat and 25% of the area in alfalfa production to use the effluent and remove all the nitrogen

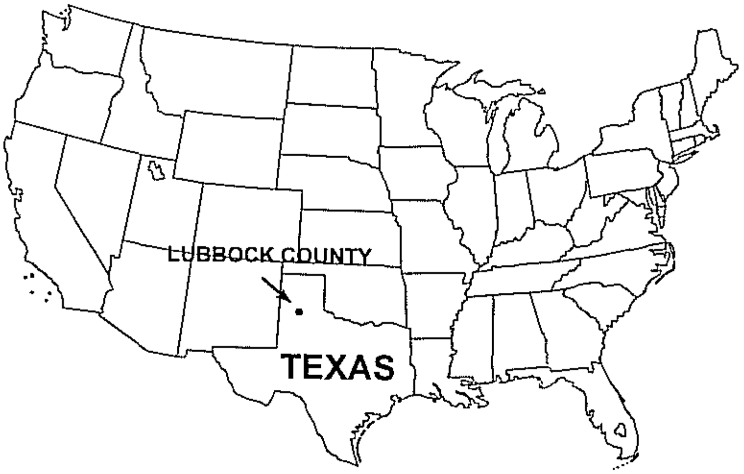

Fig. 1. Location of the study area.

from the land. Kennedy [9] analyzed annual cropping patterns that would maximize net returns to the city farm. With no storage facility, the model was designed to apply the daily effluent received by the farm directly to the fields. Kennedy [9] found that a cropping pattern of 26.3% of the area in a corn-wheat rotation, 9.5% of the area in alfalfa, 8% of the area in jose wheat grass, 18.5% of the area in forage sorghum-wheat rotation, 17.7% of the area in wheat grain, and 20% of the area in grain sorghum-wheat rotation would be optimal. The current study extends the efforts of Borrelli and Fedler [2] and Kennedy [9] by including the intertemporal use of wastewater which is made possible by the inclusion of a wastewater storage facility.

2.2. *Effluent supply and land limiting constituents*

The effluent used in this analysis was the actual monthly effluent flow received by the farm from October 1991 to September 1992. Previous studies assumed a constant daily average of effluent (approximately 49 million liters per day). Using the actual monthly effluent levels (Table 1) rather than a constant daily average simulates more closely the actual situation.

Borrelli and Fedler [2] found the nitrogen concentration in the effluent of the city of Lubbock, 34.1 mg/l, to be the relatively abundant constituent that must be used in the crop production process in order for the city to comply with EPA requirements. The same nitrogen concentration level was used in the current study. The other constituents in the effluent reported by Borrelli and Fedler [2] — BOD, COD, P, CU, Ni, and Zn — were below the recommended rates reported by the EPA [8]. The effect of heavy metals is minimal. Based on the guidelines reported by EPA [8],

Table 1
Monthly effluent discharge to the city farm, 1991–1992

Month	Effluent (m^3)
Oct.	1 642 481
Nov.	1 242 303
Dec.	1 370 071
Jan.	1 494 282
Feb.	1 436 206
Mar.	1 611 191
Apr.	1 240 373
May	1 587 961
Jun.	1 768 470
Jul.	1 170 833
Aug.	1 677 591
Sep.	1 737 749
Total	17 979 517

Source: Water Utilities Process Control, 1992.

Table 2
Nitrogen uptake rates for selected crops

Crop	Potential uptake (kg/ha/year)	Adjusted uptake[a] (kg/ha/year)
Wheat	280	336
J. wheat grass	238	285
Hay grazer	169	203
Corn	202	242
Alfalfa	499	599
Soybeans	252	303
Cotton	104	125
Grain sorghum	250	300

Source: Borrelli and Fedler, 1988.
[a] The plant's uptake plus additional 20% for denitrification and volatilization.

the life of the land is more than 200 years for all the heavy metals, given the average concentration and the recommended hydraulic loading rate of 146 cm per year [2].

2.3. Crop selection

Seven different cropping activities were selected for the study. The selected crops were: alfalfa (Alfalfa), jose wheat grass (Jwgrs), wheat-corn (Whtcrn), wheat-grain (Whtgrn), wheat-grain sorghum (Whtgsg), forage sorghum-wheat (Fgswht), and cotton (Cotton). Table 2 presents the estimated nitrogen uptake for these crops. That

Table 3
Monthly recommended effluent levels (US$ha/cm) for the selected crops

Month	Whtcrn	Whtgrn	Whtgsg	Fgswht	Jwgrs	Alfalfa	Cotton
Jan.	11.91	7.62	10.16	10.41	2.06	10.41	
Feb.	11.89	7.62	10.16	7.62	2.59	8.43	
Mar.	13.36	11.43	15.04	8.89	16.87	8.92	
Apr.	3.81	15.04	10.16		6.15	20.78	
May.		9.17			5.44	24.33	7.37
Jun.	8.92				2.06	24.33	10.49
Jul.	17.83		7.62		5.11		24.13
Aug.	18.39	3.81	7.62		7.26	8.92	32.31
Sep.	22.20	8.89	7.62	6.35	5.28	5.94	
Oct.		7.47		7.62	4.11	26.72	
Nov.	19.28	11.91	10.16	7.62	2.59	7.26	
Dec.	18.47	11.89	7.62	7.62	2.11		
Total	146.00	94.84	86.16	56.13	61.62	146.00	74.30

Source: Borrelli and Fedler, 1988.

Table 4
Net returns (US$/ha) for the selected cropping systems

Month	Whtcrn	Whtgrn	Whtgsg	Fgswht	Jwgrs	Alfalfa	Cotton
Gross return	826.21	459.42	592.80	222.30	222.30	864.50	864.50
Expenses	511.29	234.65	360.62	197.60	135.85	432.25	691.60
Net return	314.92	224.77	232.18	24.70	86.45	432.25	172.91

Source: Texas Agricuitural Extension Service, 1992 and Kennedy, 1990 (labor and energy costs are not included).

table also indicates the adjusted nitrogen uptake values, given that there are some losses due denitrification and volatilization (estimated to be 20%).

Since 1990, the Texas Water Development Board permit has restricted the maximum hydraulic rate of effluent application to 146 cm per year; this was the maximum rate used in this study. The monthly recommended effluent levels for the selected crops are presented in Table 3. Data on crop expenses and returns were not available at the city farm, but were obtained from the Texas Agricultural Extension Service crop enterprise budgets [10] and Kennedy [9]. Table 4 represents the net returns of the selected cropping activities, based on 1992 price levels.

2.4. Assumptions and specification of the analytical model

A 5-year dynamic optimization model was developed to determine the optimal cropping pattern for the city farm. The objective function was to maximize the net revenues over variable costs from the produced crops. The fixed costs, including investments in items such as land and irrigation systems were considered to be irrelevant to the selection of the optimal crop mix. The planning horizon was assumed to be 5 years. The major physical requirements of the model were: (a) the potential nitrogen uptake of the selected crops (nitrogen being the most land-limiting constituent) must be greater than or equal to the amounts of nitrogen available in the effluent supply, and (b) the farm must utilize all the annual effluent supply, given the current maximum storage capacity of the farm reservoir. The model accounted for the monthly stored effluent levels and the monthly effluent used by the crops, and determined the cropping pattern that generates the highest net returns to the farm.

The model was designed such that the water diverted to the farm in a given month could be applied directly or stored in the reservoir for future use. The maximum storage capacity was assumed to be the current capacity (1558 million liters). July was considered as the starting month in the model, and the reservoir was assumed to be full at that time.

Two basic scenarios were evaluated. The first scenario assumed that cropland availability was 1539 ha, the total cropland available prior to 1990. In the second scenario land availability was increased to 1944 ha, the current available cropland. Changing the land availability provides information on whether land or the effluent supply is the most limiting factor in the Lubbock case. Furthermore, such information determines the degree to which the city could increase the effluent supply to the farm, given the currently available land. In both scenarios, a 2% increase in the annual effluent supply levels was assumed to reflect a potential increase in the effluent diverted to the land site. The scenarios were given the following codes: MOD1 for the 1539 ha model and MOD2 for the 1944 ha model.

2.5. Model specification

The wastewater effluent supplied to the city farm through the year was divided into 12 month periods (*m*), in each yearly interval (*t*). The net return function from different cropping activities at a given year can be expressed as:

$$NR_t = \sum_{k=1}^{7} GR_{Kt}X_{Kt}\,(EFAP_{Kt}\,(EFAV_{tm},\, EFST_{tm})) - C_{Kt}X_{Kt} \tag{1}$$

where NR_t represents the net returns to the city farm from the different cropping activities in year t; K represents the cropping activities; GR_{Kt} represents the gross return per hectare from crop K in year t; X_{Kt} represents the ha of crop K in time t; $EFAP_{Kt}$ represents the effluent applied to crop K in year t; $EFAV_{tm}$ represents the effluent available to the farm at a given month in a given year; $EFST_{tm}$ represents the effluent stored in the farm reservoir at a given month in a given year; and C_{Kt} represents the total variable cost of producing one hectare of crop K in year t. Eq. 1 states that the net returns from producing the different crops is a function of the gross returns and the variable costs of production. The production levels and number of hectares in the production of the different crops depend on the annual effluent quantity applied to the different crops. The annual effluent applied to the different cropping activities depends on the effluent monthly flow and the stock of effluent in the reservoir in a particular year.

The objective function in the optimization model was to maximize the present value of net returns over the planning horizon. In particular, the optimization model was:

$$Max\ Z = \sum_{t=1}^{5} NR_t\,(1 + r)^{-t} \tag{2}$$

subject to:

$$\sum_{k} X_{Kt} \leq L_t, \text{ for all } t \tag{3}$$

$$EFAV_{tm+1} = EFAV_{tm} + EFST_{tm} - \sum_{k=1}^{7} EFAP_{tm}, \tag{4}$$

$$EFST_{tm} \leq STCAP, \tag{5}$$

$$\sum_{k} Nit_{kt} X_{Kt} \geq NitAV_t, \tag{6}$$

$$EFAV_{tm_{(0)}} = EFST_{tm_{(0)}}, \tag{7}$$

$$X_{Kt}, EFAP_{Kt} \geq 0. \tag{8}$$

where Z in Eq. 2 represents the present value of net returns and r is the discount rate (assumed to be 5%). The control variable in the model is X_{Kt}. Eq. 3 is the cropland constraint equation which bounds cropland availability (L_t). Eq. 4 is the equation of motion, which updates the state variable, stock of the effluent available to the farm, where $EFAP_{tm}$ is the monthly effluent applied to the crops in a given year. Eq. 4 states that the effluent available to the farm for next month depends on the effluent available, the effluent stored, and the effluent applied to the different crops in the current month for a given year. Eq. 5 states that the effluent stored in the farm reservoir at any given month cannot exceed the maximum storage capacity of the reservoir ($STCAP$). Eq. 6, the environmental constraint equation, states that the selected crops and their associated areas must remove all the nitrogen available ($NitAV$) in the effluent supplied to the farm, where Nit_{kt} represents the nitrogen requirements of crop K in time t. Eq. 7 specifies the initial condition of the effluent stock available to the farm at the beginning of the planning horizon ($EFAV_{tm_{(0)}}$) equals the amount of effluent stored. The conditions in Eq. 8 represent the non-negativity constraints.

3. Results and analysis

The two models formulated were solved using the General Algebraic Modelling System [11]. The present value of net returns for scenario MOD1 was US$2 281 615 (Table 5). Through time, the optimal cropping pattern showed a reduction in the Whtcrn and Cotton areas, being replaced by increasing areas of Alfalfa and Whtgsg.

The changes in cultivated areas of Whtcrn and Whtgsg in the first 2 years of the planning horizon result from the assumption that the reservoir is full at the beginn-

Table 5
Optimal cropping activities for MOD1[a] (ha)

Year	Whtcrn	Whtgsg	Alfalfa	Cotton	Total land
1	337	319	743	140	1539
2	99	653	759	28	1539
3	135	622	779	3	1539
4	174	563	802		1539
5	213	499	827		1539

[a] Present Value of Net Returns = US$2 281 615.

ing of the planning horizon and that all the effluent and nitrogen must be consumed. Given that the reservoir capacity is 1558 million liters and the average monthly effluent supplied to the farm was 1498 million liters, the initial stored water in the reservoir represents approximately 104% of the monthly average. This explains why a relatively larger number of acres are allocated to Whtcrn in the first year, because it is one of the major water- and nitrogen-consuming activities (146 cm of effluent/ha/year).

Once the effluent volume declines, the Whtgsg area is increased to replace the decline in the Whtcrn area. Thus, because of the presence of relatively more water in year 1 (full reservoir), about 22% of the farm area should be allocated to Whtcrn. In the second year, the assumed 2% increase in the monthly effluent reduced the total available effluent supplied to the farm as compared to the first year. Therefore, a substantial reduction in the Whtcrn area occurs (almost a 71% reduction). This reduction, however, was offset by an increase in the area of Whtgsg. Because the discounted marginal profit per unit of effluent allocated to Whtcrn is higher than that associated Whtgsg, when effluent availability is higher, more of the Whtcrn area is brought into the solution. This observation is of value in relation to possible future increases in effluent volume.

Table 5 also indicates that the 1539 ha are sufficient to use all the effluent and remove all the nitrogen from the land, even with an annual increase in the effluent supply. Furthermore, additional application of nitrogen fertilizer is required each year to achieve the assumed crop yields and projected net revenues.

Table 6 presents the annual nitrogen deficiency levels for MOD1. This indicates that more effluent could be applied per hectare (i.e. increase the maximum hydraulic rate), implying that more effluent could be utilized on the farm. MOD1's dynamic solution increased net returns 103% over the engineering solution of Borrelli and Feddler [2]. This result is mainly due to the fact that the monthly effluent requirements associated with their solution can be satisfied in only about 50% of the available area. A comparison between the results of MOD1 and those of Kennedy [9] indicates that the presence of the reservoir increases annual net returns by 58%. It is important to point out, that this increase in net returns results from the ability to adopt a more flexible production optimal decision rule, due to monthly wastewater transfers which are possible because of the reservoir.

Table 6
Nitrogen requirements and deficiencies for MOD1 (kg)

Year	Nitrogen consumed	Nitrogen applied in the effluent	Nitrogen deficiency
1	750 280	566 033	184 247
2	787 091	277 353	209 738
3	797 723	588 901	208 822
4	799 386	600 678	198 702
5	799 742	612 692	187 050

Table 7
Optimal cropping activities for MOD2[a] (ha)

Year	Whtgsg	Alfalfa	Cotton	Total land
1	868	621	406	1895
2	802	723	120	1645
3	826	729	129	1684
4	850	736	139	1725
5	874	743	149	1766

[a] Present Value of Net Returns = US$2 316 977.

For the MOD2 scenario, the present value of net returns was US$2 316 977 (Table 7). When compared to MOD1 scenario's optimal solution, net returns increase by 1.6% due to the larger cropland base. As shown in Table 7, for MOD2 the maximum cropland requirement occurs in the fifth year, with 1766 ha being utilized and 178 left idle. This result also shows that the effluent flow, not cropland, is the limiting factor given the current effluent supply level. This implies that more effluent could be utilized at the city farm. Furthermore, in this scenario the total available nitrogen in the effluent was utilized, and additional amounts of nitrogen would also be required to fulfill the production optimal decision rules.

4. Summary and conclusions

The overall objective of this study was to determine the optimal cropping pattern to maximize net returns from municipal wastewater use in crop production, while meeting environmental standards. The results indicate that, the city can reduce its net cost of effluent treatment by the cost of secondary effluent treatment plus about US$450 000 less the annual fixed cost of operating the city farm. Furthermore, given the current effluent supply, 1539 ha of cropland are sufficient to utilize the effluent and remove the nitrogen, even with a 2% increase in the annual flow. Also, it was found that when cropland is increased to 1944 ha, some of the area could be left idle. The idling of this area indicates that the effluent is the limiting factor when more cropland is brought into the solution. This is an important result because of the trade-off between cropland and the wastewater storage facility. In other words, the presence of a storage facility decreases cropland requirements for land application treatment. That is, more effluent could be used, given the current cropland availability condition.

Some conclusions can be drawn from the results obtained. Land application of wastewater in crop production offers a cost effective means of treatment that is environmentally safe. In the particular case analyzed in this study, the city farm can utilize all the wastewater effluent supplied with the currently available cropland. The nitrogen constituent in the effluent, being the major concern, would be totally removed, and additional nitrogen would be needed to fulfill the optimal decision rule. In addition, net returns would increase as both cropland and effluent levels increase.

The net cost to municipalities of wastewater treatment and disposal can be affected substantially by selecting economically optimal sets of cropping enterprises. Furthermore, the presence of a wastewater storage facility allows the adoption of flexible and practical cropping patterns via monthly water transfers which result in higher net revenues.

Overall, the optimal cropping patterns obtained in this study are flexible and reliable. Also, with the use of proper irrigation practices and a good monitoring system, as the one followed by the city of Lubbock to monitor nitrogen concentration levels and other constituents in both the soil and effluent, the proposed optimal decision rules can be realistically achieved. For those interested readers, a documented copy of the optimization models used, which could be easily modified to fit particular characteristics of other area(s), is available from the authors.

Acknowledgements

The authors thank Clifford B. Fedler, Rex P. Kennedy, and John Hindeman for their technical assistance. Publication T-1-414, College of Agricultural Sciences and Natural Resources, Texas Tech University.

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