HEAVY METAL UPTAKE BY BLUE GRAMA GROWING IN A DEGRADED SEMIARID SOIL AMENDED WITH SEWAGE SLUDGE

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Abstract. Sewage sludge application to semiarid grassland may represent a beneficial means of utilizing this waste product for restoration of degraded sites. Consequently, dried municipal sewage sludge was applied at three rates (22.5, 45, and 90 Mg ha^{-1}) to a degraded semiarid grassland soil in order to determine the effects of sludge amendments on forage productivity, soil heavy metal content, and metal uptake by blue grama (Bouteloua gracilis). Soil and plant properties in control and amended plots were measured after 1, 2, and 5 growing seasons. Soil nutrients increased linearly with increased sludge application in the first two growing seasons. Consequently, forage quality and total production of blue grama improved significantly over the unamended control as the tissue levels of N, P, K, and crude protein increased. Cadmium and Pb in the sludge-treated plots did not increase significantly over the control after 1 and 2 growing seasons. Levels of DTPA-extractable soil micronutrients (Cu, Fe, Mn, Zn) increased linearly with increased sludge application rate to soil concentrations recommended for adequate plant growth. Soil N, P, and K concentrations remained higher in the sludge-amended soils after 5 growing seasons, while Cu and Cd increased to slightly above desireable limits as the soil pH decreased to 7.4 and 7.0 in the 45 and 90 Mg ha^{-1} treatments, respectively. However, with the exception of Mn which remained within desirable limits, metal concentrations (including Cu and Cd) in blue grama tissue were not significantly different from the control treatment after five growing seasons. Based on soil and plant tissue metal concentrations, it appears that sludge applied at rates between 22.5 and 45 Mg ha^{-1} will maintain the most favorable nutrient levels coupled with significant improvements in forage production in this semiarid grassland environment.

1. Introduction

Potential benefits and environmental problems associated with sewage sludge application to land have been extensively studied in reclamation (Sopper and Kerr, 1979), and in agricultural systems wherein sludge has been utilized as a soil amendment and source of fertilizer (Sommers, 1977). Sludge has been shown to provide significant amounts of organic matter and essential plant nutrient elements when applied to agricultural soils (Elliott, 1986). However, sludge contains other elements that might be harmful to plants and the food chain if applied in excessive amounts (EPA, 1978). Depending upon source, sludge contains varying concentrations of Al, B, Cd, Cu, Ni, Pb, and Zn (Valdares *et al.*, 1983). Cadmium has been identified as the potentially most hazardous of the heavy metal elements when sludge is applied to land (Ryan *et al.*, 1982).

Research on heavy metal uptake by plants resulting from sludge application has dealt mostly with agriculturally important crop plants (Chaney, 1983). Vegetables such as beets, tomatoes, and lettuce, and grain crops such as corn and wheat have been reported to accumulate metals in varying quantities in sludge-amended soils (Kim *et al.*, 1988). In contrast, few studies have determined the effects of sludge on native plants for livestock grazing in the semiarid Southwest (Lane, 1988).

In a preliminary study, dried, anaerobically digested sewage sludge was applied to a degraded grassland site located in north-central New Mexico to measure the effects of sludge on forage productivity and quality. Sludge amendments significantly improved the forage quality of blue grama (*Bouteloua gracilis*), galleta (*Hilaria jamesii*), and bottlebrush squirreltail (*Sitanion hystrix*) over a control (unamended soil) (Fresquez *et al.*, 1990a). Although soil pH in the sludge-amended soil decreased slightly from 7.8 to 7.4 after two growing seasons, heavy metal solubility did not increase significantly. Consequently, the levels of heavy metals in tissues collected from plants growing in the sludge-amended soils were not significantly different from plants growing in the control treatment. However, after 4 yr the soil pH decreased from 7.8 in the control to 7.0 in the sludge-amended

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treatment applied at the highest rate (90 Mg ha^{-1}) (Fresquez *et al.*, 1990b). Normally, heavy metal solubility increases as soil pH decreases to 7.0 (Bohn *et al.*, 1979); therefore, the decrease in soil pH from 7.8 to 7.0 established a potential for solubilization of heavy metals and the subsequent uptake of these elements by plants.

The objectives of this paper are 1) to summarize the extent of heavy metal accumulation in the soil and plant tissue collected from the dominant grassland species (blue grama) growing in this sewage sludge-amended soil, and 2) to evaluate the long-term benefits of sludge application to forage production in an amended degraded range site. Application of dried municipal sludge as a soil amendment may represent a beneficial means of restoring degraded rangeland, but potential adverse effects to the environment must be evaluated before this practice can be considered acceptable.

2. Materials and Methods

In June 1985, dried anaerobically digested sewage sludge obtained from the wastewater treatment facility in Albuquerque, New Mexico, was surface-applied (one-time application) to a degraded semiarid grassland site located 70 km northwest of Albuquerque (Figure 1). Sewage sludge was applied at rates of 0, 22.5, 45, and 90 Mg ha^{-1} (based on oven-dried weight) to each of four plots (3 m X 20 m) in a completely randomized block design consisting of a total of 16 plots. The area was fenced to prevent disturbance by livestock and wildlife. The site was classified as a *Gutierrezia sarothrae/Bouteloua gracilis-Hilaria jamesii* (snakeweed/blue grama-galleta) plant community occurring on a moderately deep, fine-silty, mixed, mesic Ustollic Camborthid (Las Lucas series). This soil/vegetation association is prevalent throughout much of the Upper Rio Puerco Watershed and representative of degraded grassland occurring within the watershed (Francis, 1986). The Rio Puerco Watershed area is 207,172 ha in size and ranges in elevation from 1662 to 2743 m above sea level, with mean annual precipitation ranging from 216 to 322 mm. Seasonal precipitation (April - September) measured by a standard rain gauge at the study site was 147, 239, and 201 mm in 1985, 1986 and 1989, respectively.

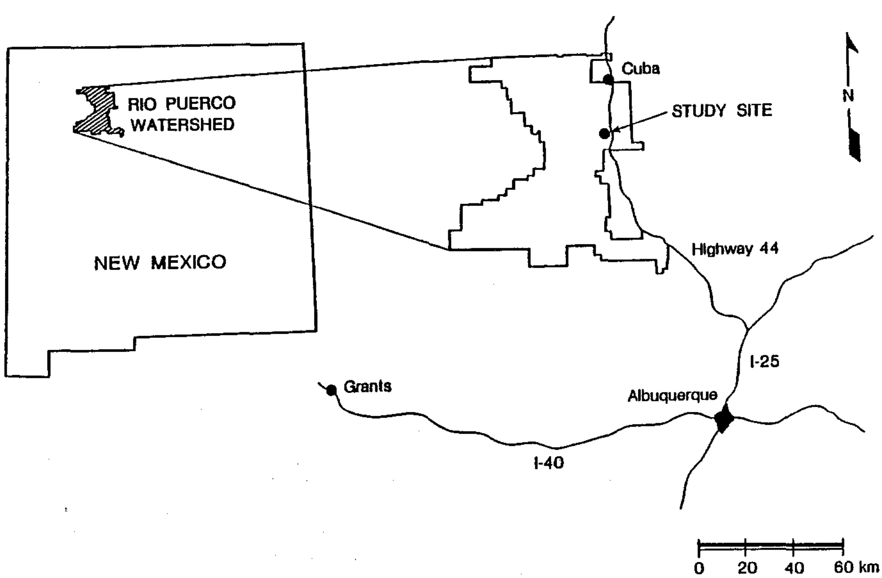

Fig. 1. Location of the study site within the Rio Puerco Watershed, north-central New Mexico.

Soil samples were collected from non-rhizosphere soil at each of the 16 plots in June 1985 (pretreatment) and subsequently in August of 1985, 1986, 1987, 1988, and 1989. Five subsamples were taken from each plot at 0 to 15 cm depth with a 5-cm diameter bucket auger. Subsamples were composited in sealable, sterile plastic containers, placed in an ice-chest, and transported back to the laboratory where they were passed through a 2-mm sieve. The composite samples were subsequently analyzed for texture, pH, organic matter content (OM), N indices (TKN, NH_4-N, NO_3-N), available P, electrical conductivity (EC), water-soluble cations, and heavy and trace metals.

All heavy and trace elements, with the exception of hot water extractable B, were extracted from the soil samples using the DTPA (diethylenetriaminepentaacetic acid) method (AOAC, 1984). Methods employed for other soil chemical analyses including soil pH, EC, OM, total and available-N, available-P, and water-soluble cations have been previously described (Dennis and Fresquez, 1989). Chemical properties of the pretreatment soil and applied sewage sludge are reported in Table I.

Blue grama plants were harvested for tissue analysis prior to seed development in 1985, 1986, and 1989. Plants were harvested at crown level; composite samples for blue grama from each of the 16 treatment plots consisted of five systematically obtained subsamples. The blue grama tissue samples were rinsed with distilled water, dried at 70°C for 48 hr, and then ground and sieved through a 40-mm screen. Perchloric acid digests of the plant tissues (AOAC, 1984) were subsequently analyzed for heavy metal concentrations. Crude protein in the tissues was estimated by multiplying percent N by 6.25 (Van Soest, 1982).

Differences in soil chemical and plant tissue properties between the sludge- treated and unamended plots were evaluated using a one-way analysis of variance at the 5% probability level. Orthogonal polynomials were used to characterize the relationships in these properties among sludge application rates at the 5% probability level. Tukey's multiple range test was employed to facilitate interpretation of the polynomial relationships at the 5% probability level. Additionally, Dunnett's multiple comparison test (α = 0.05 and 0.10) (Dunnett, 1980) was utilized in comparisons between treatments where variance heterogeneity was observed.

3. Results and Discussion

3.1 SOIL NUTRIENTS AND HEAVY METALS

During the first two growing seasons, with the exception of OM, soil nutrients and EC increased linearly with increased sewage sludge application rate (Table II). A small change in soil pH from 7.8 to 7.5 in the 90 Mg ha^{-1} treatment during the first growing season and to 7.4 in the second growing season was probably due to leachates from the applied sludge, which was previously determined to be slightly acidic (Table I). Additionally, acid-producing microbial reactions in the soil (i.e., nitrification) may have contributed to the decrease in soil pH (Miller, 1973).

Micronutrients that significantly increased in the first two growing seasons included DTPA-extractable soil Cu, Mn, and Zn (Table III). These micronutrients increased linearly with sludge application to concentrations commonly encountered in non-degraded soils, yet were maintained well below toxic levels (e.g. >10 to 40 mg kg^{-1} for Cu, >10 to 60 mg kg^{-1} for Mn, and >20 to 40 mg kg^{-1} for Zn are considered phytotoxic and therefore undesirable; Viets and Lindsay, 1973; Tiedemann and Lopez, 1982). The higher micronutrient concentrations resulting from the sludge amendments were probably directly related to sludge decomposition (McCaslin and O'Conner, 1982) rather than to the solubilization of preexisting soil micronutrients as a result of decreased pH.

Soil pH continued to decrease with the highest sludge application rate through the 5 yr study period (Table II). Normally, metals become more soluble as pH decreases (Bohn *et al.*, 1979). Although soil pH decreased, DTPA-extractable soil Cu and Cd increased only to concentrations slightly above those considered acceptable during the fifth growing season (Table III). Copper and Cd concentrations were generally below phytotoxic levels for most plants (Table IV) through most of the study period (>10 to 40 mg kg^{-1} and >0.1 to 1.0 mg kg^{-1} for Cu and Cd, respectively) (Tiedemann and Lopez, 1982).

TABLE I

Chemical and physical properties from the pretreatment clay loam soil (means from 16 plots) and dried sewage sludge.

	WATER-SOLUBLE CATIONS				PHOSPHORUS and NITROGEN						
	Na	Ca	Mg	K	P	NH_4-N	NO_3-N	TKN	OM ($g\ kg^{-1}$)	EC ($ds\ m^{-1}$)	pH
	mg kg^{-1}										
SOIL	5	52	14	6	4	3	2	733	13	0.39	7.8
SLUDGE	587	58	21	770	1599	3681	7	48600	500	18.01	6.8

	HEAVY and TRACE METALS (DTPA-Extractable)								TEXTURE		
	Al	B	Cu	Cd	Fe	Mn	Pb	Zn	Sand	Silt	Clay
	mg kg^{-1}								g kg^{-1}		
SOIL	0.10	0.02	1.30	0.01	3.5	3.8	0.80	0.20	444	256	300
SLUDGE	0.10	0.10	47.50	0.24	259.2	11.8	3.30	150.00	--	--	--

TABLE II

Chemical properties from unamended and sewage sludge amended blue grama dominated soils.

TREATMENT ($Mg\ ha^{-1}$)	WATER-SOLUBLE CATIONS Na	Ca	Mg	K	PHOSPHORUS and NITROGEN P	NH_4-N	NO_3-N	TKN	OM ($g\ kg^{-1}$)	EC ($ds\ m^{-1}$)	pH
	-------	-------	-------	-------	mg kg^{-1}	-------	-------	-------			
FIRST GROWING SEASON											
0	11c[1]	43c	11c	6b	5c	3b	2b	729b	12a	0.36c	7.8a
22.5	22c	134bc	29bc	10b	15bc	9b	22ab	817ab	13a	1.06bc	7.7ab
45.0	39b	201ab	46ab	17a	20b	20ab	42ab	845ab	14a	1.66ab	7.6b
90.0	59a	256a	56a	19a	31a	51a	61a	924a	12a	2.23a	7.5b
SECOND GROWING SEASON											
0	11b	47b	13b	4b	4c	3c	1c	665b	14ab	0.37b	7.8a
22.5	27ab	133ab	33ab	20bc	20bc	10bc	10bc	828ab	15a	0.96ab	7.6ab
45.0	27ab	168ab	44ab	44b	44b	22b	28b	843ab	15ab	1.26ab	7.4b
90.0	55a	264a	71a	72a	72a	39a	54a	987a	12b	1.97a	7.4b
FIFTH GROWING SEASON											
0	1a	58c	15c	4b	9b	4b	7c	682b	14b	0.40c	7.8a
22.5	2a	95b	24b	8ab	26ab	4b	14b	890b	18ab	0.66b	7.7a
45.0	1a	125a	38a	11ab	42ab	39a	22a	1869a	26a	0.82ab	7.4b
90.0	3a	130a	44a	16ab	57a	42a	28a	1814a	23ab	0.90a	7.0b

[1]Means within the same column and year followed by the same letter are not significantly different at the 0.05 level by Tukey's multiple range test.

TABLE III

Heavy and trace metals from unamended and sewage sludge amended blue grama dominated soils.

TREATMENT ($Mg\ ha^{-1}$)	Al	B	Cu	Cd	Fe	Mn	Pb	Zn
	----	----	----	----	$mg\ kg^{-1}$	----	----	----
FIRST GROWING SEASON								
0	0.20a[1]	0.06a	1.04c	0.01a	3.31a	3.46b	0.55a	0.29c
22.5	0.20a	0.06a	1.19bc	0.01a	3.22a	4.21ab	0.60a	0.35bc
45.0	0.20a	0.07a	1.60ab	0.01a	3.36a	5.32ab	0.58a	0.61ab
90.0	0.20a	0.09a	2.10a	0.01a	3.47a	6.10a	0.60a	0.76a
SECOND GROWING SEASON								
0	0.20a	0.07a	0.92b	0.01a	3.33a	5.74b	0.63a	0.27b
22.5	0.20a	0.10a	2.21ab	0.01a	3.94a	7.03ab	0.60a	0.79ab
45.0	0.20a	0.10a	2.99a	0.02a	4.32a	7.26ab	0.65a	1.01ab
90.0	0.23a	0.10a	3.48a	0.02a	4.41a	9.99a	0.68a	1.20a
FIFTH GROWING SEASON								
0	0.16a	0.09b	0.88b	0.01b	2.9b	3.7a	0.76b	0.17c
22.5	0.15a	0.13b	2.40b	0.01b	3.5b	3.1a	0.84b	1.06bc
45.0	0.17a	0.19b	23.52a	0.15a	9.6ab	5.4a	1.45ab	7.78ab
90.0	0.24a	0.40a	29.78a	0.20a	13.7a	6.9a	1.61a	9.67a

[1]Means within the same column and year followed by the same letter are not significantly different at the 0.05 level by Tukey's multiple range test.

TABLE IV

Chemical and heavy metal contents of blue grama tissue from unamended and sewage sludge amended grassland soils.

TREATMENT ($Mg\ ha^{-1}$)	P	K	Ca	Mg	TKN	CP	NO_3-N	Al	B	Cu	Cd	Fe	Mn	Pb	Zn
	$g\ kg^{-1}$						$mg\ kg^{-1}$								
							FIRST GROWING SEASON								
0	1.5b[1]	6.2c	6.1a	2.3a	16c	100c	2b	647a	29a	3c	<0.5a[2]	421a	31b	1.0a	26b
22.5	1.8b	9.2b	6.1a	2.1a	22bc	138bc	11ab	270b	28a	5bc	<0.5a	204b	43ab	1.3a	83a
45.0	2.4a	12.1a	5.1b	2.0a	27ab	169ab	15ab	194bc	21b	8ab	<0.5a	178b	52ab	1.0a	77a
90.0	2.6a	12.9a	5.4ab	2.0a	28a	175a	20a	144c	20b	10a	<0.5a	154b	60a	1.8a	73a
							SECOND GROWING SEASON								
0	1.2c	3.3b	5.4a	1.8a	8c	50c	6b	1494a	40a	5a	<0.5a	437a	22b	1.0a	22b
22.5	1.7bc	7.8a	3.4bc	1.3a	17b	106b	29b	617b	20b	7a	<0.5a	210b	40ab	1.3a	31a
45.0	2.1ab	8.8a	3.0c	1.4a	21ab	131ab	144ab	489b	19b	7a	<0.5a	187b	65ab	1.0a	42a
90.0	2.4a	9.1a	4.1b	1.6a	21a	131a	181a	313b	21b	8a	<0.5a	131b	133a	1.0a	47a
							FIFTH GROWING SEASON								
0	1.9b	8.9b	3.9a	1.4b	20a	123a	30b	456a	54a	10a	<0.5a	333a	31b	1.0a	26a
22.5	2.3b	11.0a	4.7a	2.0a	24a	152a	232a	298ab	58a	11a	<0.5a	244ab	31b	1.0a	26a
45.0	2.4b	11.4a	4.6a	2.0a	25a	154a	228a	310ab	54a	11a	<0.5a	247ab	39ab	1.0a	23a
90.0	3.6a	12.0a	4.9a	2.1a	25a	156a	298a	169b	56a	13a	<0.5a	165b	49a	1.0a	21a

CP = Crude Protien

[1]Means within the same column and year followed by the same letter are not significantly different at the 0.05 level by Tukey's multiple range test.

[2]Cd levels were all below the minimum detection limit, ($0.5\ mg\ kg^{-1}$), regardless of treatment.

3.2 CHANGES IN PLANT TISSUE QUALITY

The sludge amendments significantly increased the nutritional value of blue grama in the first two growing seasons following application (Table IV). Tissue N, P, K, and crude protein increased linearly with the application of sludge to recommended tissue concentrations (Stout, 1961; Tiedemann and Lopez, 1982). Levels of these three macronutrients, especially P, have been reported low or deficient in New Mexico rangeland forage (Watkins, 1937; Nelson *et al.*, 1970). Cattle require forage that contains approximately 59 g kg^{-1} of crude protein. As shown in Table IV, the amount of crude protein in blue grama increased linearly from 100 g kg^{-1} in the control plots to 175 g kg^{-1} in the plots with the highest sludge application rate during the first growing season. A similar increase was observed for N, P, and K, and the trend was repeated during the second growing season. The statistical significance of increased macronutrient and crude protein levels in the amended vs the control plots largely diminished after 5 growing seasons.

Since the pretreatment chemical analysis of the sludge showed no exceptionally large concentrations of DTPA-extractable toxic heavy metals Cd and Pb (Table I) and no significant differences in soil Cd and Pb were observed through the first two growing seasons as a result of the sludge applications (Table III), it was not surprising that Cd and Pb concentrations in blue grama tissue in the amended plots were not significantly different from those in the control after two growing seasons (Table IV). In contrast, levels of tissue micronutrients (Cu, Mn, and Zn) increased linearly over the control with increased sludge application rate to levels considered adequate for plant growth (Stout, 1961; Tiedemann and Lopez, 1982).

After 5 yr, with the exception Mn which was still within desirable levels (Tiedemann and Lopez, 1982), concentrations of metals, including Cu and Cd, in blue grama plant tissue were not significantly different from the control. As shown in Table IV, blue grama does not appear to be accumulating significant heavy metal concentrations from the sludge amendments that could subsequently be transferred to grazing animals. This is a significant finding because concerns over heavy metal accumulations, particularly increased Cd levels, frequently limit sewage sludge application to land (Elliott, 1986).

Aluminum and Fe decreased significantly in blue grama tissue with increased sludge application (Table IV). Since blue grama growing in both the unamended and all three sludge-amended treatments contained tissue Fe well above recommended levels (Viets and Lindsay, 1973; Tiedemann and Lopez, 1982), the greater production of blue grama herbage from the amended plots coupled with the lower amounts of tissue Al and Fe suggested a dilution effect (Dennis *et al.*, 1988). Calculations based on Fe concentration and plant yield showed that total tissue Fe per plant in the sludge-amended plots (average = 839 mg Fe) was equal to or greater than total tissue Fe per plant in the unamended plots (761 mg Fe).

3.3 CHANGES IN BLUE GRAMA FORAGE PRODUCTION

The positive effects of the added sludge on blue grama forage production are clearly evident (Table V). Blue grama production in the sludge-treated plots was significantly greater than production in the unamended plots during the first and second growing seasons, ranging from 1.5 to almost 3.0 times greater than yields in the unamended control plots. The greatest increases were realized for the 90 Mg ha^{-1} amendment.

Blue grama yields remained higher in the 45 and 90 Mg ha^{-1} sludge-amended plots after 5 growing seasons, although the benefits of the added sludge were minimal for the lowest (22.5 Mg ha^{-1}) sludge amendment rate. Additionally, variability in blue grama production within the control plots, and particularly in those plots with the highest sludge application rate (90 Mg ha^{-1}), increased greatly during the fifth growing season. This increased "within treatment" variability is largely responsible for the lack of statistical difference (α = 0.05) observed between the control and the amended plots during the fifth growing season, although average blue grama production for the 45 and 90 Mg ha^{-1} treatment plots remained nearly double that of the control. Nonetheless, the 45 Mg ha^{-1} treatment was significantly different from the control at α = 0.10 (Table V).

TABLE V
Blue grama production in sludge amended vs unamended grassland soils, Rio Puerco Watershed, after one, two and five growing seasons.

Treatment (Mg ha^{-1})	Production (kg ha^{-1})	S.E.
First Growing Season (ppt. = 147 cm)		
0	270b[1]	22
22.5	480ab	96
45.0	433ab	100
90.0	509a	62
Second Growing Season (ppt. = 239 cm)		
0	392b	76
22.5	575ab	163
45.0	824ab	114
90.0	1067a	227
Fifth Growing Season (ppt. = 201 cm)		
0	281a	39
22.5	291a	75
45.0[2]	506a	51
90.0	500a	178

[1]Means within the same column and year followed by the same letter are not significantly different at the 0.05 level by Tukey's multiple range test.
[2]Significantly different from the control at the 0.10 level by Dunnett's multiple comparison test.

4. Conclusions

Sewage sludge application to a degraded semiarid grassland soil significantly increased soil N, P, and K without adversely increasing heavy metal concentrations after 1, 2, and 5 growing seasons. Yields of blue grama increased two- to three-fold over the unamended control after two growing seasons; these increases were most likely related to increased N or P supplied by the sludge. Likewise, the forage quality of blue grama significantly increased with the application of sludge, as demonstrated by increased levels of plant tissue N, P, K, and crude protein.

Plant tissue heavy metal concentrations generally remained within recommended levels through the 5 yr study. Although soil heavy metals such as Cu and Cd in the 45 and 90 Mg ha^{-1} sludge treatments increased above recommended levels as soil pH decreased to 7.0 during the fifth growing season, at no time did their concentrations attain phytotoxic levels. Consequently, Cu and Cd tissue concentrations in the treated plots did not exceed recommended levels at any time during the study and were not significantly different from those in the control plots after the fifth growing season.

Although average blue grama production remained higher in the sludge-amended plots through the entire study, within treatment plot variability did increase appreciably during the fifth growing season, thereby decreasing the significance of contrasts between the sludge-amended and control plots.

Considering soil and plant tissue metal concentrations, it appears that a one-time sludge application at a rate between 22.5 and 45 Mg ha^{-1} will produce significant vegetative growth increases in this semiarid grassland environment (Table V) while maintaining the most favorable soil and plant tissue nutrient levels (Tables III and IV). The improvements in grassland quality and productivity demonstrated here are encouraging as they suggest a potential means of utilizing sewage sludge in rangeland restoration efforts without inducing harmful environmental effects.

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