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The increased production of sewage sludge in the USA has led many municipalities to consider the application of sludge to agricultural land as a feasible means of sludge disposal and nutrient recycling. Therefore, a long-term field study was initiated in 1982 in Adams County, Colorado, with the objective of evaluating the effects of sewage sludge on, gross income, yields, grain protein, and elemental content of dryland hard red winter wheat (*Triticum aestivum* L., 'Vona') compared to commercial NH_4NO_3 fertilizer. This report covers plant data for the last three years of this 5-yr study where sludge rates ranged from 0 to 18 dry ton/acre, and N fertilizer rates ranged from 0 to 120 lb N/acre. Sludge application has produced greater gross income than N fertilizer treatments primarily due to the protein premiums paid for high protein grain. Application of the 3 ton/acre sludge rate resulted in an average of $45/acre/year increase in income compared to the commonly used N rates of 50 to 60 lb N/acre. In two of the three years, neither the sludge nor the N fertilizer treatments resulted in significant yield responses. The mean grain yields of the sludge and N fertilizer treatments ranged from 50 to 71 bu/acre and 51 to 64 bu/acre, respectively, while protein content ranged from 13.3 to 15.5% and 11.0 to 12.7%, respectively. In addition, sludge application has resulted in greater soil NH_4-N and NO_3-N compared to the N fertilizer treatments at boot stage over the last three years. However, because of the potential for NO_3^- contamination of groundwater due to oversupply of N (and the potential for metal build-up in the soil) by the 12 and 18 ton/acre rates, the lower sludge rate of 3 ton/acre is recommended for this dryland wheat production system. Grain levels of P and Zn have been increased by sludge application while the concentrations of Cd, Ni, and Pb have remained very low.

APPLICATION of municipal wastes to cropland is a feasible disposal and nutrient recycling option for cities in certain climatic zones. If loading rates of sewage sludges low in trace metals is based on the N needs of a crop, very little potential for health or environmental problems related to the trace metals will exist (USEPA, 1983). The impact of potentially toxic trace metals in sludge applied to cropland can be further reduced by growing crops which do not accumulate these metals in edible portions of the plant and by applying sludges to soils with near neutral or alkaline pH (Logan and Chaney, 1983).

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Over the last two decades, sewage sludges have been established as viable alternatives to commercial fertilizers with respect to plant nutrition. A number of researchers have reported increased yields with various agronomic crops due to sludge application (Coker, 1966; Kelling et al., 1977; Watson et al., 1985). Of the plant macronutrients, N and P are contained in substantial quantity in most sewage sludges. The median total N and P content of U.S. sludges were 3.3% and 2.3%, respectively (Sommers, 1977). In contrast to commercial N and P fertilizers, however, most sludge N and P is not immediately plant available and must be released by mineralization. The slow release of nutrients by microbial mineralization reactions can increase plant availability of N and P throughout the growing season (Kelling et al., 1977; Soon et al., 1978; Utschig, 1985; Utschig et al., 1986). Sewage sludges are also excellent sources of many micronutrients such as Cu, Zn, Mo, Fe, and Mn. While much of the research that has focused on these elements is concerned with potential plant toxicities, favorable crop responses to these elements may occur (McClaslin and O'Connor, 1982; Logan and Chaney, 1983; Utschig, 1985; Utschig et al., 1986).

Little information, however, exists on the economic aspects of sludge application to agronomic crops. If sludge use on cropland does not result in income levels competitive with commercial fertilizers, then farmers will not consider sewage sludge application as a fertilizer alternative. In an economic evaluation of sewage sludge applied to an agronomic crop there are two points of particular importance which should be considered. First, there is the cost of disposal by land application vs. disposal in a municipal landfill. These methods are the only alternatives in Colorado. Based on information obtained from the waste treatment facility of the cities of Littleton/Englewood, CO, the cost of disposal of dewatered sewage sludge (16 to 40% solids) totals $100/dry ton of sludge. Of this cost, approximately $80/dry ton is for hauling the sludge to the landfill site, and about $20/dry ton is the cost for permits and disposal in the landfill. The cost of land application of dewatered sludge to a site approximately 40 mi from the Littleton/Englewood waste treatment facility was estimated by the cities to cost $100/dry ton. The cost of hauling sludge to the site for land application was considered to be greater than the hauling cost to the landfill (about $90/dry ton), but the cost of a permit for land application (about $10/dry ton) is less than the landfill fee. Thus, the two disposal alternatives available to the cities cost essentially the same.

The second consideration for sewage sludge disposal is the environmental aspect of land application vs. landfill disposal. The quality of the sludge produced by the Littleton/Englewood waste treatment facility has been classified as Grade I or II by the Colorado Department of Health (1985) for the last three years. Thus, the sludge has been determined to be safe for application on agricultural land. Since the cost of the disposal alternatives is about the same, it is logical to choose the most environmentally beneficial means of disposal. The USEPA (1983) encourages waste treatment facilities to pursue land application as the primary disposal means because of the beneficial use (recycling of nutrients) and environmental protection gained from land application of sewage sludge to meet crop nutrient needs. For these reasons, the Littleton/Englewood waste treatment facility has chosen land application as their disposal/recycling method. Obviously, the high cost of sludge disposal could not, and should not, be passed on to the farmer interested in using sludge on agricultural land. Since the sludge is disposed of at essentially the same cost by either land application or landfill disposal, the current policy of the cities of Littleton and Englewood is to give and apply the sludge free to farmers. Other waste treatment facilities in Colorado have adopted similar policies. In Ft. Collins, the waste treatment facility will subsurface inject liquid sludge to dryland areas at no charge to the farmers. The Denver Metro waste treatment facility currently charges just $3/acre for subsurface injection of 2 dry ton/acre of liquid sludge to dryland wheat areas or 7 dry ton/acre to irrigated areas.

Application of sewage sludge to cropland has been shown to be an agronomically sound practice in terms of supplying the nutrient requirements of crops and can replace commercial fertilizers when the application rate is based on the N needs of crops. However, published data on the potential economic benefits of sewage sludge application to agronomic crops is virtually nonexistent. Therefore, the objectives of this long-term study are to determine the effect of various sludge loading rates on the potential gross income, yield, protein, and elemental content of hard red winter wheat compared to the use of commercial N fertilizer.

MATERIALS AND METHODS

The details of soil type, site location, treatment rates, sludge chemical composition, and statistics are described in detail by Lerch et al. (1990).

Soil samples were collected at or near boot stage Feekes stage 10; (Feekes, 1941) from 0 to 6 in. depth, air-dried, and ground to pass a 0.08-in. sieve. The NO_3-N and NH_4-N levels were determined as described by Lerch et al. (1990). Plant samples were obtained at boot stage by sampling and compositing the above-ground portion of the plants from at least three locations within each plot. Total plant N was determined on a H_2SO_4-H_2O_2 digest (Thomas et al., 1976) followed by NH_4^+ determination with the Technicon Autoanalyzer (Technicon, 1977).

Grain yields were determined by harvesting a 50 ft by 4 ft area and weighing the grain in the field. Grain protein content was measured by a near infrared method using a Dickey-John GAC III (Illinois). Grain elemental

Table 1. Effects of N fertilizer and sludge rates on yield and protein content of wheat grain, 1984–87.

N fertilizer		1984–85 Location A		1985–86 Location B		1986–87 Location A	
1984–85 & 1986–87	1985–86	Yield	Protein	Yield	Protein	Yield	Protein
—— lb N/acre ——		bu/acre	%	bu/acre	%	bu/acre	%
0	0	58	10.9	60	12.2	50	10.1
25	30	62	9.6	61	11.9	55	11.0
50	60	63	10.6	62	12.5	49	13.9
100	90	71	12.8	58	13.2	51	15.7
	120	--	--	64	13.3	--	--
Mean		64	11.0	61	12.6	51	12.7
Linear		*	NS	NS	*	NS	**
Quadratic		NS	NS	NS	NS	NS	NS
Sewage sludge							
dry ton/acre							
0		58	10.2	66	11.4	50	10.1
3		75	14.3	60	13.6	52	15.9
6		79	14.4	58	13.9	53	16.4
12		72	15.0	63	13.6	49	17.2
18		--	--	60	13.8	46	17.9
Mean		71	13.5	61	13.3	50	15.5
Linear		NS	**	NS	**	NS	**
Quadratic		*	**	NS	*	*	**
N fertilizer vs. sludge		*	**	NS	NS	NS	**

*,** Significant at the 0.05 and 0.01 probability levels, respectively.

concentrations of Cd, Cu, Ni, P, Pb, and Zn were measured in concentrated HNO_3 digests (Havlin and Soltanpour, 1980) by the inductively coupled plasma-atomic emission spectrophotometer (ICP-AES).

The grain prices used for each year were the most current for that harvest year. Nitrogen fertilizer costs were based on anhydrous ammonia because this is the N fertilizer most commonly used in eastern Colorado for winter wheat production. The Littleton/Englewood sewage sludge and its application is currently free to farmers within a 40 mi radius of the waste treatment facility; therefore, no application cost for sludge was considered. Statistical analyses were completed as described by Lerch et al. (1990).

RESULTS AND DISCUSSION

Grain Yields and Protein Content

Sludge and N fertilizer treatments generally did not affect grain yields differently in two of the three years studied (Table 1). Only in the 1984–85 season were mean grain yields of the sludge treatments (71 bu/acre) significantly greater than the N fertilizer treatments (64 bu/acre). The only significant yield responses to the sludge rates throughout this study have shown quadratic trends (Utschig, 1985; Utschig et al., 1986). The quadratic yield depression of the 12 and 18 ton/acre sludge rates in 1986–87 may be the result of too much available soil N in the plow layer. The soil N data at harvest (Lerch et al., 1990) shows that accumulation of high levels of NH_4-N and NO_3-N in the top 8 in. has occurred, particularly for the 18 ton/acre rate. The residual soil N levels of this rate were up to about 108 lb NH_4-N/acre in 1985–86 and 128 lb NO_3-N/acre in 1986–87.

Table 2. Estimated protein premiums and gross income of winter wheat for 1984-1987.

N fertilizer		1984-85 Location A			1985-86 Location B			1986-87 Location A		
1984-85 & 1986-87	1985-86	Protein premium	Fertilizer or sludge cost	Gross income	Protein premium	Fertilizer or sludge cost	Gross income	Protein premium	Fertilizer or sludge cost	Gross income
lb N/acre		$/acre								
0	0	0	0	176	0	0	145	0	0	129
25	30	0	7	181	0	8	140	0	7	135
50	60	0	10	170	4	11	143	11	10	127
100	90	25	15	224	7	14	133	23	14	140
	120	--	--	--	11	17	149	--	--	--
Sewage sludge										
dry ton/acre										
0		0	0	176	0	0	160	0	0	129
3		41	0	268	13	0	158	24	0	158
6		43	0	282	16	0	156	28	0	165
12		47	0	267	14	0	166	31	0	156
18		--	--	--	16	0	161	33	0	152

† Gross income from yields and protein content shown in Table 4 minus the cost of fertilizer or sludge. Fertilizer costs are based on the price of anhydrous ammonia ($0.10/lb plus $4.50/acre for application).

Grain protein content has shown significant linear increases with increasing sludge or N fertilizer rates (Table 1). The sludge rates significantly increased grain protein compared to the N fertilizer, and the mean protein content of the sludge treatments ranged from 13.3 to 15.5%. In addition, in all three years, the 3 ton/acre sludge rate resulted in higher grain protein content than any of the N rates applied. As will be discussed in more detail later, the higher grain protein of the sludge treatments appears to be the result of the greater available soil N levels at the latter part of the growing season (Lerch et al., 1990).

Sommers et al. (1981) and the USEPA (1983) predict that the organic N in anaerobically digested sewage sludge mineralizes for the first, second, third, and subsequent years thereafter at rates of 20, 10, 5, and 3%, respectively. Using the design application equations recommended by the USEPA (1983) and the sludge N composition data from all five years of this field study (Utschig et al., 1986; Lerch et al., 1990), the predicted total available N of the 3 ton/acre rate would be 125, 51, and 36 lb N/acre for 1984-85, 1985-86, and 1986-87, respectively. Since straw is returned to the soil in dryland winter wheat agroecosystems, grain harvest represents the only crop removal of N. Therefore, on the basis of grain yield, protein content (Table 1), and test weight (data not included), N removal was 113, 86, and 87 lb/acre in 1984-85, 1985-86, and 1986-87, respectively. These figures indicate that little, if any, soil N accumulation would be expected for the 3 ton/acre sludge rate. However, Lerch et al. (1990) have reported significantly increased soil NO_3-N concentrations compared to the control and the 50 and 60 lb N/acre rates down to 35 in. associated with the 3 ton/acre rate. Thus, the design sludge mineralization rates recommended by USEPA (1983) appear to be too low for this system.

Potential Income

In the last three years, all rates of sludge applied have resulted in higher gross income/acre than any of the N fertilizer rates used (Table 2). Furthermore, every sludge rate applied has resulted in a protein price premium due to the higher grain protein content (which is generally paid for wheat with greater than 12% protein). Protein price premiums for sludge application over the three years have ranged from $13 to $47/acre. On the other hand, N fertilizer rates of 50 lb N/acre and greater have generally resulted in protein price premiums which have ranged from $0 to $25/acre. At a recommended N fertilizer rate of 50 to 60 lb N/acre, the gross income totaled $339/acre for the three years while with a recommended sludge rate of 3 ton/acre the gross income totaled $584/acre. Thus, the sludge averaged about $45/acre increased income/year compared to the N fertilizer. Most of the increase in income was due to protein premium payments for the higher quality wheat. Protein premiums are commonly paid to wheat producers throughout eastern Colorado as well as the central Great Plains. However, if a grower in a particular area is not able to receive a protein premium payment for high quality wheat, the gross income would still exceed that received from N fertilizer because the sludge is supplied and applied free to farmers' fields.

Boot Stage Soil and Plant Nitrogen

The soil NH_4-N and NO_3-N content (at 0-6 in.) at boot stage generally showed linear increases with increasing sludge and N fertilizer rates for all three years (Table 3). The mean soil NH_4-N and NO_3-N contents of the sludge treatments were also significantly higher than the N fertilizer treatments for all three years. The potential for NO_3-N contamination of groundwater due to sludge application at rates exceeding 3 ton/acre has been documented for this study (Lerch et al., 1990). Other studies also have shown the potential for NO_3-N contamination (Hinesly et al., 1974; Brown, 1975; Higgins, 1984).

The total plant N content at boot stage also tended to linearly increase with increasing sludge and N fertilizer rates over all three years (Table 3). The mean total plant N of the sludge treatments was significantly greater (up to 1.3 times higher) than the N fertilizer treatments in all three years. Furthermore, the lowest sludge rate (3 ton/acre) resulted in plant N contents which were greater than the 50 and 60 lb N/acre. Thus, the lowest sludge

Table 3. Effects of N fertilizer and sludge rates on topsoil (0–6 in.) NH_4-N and NO_3-N and plant N at boot stage, 1984–1987.

N fertilizer 1984–85 & 1986–87	N fertilizer 1985–86	1984–85 Location A Soil NH_4-N	1984–85 Location A Soil NO_3-N	1984–85 Location A Plant N	1985–86 Location B Soil NH_4-N	1985–86 Location B Soil NO_3-N	1985–86 Location B Plant N	1986–87 Location A Soil NH_4-N	1986–87 Location A Soil NO_3-N	1986–87 Location A Plant N
lb N/acre		ppm		%	ppm		%	ppm		%
0	0	10	2	1.6	9	2	1.9	3	1	2.2
25	30	9	2	1.8	8	1	2.1	4	1	2.3
50	60	11	3	2.0	10	2	2.0	4	1	2.5
100	90	14	3	2.8	9	3	2.5	6	2	3.1
	120	--	--	--	12	5	2.4	--	--	--
Mean		11	3	2.1	10	2	2.2	4	1	2.5
Linear		*	*	**	**	**	*	NS	*	**
Quadratic		NS	NS	NS	*	*	NS	NS	NS	*
Sewage sludge										
dry ton/acre										
0		12	8	2.4	10	1	2.1	3	1	2.2
3		17	13	2.6	14	5	2.7	5	3	3.1
6		20	26	3.0	14	6	2.8	4	10	3.1
12		28	45	2.8	15	9	2.7	9	7	3.2
18		--	--	--	25	12	3.0	8	16	3.3
Mean		19	23	2.7	16	7	2.7	6	7	3.0
Linear		**	*	NS	*	**	**	**	**	**
Quadratic		NS	NS	NS	NS	NS	NS	NS	NS	**
N fertilizer vs. sludge		*	**	**	*	**	*	*	*	**

*,** Significant at the 0.05 and 0.01 probability levels, respectively.

Table 4. Effects of N fertilizer and sludge rates on elemental content of wheat grain, 1984–87.

N fertilizer 1984–85 & 1986–87	N fertilizer 1985–86	1984–85 Location A† P	1984–85 Location A† Zn	1984–85 Location A† Cu	1985–86 Location B‡ P	1985–86 Location B‡ Zn	1985–86 Location B‡ Cu	1986–87 Location A§ P	1986–87 Location A§ Zn	1986–87 Location A§ Cu
lb N/acre		%	ppm		%	ppm		%	ppm	
0	0	0.38	26	5	0.34	23	6	0.43	26	4
25	30	0.37	24	5	0.33	22	5	0.39	24	4
50	60	0.37	24	5	0.32	21	5	0.37	25	4
100	90	0.36	26	6	0.34	22	5	0.49	34	5
	120	--	--	--	0.34	21	5	--	--	--
Mean		0.37	25	5	0.33	22	5	0.42	27	4
Linear		NS	NS	NS	NS	NS	NS	NS	NS	*
Quadratic		NS	NS	NS	NS	NS	NS	NS	NS	NS
Sewage sludge										
dry ton/acre										
0		0.38	25	6	0.35	23	5	0.43	26	4
3		0.41	33	6	0.43	38	6	0.47	38	4
6		0.41	34	6	0.43	40	6	0.50	41	4
12		0.47	45	7	0.42	39	6	0.52	43	5
18		--	--	-	0.39	42	5	0.65	66	7
Mean		0.42	34	6	0.40	36	5	0.51	43	5
Linear		**	**	NS	NS	*	NS	**	**	**
Quadratic		NS	NS	NS	*	NS	NS	NS	NS	NS
N fertilizer vs. sludge		**	**	**	**	**	NS	*	**	NS

*,** Significant at the 0.05 and 0.01 probability levels respectively.
† All samples had no more than 0.2 ppm Cd, 2.2 ppm Pb, and 1.3 ppm Ni.
‡ All samples had no more than 0.4 ppm Cd, 0.6 ppm Pb, and 0.9 ppm Ni.
§ All samples had no more than 0.3 ppm Cd, 0.6 ppm Pb, and 2.0 ppm Ni.

rate provided adequate N levels to the plant with fewer limitations to long-term application than the higher loading rates (due to the build-up of metals and NO_3-N in the soil). Increased plant N at the latter part of the growing season can lead to greater N content of grain upon maturation. From 50 to 100% of the N content of the grain at harvest has been shown to be the result of translocation from stems, leaves, and roots (Harper et al., 1987; Daigger et al., 1976) with the majority of the translocated N coming from the stems and leaves (Harper et al., 1987). In addition, wheat will continue to take up N from the soil, even after anthesis, so that the greater availability of N to the plant near the end of the growing season directly affects the quality of the grain produced. It is in this context that sewage sludge application to wheat has offered an advantage over the commercial N fertilizer in this study.

Selected Plant Nutrients and Trace Metals

In two out of three years (1985–86 and 1986–87), grain P content increased linearly with increasing sludge rate, and in all three years, sludge application resulted in significantly higher grain P content than N fertilizer application (Table 4). The average grain P content of the sludge treatments ranged from 0.40% (in 1985-86) to 0.51% (in 1986-87). Grain P content was increased by sludge application to the greatest extent in 1985-86 and 1986-87, with an average grain P content 1.2 times greater than the N fertilizer treatments.

The Zn content of the grain was linearly increased as a result of sludge application (Table 4). The average Zn content of the sludge treatments ranged from 34 to 43 ppm with the highest grain Zn content being 66 ppm from the 18 ton/acre rate. This level of Zn is still well below levels reported to be toxic to livestock (Logan and Chaney, 1983). Generally, the highest sludge (12 and 18 ton/acre) rates resulted in significantly greater grain Zn content than the control. Only in 1985-86, did the 3- and 6-ton/acre rates result in significantly elevated grain Zn levels compared to the control (mean separation value not shown). However, even the lowest sludge rates resulted in grain Zn contents greater than any of the N fertilizer treatments, and the mean grain Zn content of the sludge treatments was significantly greater than that found in the N fertilizer treatments in all three years.

Grain Cu levels were, in general, unaffected by sludge application with the exception of the 1986-87 season in which sludge application resulted in a significant linear increase in grain Cu. The 1984-85 growing season was the only year that overall grain Cu content was significantly higher for sludge compared to the N fertilizer treatments.

Levels of trace metals such as Ni, Cd, and Pb in the grain were measured for all three treatments (Lerch, 1987). Grain Ni content was significantly increased by sludge application in 1985-86, with an average Ni content in the grain of 0.8 ppm compared to the N fertilizer treatments, which had an average of 0.5 ppm. The highest measured grain Ni levels never exceeded 2.2 ppm. Grain Cd content was significantly increased by sludge application in 1985-86 and 1986-87. However, the grain Cd levels were all less than 0.5 ppm, and in 1986-87, Cd levels were not greater than 0.3 ppm, even after three years of sludge application. Grain Pb content was not affected by sludge application and Pb levels were all below the detection limit of 0.6 ppm in 1985-86 and 1986-87.

SUMMARY

The potential for groundwater NO_3^- contamination based on boot stage and harvest soil N data (Lerch et al., 1990), coupled with the plant N, grain protein, and N removal data, shows that 3 ton/acre is the maximum safe loading rate for a dryland winter wheat-fallow management system in the central Great Plains. This lower sludge loading rate results in adequate plant N, P, and grain protein levels without the greater potential for NO_3^- leaching and high levels of heavy metals in the soil that may result from the higher loading rates. In addition, the 3 ton/acre rate resulted in greater gross income than any of the N fertilizer rates studied. The application of 3 ton/acre of the Littleton/Englewood sewage sludge to dryland winter wheat in eastern Colorado appears to be an environmentally feasible and economically beneficial method of sludge reuse.

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