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Metropolitan Water Reclamation District of Greater Chicago

RESEARCH AND DEVELOPMENT DEPARTMENT

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CORN YIELDS AND NUTRIENT COMPOSITION DURING LONG-TERM BIOSOLIDS APPLICATIONS TO CALCAREOUS STRIP-MINE SOIL

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DISCLAIMER

Mention of proprietary equipment and chemicals in this report does not constitute endorsement by the Metropolitan Water Reclamation District of Greater Chicago (District).

SUMMARY AND CONCLUSIONS

A long-term experiment using corn (*Zea mays* L.) was initiated in 1973 on calcareous strip-mine spoil to evaluate the effects of biosolids (anaerobically digested waste-activated sludge) on the soil-crop system. Treatments consisted of a control (336-224-112 kg ha^{-1} $year^{-1}$ N-P-K fertilizer) and applications of liquid biosolids, weather permitting, at weekly rates of 0.64, 1.27, and 2.54 cm from 1973 to 1984. From 1985 to 1995, dewatered biosolids was usually applied at yearly rates of 16.8, 33.6, and 67.2 dry Mg ha^{-1}. The maximum-amended treatment from 1973 to 1995 received a total of 1,481 dry Mg ha^{-1} of biosolids.

Long-term biosolids applications from 1973 to 1995 had significant impacts on corn grain and stover yields and the N, P, and K composition of corn leaves. Grain and stover yields, although variable yearly, increased with higher rates of biosolids application. Biosolids applications had a greater impact on grain yields as compared to stover yields. Regression analysis showed that growing season rainfall was a significant climatic factor affecting grain yields on mine spoil with a limited rooting depth.

Leaf N, P, and K levels responded differently to biosolids applications. Leaf N levels increased with higher rates of biosolids application, while leaf P and K levels

usually did not vary significantly in the biosolids treatments. The form of biosolids applied, liquid versus dewatered, had an impact on leaf N concentrations. During liquid biosolids applications (1973-1984), leaf N levels were usually within the N sufficiency range. However, with dewatered biosolids applications (1985-1995), the leaf N levels were generally below the N sufficiency range. Leaf P and K levels during the 1973 to 1995 interval were usually within the sufficiency range for these elements, indicating they were not limiting nutrients for corn.

Total N, P, and K uptake by corn, although variable, increased with higher rates of biosolids application. Regression analysis indicated that total N and P uptake were significant factors affecting corn grain yields. Total N uptake was higher under liquid versus dewatered biosolids applications, and total P uptake was higher in the one-fourth and one-half maximum-amended treatments under liquid versus dewatered biosolids applications. Total N, P, and K uptake by corn grown on biosolids-amended mine spoil was usually less than that observed for corn grown on biosolids-amended productive agricultural soils. The percent uptake of biosolids-applied N(5.6-14.9%), P(1.2-3.2%), and K(23.3-29.4%) by corn during the study was similar to that observed in other studies on biosolids-amended soils.

Major factors playing a significant role in corn production on biosolids-amended mine spoil were the physical characteristics of mine spoil, the nutrient composition of the applied biosolids, total N and P uptake, and growing season rainfall. Biosolids applied N and P were also significant variables. Because of compaction during strip mining, the limited rooting depth was the major soil physical factor limiting yields. The major biosolids factors were the amounts of N and P supplied during biosolids applications. Regression analysis showed that biosolids applied total Kjeldahl-N, NH_4-N, plant available nitrogen (PAN), biosolids applied P and total N and P uptake were important factors affecting grain yields.

The actual amount of PAN in the dewatered and aged anaerobically digested biosolids, determined by using a seven day test to predict the long-term decomposition, was 25 percent of the IEPA's formula normally used to calculate PAN for anaerobically digested biosolids. The estimated mineralization rate of the biosolids organic nitrogen based on a computer simulation was about 5 percent as compared to the recommended rate of 20 percent used in the formula. For successful crop production on agricultural land and under more stressful conditions such as mine spoil, the actual amounts of PAN in applied biosolids is an important factor that needs to be determined.

Applying biosolids in amounts greater than the calculated PAN on mine spoil, as was done in this study, did not result in the corn grain yields projected for productive agricultural soils. Grain yields equivalent to those found on productive agricultural soils will not occur unless other mine spoil and environmental factors are not limiting.

INTRODUCTION

Biosolids disposal and recycling options currently available to municipal agencies treating waste water include incineration, landfilling, and land utilization. The quantity of biosolids applied to land in the United States has steadily increased during the last two decades, from 0.86 million dry Mg in 1972 to 2.8 million dry Mg in 1998 (USEPA, 1999). The National Research Council in 2002 estimates that 3.4 million dry Mg of biosolids are applied to land yearly (National Research Council, 2002).

The widely recognized agricultural benefits from the land application of biosolids include the N, P, and K provided to crops through biosolids and organic matter to enrich the soil. Early investigators (Lunt, 1959; Niles, 1944) recognized the fertilizer value of applying biosolids to land. In addition to its use as a fertilizer on agricultural lands, biosolids have been used in the reclamation of disturbed lands. These disturbed lands include those surface mined for coal (Feuerbacher et al., 1980; Hinesly and Redborg, 1984; Joost et al., 1987; Sopper, 1991), copper mine spoils (Berry 1982; Sabey et al., 1990), and borrow pits (Berry and Marx, 1980).

Numerous studies have been conducted on the impact of biosolids applications on crop yields including corn. Kelling et al. (1977) observed marked increases in the N and P concentrations of corn with increasing rates of biosolids in the field. Lutrick et al. (1975) reported that various rates of biosolids application increased corn-tissue N, but that tissue P and K were not affected. Pietz et al. (1982) reported that grain yields on calcareous mine spoil were significantly affected by biosolids applications, but that tissue levels of N, P, and K varied in response to biosolids applications. In a 20-year experiment with biosolids application to agricultural land, Clapp et al. (1994) reported that corn yields on biosolids treatments equaled or exceeded those of control treatments receiving commercial fertilizer, and that corn tissue took up N, P, and K in similar amounts from the biosolids-amended and control areas, which received commercial fertilizer.

In the early 1970's, limited knowledge was available on the impact of biosolids on strip-mine spoils used for row crop production (corn [*Zea mays* L.] and soybeans [*Glycine max* (L.) Merr.]). The District felt that the effects of biosolids-applied elements on the mine spoil-crop system needed to be considered in evaluating the impact of biosolids application on mine spoil reclamation. In 1973, the District initiated a long-term experiment at its Fulton County, Illinois land reclamation site with the intent of applying the highest possible yearly amounts of biosolids for remediating mine spoil land and growing crops (Pietz et al., 1982).

The objectives of this paper are to report the effects of yearly biosolids applications on the yields, tissue-N, -P, and -K contents, and the total uptake of these elements by corn from 1973 to 1995.

MATERIALS AND METHODS

Experimental Procedure

Anaerobically digested, waste-activated biosolids (pH 7.2-8.0) from holding basins at the District's Fulton County, Illinois land reclamation site were applied yearly from 1973 to 1984 to 4.6- by 12.2-m experimental plots on calcareous strip-mine spoil (pH 7.8, bulk density 1.6 g cm^{-3}, $CaCO_3$ equivalent 32 g kg^{-1} (Pietz et al, 1982)). From 1985 to 1995, dewatered biosolids (pH 6.0-7.9) from either the holding basins at the site or from Chicago were applied to the experimental plots. The concentrations of total solids and nutrients applied yearly in both the liquid and dewatered biosolids applied are shown in Table 1.

The plot design was a randomized block with four treatments per block and four replications. Corn ('Pioneer 3517') was grown on lister ridges 72.6 cm apart at a population of 50,000 plants ha^{-1}. Treatments were a control receiving 336-224-112 kg ha^{-1} of N-P-K fertilizer yearly, and plots applied at weekly biosolids rates of 0.64, 1.27, and 2.54 cm per application to the intervening furrows as often as weather conditions permitted during the growing season and late fall. The biosolids-amended treatments will be referred to as the

TABLE 1

CONCENTRATIONS OF TOTAL SOLIDS AND NUTRIENTS IN BIOSOLIDS APPLIED TO CALCAREOUS MINE SPOIL

Year	Annual Total Solids Content	Nutrients in Applied Biosolids			
		Total Kjeldahl-N	NH_4-N	P	K
	g kg^{-1}	---------------mg kg^{-1} dry wt-------------			
1973	10.6	119,000	81,700	30,700	9,880
1974	41.8	53,300	24,100	44,200	4,500
1975	42.1	47,700	23,700	21,500	5,130
1976	39.0	51,200	23,200	41,400	5,590
1977	45.5	50,800	18,300	33,200	3,360
1978	43.9	50,400	22,300	32,500	5,750
1979	46.6	46,400	21,300	29,900	4,440
1980	42.1	43,200	19,000	33,900	6,130
1981	46.6	48,200	21,600	26,700	3,420
1982	49.6	45,200	18,200	27,300	2,610
1983	56.6	44,200	17,100	26,800	2,580
1984	48.3	57,000	15,640	30,600	2,240
1985	529	14,300	1,230	48,960	444
1986	587	11,600	9,400	12,210	900
1987	410	20,200	2,450	10,810	1,330

TABLE 1 (Continued)

CONCENTRATIONS OF TOTAL SOLIDS AND NUTRIENTS IN BIOSOLIDS APPLIED TO CALCAREOUS MINE SPOIL

Year	Annual Total Solids Content	Nutrients in Applied Biosolids			
		Total Kjeldahl-N	NH_4-N	P	K
	g kg^{-1}	--------------mg kg^{-1} dry wt--------------			
1988	609	10,800	264	13,360	1,420
1989	694	8,200	17.0	11,520	1,380
1990	630	10,700	13.5	13,550	2,420
1991	684	9,630	152	10,940	2,360
1992	623	26,460	2,000	32,120	2,080
1993	570	12,300	102	17,550	2,460
1994	673	12,600	290	20,820	1,490
1995	676	11,670	522	19,730	2,300

maximum (receiving the highest application rate), the one-half maximum (receiving half the maximum application rate), and the one-fourth maximum (receiving one quarter of the maximum application rate). In addition, the biosolids-amended plots received 112 kg K ha^{-1} each spring. Commercial fertilizer and previously applied biosolids were incorporated to a depth of 20 cm by disking prior to planting. The yearly amounts of liquid biosolids applied to the maximum treatments from 1973 to 1984 are shown in Table 2.

The use of liquid biosolids on the treatments was terminated after 1984. Beginning in 1985, dewatered biosolids were land applied each spring prior to the planting of corn. Application rates for total solids and nutrients applied to the maximum treatments are shown in Table 2. Biosolids and fertilizer were incorporated to a depth of 20 cm by disking prior to planting.

Annual and growing season precipitation, May through September, for each year is shown in Figure 1. From 1973 through 1995 the mean annual precipitation was 95.3 cm (37.5 inches) and varied from 53.5 to 171.3 cm (21.1 to 67.4 inches), and the mean annual growing season precipitation was 45.4 cm (17.9 inches) and ranged from 15.7 to 70.4 cm (6.2 to 27.7 inches).

TABLE 2

ANNUAL AMOUNTS OF TOTAL SOLIDS AND NUTRIENTS APPLIED BY BIOSOLIDS APPLICATIONS TO CALCAREOUS MINE SPOIL IN THE MAXIMUM TREATMENT

Year	Annual Total Solids Applied	Nutrients in Applied Biosolids			
		Total Kjeldahl-N	NH_4-N	P	K
	Mg ha^{-1}	kg ha^{-1}			
1973	11.9	1,410	969	365	117
1974	51.0	2,830	1,280	2,350	239
1975	59.6	3,060	1,490	1,380	329
1976	57.1	3,040	1,380	2,460	332
1977	78.0	4,110	1,480	2,690	272
1978	64.3	3,240	1,430	2,090	370
1979	79.6	3,700	1,700	2,380	354
1980	69.8	3,010	1,330	2,360	428
1981	45.5	2,090	982	1,210	156
1982	68.7	3,110	1,250	1,880	179
1983	71.7	3,170	1,230	1,920	185
1984	67.0	3,820	1,050	2,050	150
1985	63.7	911	78.4	3,120	28.3
1986	75.2	872	707	918	67.7

TABLE 2 (Continued)

ANNUAL AMOUNTS OF TOTAL SOLIDS AND NUTRIENTS APPLIED BY BIOSOLIDS APPLICATIONS TO CALCAREOUS MINE SPOIL IN THE MAXIMUM TREATMENT

Year	Annual Total Solids Applied	Nutrients in Applied Biosolids			
		Total Kjeldahl-N	NH_4-N	P	K
	Mg ha^{-1}	kg ha^{-1}			
1987	80.8	1,630	198	873	108
1988	67.2	726	17.7	898	95.4
1989	67.2	551	1.1	774	92.7
1990	67.2	719	0.9	911	163
1991	67.2	647	10.2	735	159
1992	67.2	1,780	134	2,160	140
1993	67.2	827	6.9	1,180	165
1994	67.2	847	19.5	1,400	100
1995	67.2	784	35.1	1,330	155

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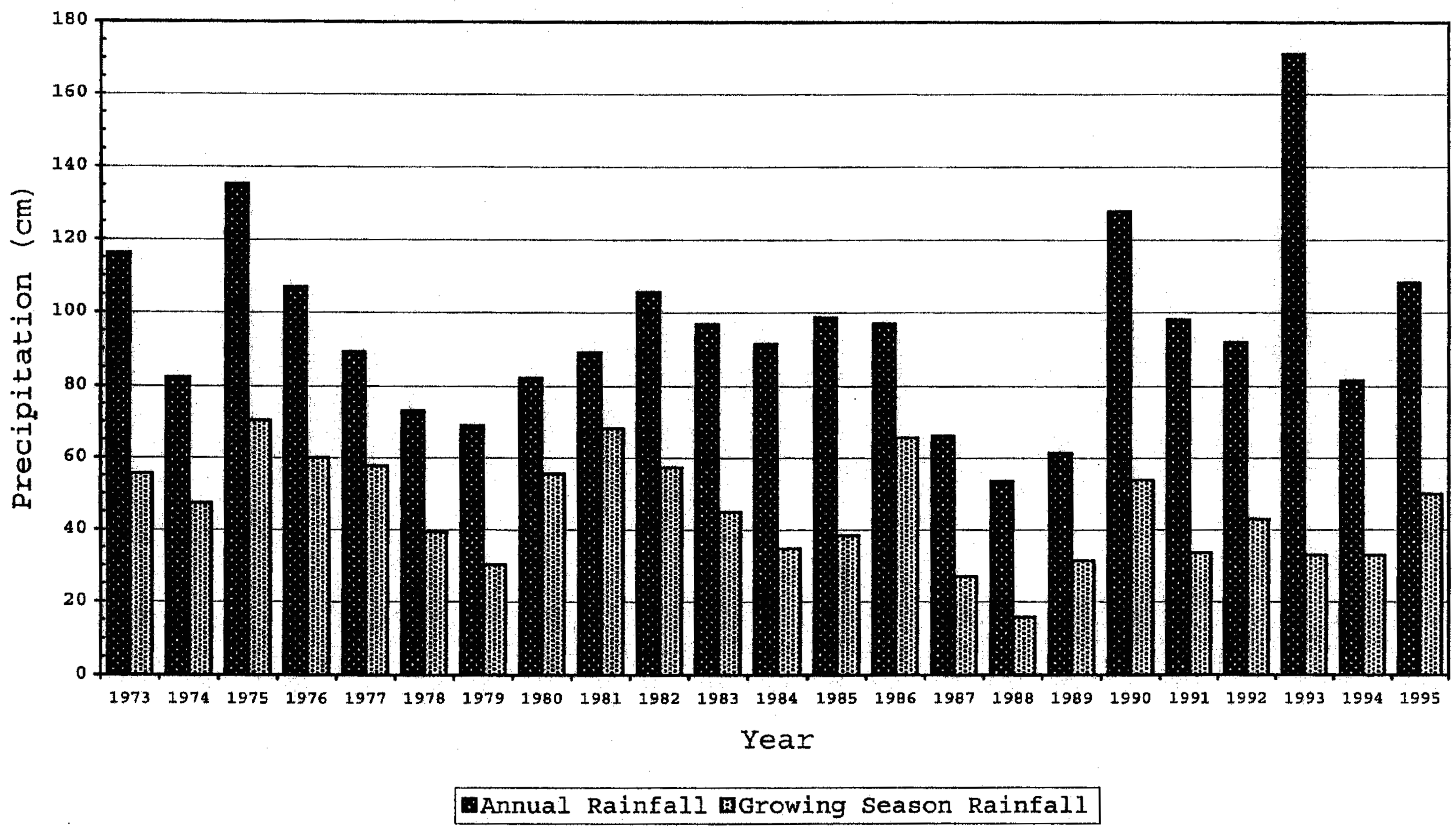
FIGURE 1

ANNUAL AND GROWING SEASON PRECIPITATION AT EXPERIMENTAL PLOTS IN FULTON COUNTY, ILLINOIS



In 1987, the available supply of the corn hybrid Pioneer 3517 was depleted. A new hybrid, Pioneer 3377, was substituted, and this hybrid was used from 1987 through 1995.

Biosolids Sampling and Analyses

The variation of total solids in the liquid biosolids during applications necessitated a composite biosolids sample being collected from each replication every time biosolids were applied (Pietz et al., 1982). A composite sample of dewatered biosolids was collected from each replication during application. These samples were analyzed for total solids, total Kjeldahl-N, NH_4-N, and total P (persulfate digestion) according to *Standard Methods* (American Public Health Association, 1992). Total K in liquid biosolids was analyzed by drying biosolids samples (110°C) to constant weight and grinding the samples to pass an 80-mesh screen. The samples were prepared for analysis by slow-heating to 500°C for 24 hours, dissolving the ash in 1*N* HCl, and analyzing the element by atomic absorption spectrometry. Dewatered biosolids were analyzed for K by nitric acid digestion on a hot plate according to *Standard Methods* (American Public Health Association, 1992) and analyzing the element by atomic absorption spectrometry. Element concentrations in biosolids are expressed on an oven-dry weight basis at 110°C.

Corn Tissue Sampling and Analyses

Corn leaf samples were collected opposite and below the primary ear shoots when approximately 10 percent of the plants had tasseled. Leaf samples were washed in distilled water, dried at 65°C for 48 hours, and ground in a Wiley mill containing a 20-mesh stainless steel screen. Grain (15.5 percent moisture) and stover (total above ground dry matter excluding grain at 65°C) yields were determined by hand-harvesting the center two rows of each plot. Stover yields were not determined in 1973, and grain and stover yields were not determined in 1979 because of a low plant population caused by a dry summer. Representative grain and stover samples selected for elemental analyses were dried and ground in the same manner as leaf samples.

Subsamples of leaf, grain, and stover to be analyzed for K were wet-ashed in concentrated HNO_3 at 90°C, followed by $HClO_4$ at 200°C. Samples were heated to dryness and dissolved in 1*N* HNO_3 for the determination of K by atomic absorption spectrophotometry. Potassium analyses of 1978 and 1979 corn leaf, grain, and stover samples were not conducted (Hinesly et al., 1984).

Total N in plant samples was determined according to the micro-Kjeldahl procedure (Nelson and Sommers, 1980). Plant P, after dry ashing the sample at 500°C for 4 hours, was determined using a modified vanadomolybdate procedure (Jackson, 1958). After 1979, the procedure for P determination was changed to wet oxidation using the micro-Kjeldahl procedure (Nelson and Sommers, 1980). Phosphorus was determined by using the Technicon AutoAnalyzer (Isacc and Jones, 1970) and in later years by the Lachat Analyzer (Lachat Instruments, Milwaukee, Wisconsin). Element concentrations in corn are expressed on an oven-dry weight basis at 65°C.

Statistical Analyses

Statistical analyses were used to study the effects of biosolids applications on the corn grain and corn stover yields; tissue N, P, & K contents; and the total uptake of these elements by corn using the following data sets:

- during each year,
- during the liquid biosolids application period (1973 to 1984),
- during the dewatered biosolids application period (1985 to 1995), and
- during both periods (1973 to 1995).

Single site, long-term experiments, such as this one, present problems in evaluating the long-term impacts of the treatments over years because there is often a significant relationship between treatment and year because of environmental interactions (Raun et al., 1993). The interpretation of year-by-treatment interactions by conventional analyses of variance (ANOVA) is difficult because of the complexity of factors affecting the environment. One of the best interpretations of significant year-by-treatment interactions can be given by stability analysis techniques, which use a linear regression of the yearly mean of each treatment against the yearly mean of all treatments known as the environmental mean. The environmental mean measures the response of the treatments to the environment. Stability analysis is a technique that is often used to evaluate fertility and plant breeding experiments from multi-location and single sites where treatments are applied to the same plots year after year (Eberhart and Russell, 1966; Guertal et al., 1994; Raun et al., 1993; Yates and Cochran, 1938).

Stability analysis was considered to be the most useful statistical technique to evaluate data from a single site, long-term experiment when an ANOVA showed a significant year-by-treatment interaction. This technique, along with others to be described, was to evaluate the data from this long-term experiment.

METHODOLOGY

The statistical methodologies used were a one-way ANOVA to study the yearly treatment effects, and a two-way ANOVA for a randomized complete block design to study the yearly effects, treatment effects, and the year-treatment interaction effects (Steel and Torrie, 1980). For the one-way ANOVA, the assumption of normality for each treatment was checked by using the Kolmogorov-Smirnov (K-S) method, and the assumption of equal variance for all treatments was checked by using the Bartlett's test. For the two-way ANOVA, the assumption of normality of the residuals was checked by the K-S method. If the necessary assumptions were met, a parametric ANOVA was performed on the actual values or the log transformed values. Otherwise, the analysis was performed by using the Kruska-Wallis (K-W) method known as a non-parametric ANOVA. The non-parametric ANOVA uses ranks of the data values that do not change due to any one-to-one transformation, such as the log transformation of the data values.

For stability analysis the data were tested for the existence of any auto-correlations, such as the correlation of the value with the past values that may occur in data collected over time. The use of stability analysis for a better interpretation of the year-by-treatment interaction was not appropriate if such auto-correlations occurred. We performed the test for the existence of any auto-correlations using the method developed by Box and Jenkins (1970). We found no significant auto-correlations that identified a moving average, an auto-regressive (AR), or an auto-regressive integrated moving average (ARIMA) process.

All statistical analyses involving ANOVA, linear regression, linear multiple regression, and auto-correlation checks were performed by using SAS software (SAS Institute, 2000). The graphs for stability analyses were prepared by using the Visual Basic for Applications programs.

RESULTS AND DISCUSSION

Grain and Stover Yields

Grain yields in each of the four treatments varied considerably during the 1973 to 1995 interval of biosolids application (Table 3). Mean yields ranged from 0.06 Mg ha^{-1} in the 1991 one-fourth maximum treatment to 8.60 Mg ha^{-1} in a 1986 maximum treatment. Grain yields during the liquid biosolids applications, 1973 through 1984, were the lowest in 1983 and the highest in 1981. Significant differences in yields between treatments occurred in 1974, 1976, and 1984. During dewatered biosolids applications, 1985 through 1995, grain yields were the lowest in 1991 and the highest in 1986. Significant differences between treatment yields occurred in 1985, 1989, 1990, 1991, and 1993.

A summary of mean grain yields for each treatment during liquid biosolids applications, dewatered biosolids applications, and all years is shown in Table 3. Yields in the biosolids treatments generally equaled or exceeded those in the fertilized control treatment. The only exception to this was the noticeably lower mean grain yield in the one-fourth maximum treatment as compared to the control treatment during the application of dewatered biosolids. For all years the mean

TABLE 3

ANNUAL CORN GRAIN YIELDS
ON BIOSOLIDS-AMENDED CALCAREOUS MINE SPOIL

Year	Treatments[1]				Prob (ANOVA)
	Control	1/4 Max	1/2 Max	Max	
	Liquid Biosolids Application (Mg/ha)				
1973	1.96	3.44	3.17	3.10	0.308
1974	1.11	1.44	1.74	*2.38	0.016
1975	4.00	4.96	5.41	5.15	0.149
1976	2.99	*4.38	*4.37	3.81	0.038
1977	2.37	1.60	2.09	3.01	0.082
1978	4.00	2.82	3.14	3.08	0.084
1980	2.41	2.11	2.19	3.49	0.095
1981	5.04	4.72	5.75	5.69	0.713
1982	3.20	3.78	4.38	4.78	0.117
1983	0.46	0.33	0.73	0.68	0.293
1984	3.18	4.29	*5.27	*6.68	0.001
	Dewatered Biosolids Application (Mg/ha)				
1985	2.87	*4.11	*4.90	*5.07	0.000
1986	6.65	6.28	6.61	8.60	0.388
1987	1.29	1.14	1.59	1.90	0.499
1988	1.09	0.87	0.66	0.45	0.056
1989	1.70	*4.11	*4.93	*4.38	0.000
1990	1.88	0.62	0.75	2.37	**0.007
1991	0.13	0.06	0.59	*1.70	0.008
1992	6.17	3.98	5.55	5.16	0.473
1993	2.41	0.85	2.46	*7.12	0.001
1994	4.68	1.50	2.70	5.32	0.051
1995	0.45	0.72	2.57	3.62	0.185

TABLE 3 (Continued)

ANNUAL CORN GRAIN YIELDS
ON BIOSOLIDS-AMENDED CALCAREOUS MINE SPOIL

Year	Treatments[1]				Prob (ANOVA)
	Control	1/4 Max	1/2 Max	Max	
	Summary of Treatment Means (Mg/ha)				
Liquid Biosolids	2.79	3.08	3.48	*3.80	0.029
Dewatered Biosolids	2.72	2.25	3.03	*4.15	0.004
All Years	2.76	2.67	3.25	*3.98	0.000

[1]Please see Appendix AI-1 for Dunnett T-value and ANOVA p-value.

*Significantly different from control at 5% level of significance by Dunnett test.

**Unable to detect significant difference from control by Dunnett test.

grain yield in the one-fourth maximum treatment was slightly lower than that of the control treatment.

An ANOVA for corn yields (during liquid biosolids applications) from 1973 through 1984 showed significant ($P \leq 0.05$) sources of variation for year, treatment, and year-by-treatment interaction (Table 4). Because of the significant year-by-treatment interaction, stability analysis was used to evaluate the treatment response.

A regression of the yearly mean grain yields for each treatment against the yearly environmental mean (Table 5) showed that the slopes of the regression lines for the treatments were significantly ($P \leq 0.05$) different during liquid biosolids applications. Stability analysis of the yearly mean grain yields in each of the four treatments on the yearly environmental means is shown in Figure 2. The grain yields during liquid biosolids applications were the highest in the maximum treatment followed by the one-half maximum, one-fourth maximum, and the control treatments.

An ANOVA of corn grain yields from 1985 through 1995 during dewatered biosolids applications showed significant ($P \leq 0.05$) differences for year, treatment, and year-by-treatment interaction (Table 6). Stability analysis was used to evaluate the treatment response because of the significant year-by-treatment interaction.

TABLE 4

ANALYSIS OF VARIANCE
FOR CORN GRAIN YIELDS FROM 1973 TO 1984
DURING LIQUID BIOSOLIDS APPLICATIONS

Source of Variation	Degrees of Freedom	Mean Square Error	F Ratio	P Value
Year	10	34.91	26.052	*0.000
Treatment	3	8.66	6.463	*0.000
Year x Treatment	30	1.34	1.800	*0.010
Error	132	0.73		

*Significant at 5% level of significance.

TABLE 5

REGRESSION OF TREATMENT MEANS (Y) ON ENVIRONMENTAL MEANS (X) OF CORN GRAIN YIELDS FOR EACH TREATMENT AND THE TEST FOR EQUIVALENCE OF THE FOUR REGRESSION EQUATIONS DURING LIQUID BIOSOLIDS APPLICATIONS (1973 TO 1984)

Treatment Y	Intercept a	Slope b	R^2	P Value
Control	0.0000	0.8430	0.9663	0.000
1/4 Max	0.0000	0.9461	0.9862	
1/2 Max	0.0000	1.0671	0.9960	
Max	0.0000	1.1438	0.9828	

Regression Equation: $Y = a + bX$.

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FIGURE 2

STABILITY ANALYSIS FOR TREATMENT MEANS OF GRAIN YIELDS DURING LIQUID BIOSOLIDS APPLICATIONS

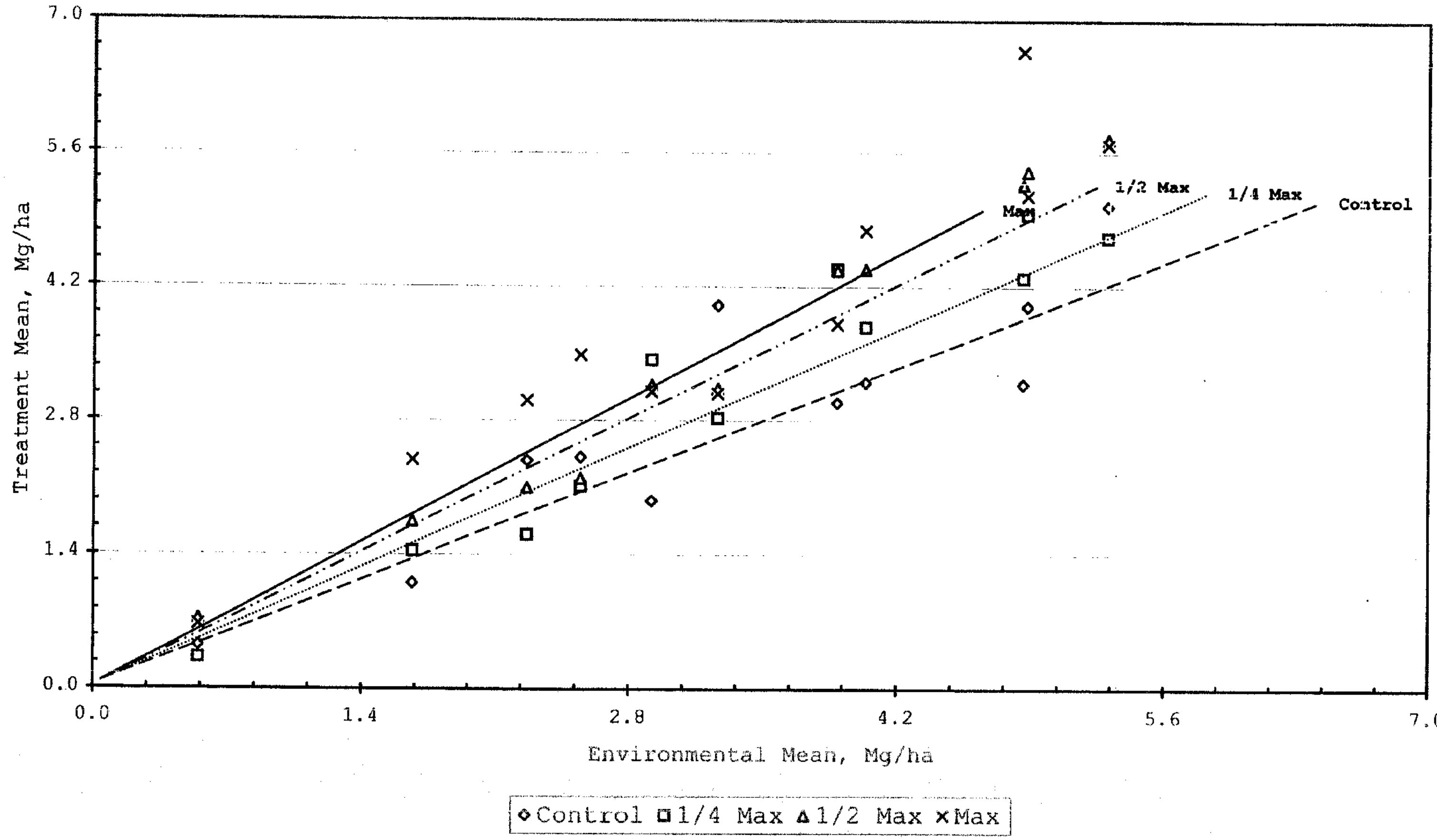

TABLE 6

ANALYSIS OF VARIANCE
FOR CORN GRAIN YIELDS FROM 1985 TO 1995
DURING DEWATERED BIOSOLIDS APPLICATIONS

Source of Variation	Degrees of Freedom	Mean Square Error	F Ratio	P Value
Year	10	63.54	13.635	*0.000
Treatment	3	30.13	6.466	*0.000
Year x Treatment	30	4.66	2.400	*0.000
Error	130	1.95		

*Significant at 5% level of significance.

A regression of yearly grain yields for each treatment against the yearly environmental means (Table 7) showed that the slopes of the regression lines for the treatments were significantly different. Stability analysis of the yearly mean grain yields in each of the four treatments on the yearly environmental means is shown in Figure 3. Grain yields during dewatered biosolids applications were the highest in the maximum treatment followed by the one-half maximum, control, and the one-fourth maximum treatments. In contrast to grain yields during liquid biosolids applications, where the yields were the lowest in the control treatment, the grain yields during dewatered biosolids applications were the lowest in the one-fourth maximum treatment.

An ANOVA for corn grain yields from 1973 through 1995 during both liquid and dewatered biosolids applications showed significant ($P \leq 0.05$) differences for year, treatment, and year-by-treatment interaction (Table 8). Because of the significant interaction between treatment and year, stability analysis was conducted to evaluate the treatment response.

A regression of the yearly mean grain yields for each treatment against the yearly environmental means (Table 9) showed that the slopes of the regression lines for the treatments were significantly different. Stability analysis of the yearly mean grain yields in each of the four treatments on the

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TABLE 7

REGRESSION OF TREATMENT MEANS (Y) ON ENVIRONMENTAL MEANS (X) OF CORN GRAIN YIELDS FOR EACH TREATMENT AND THE TEST FOR EQUIVALENCE OF THE FOUR REGRESSION EQUATIONS DURING DEWATERED BIOSOLIDS APPLICATIONS (1985 TO 1995)

Treatment Y	Intercept a	Slope b	R^2	P Value
Control	0.0000	0.9125	0.9161	0.000
1/4 Max	0.0000	0.7870	0.9157	
1/2 Max	0.0000	1.0066	0.9705	
Max	0.0000	1.2924	0.9388	

Regression Equation: $Y = a + bX$.

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FIGURE 3

STABILITY ANALYSIS FOR TREATMENT MEANS OF GRAIN YIELDS DURING DEWATERED BIOSOLIDS APPLICATIONS

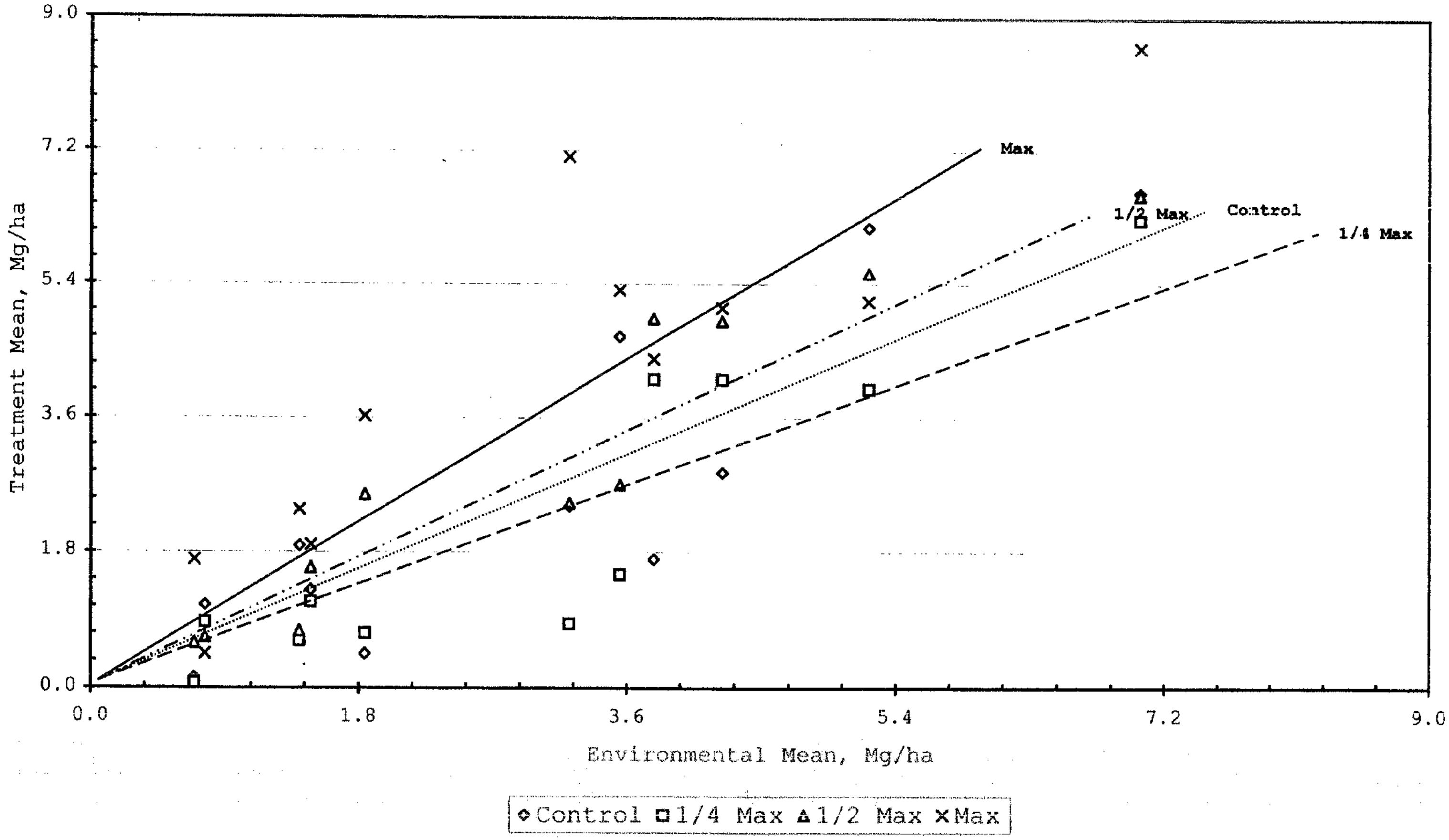

TABLE 8

ANALYSIS OF VARIANCE
FOR CORN GRAIN YIELDS FROM 1973 TO 1995
DURING LIQUID AND DEWATERED BIOSOLIDS APPLICATIONS

Source of Variation	Degrees of Freedom	Mean Square Error	F Ratio	P Value
Year	21	47.13	15.010	*0.000
Treatment	3	33.06	10.529	*0.000
Year x Treatment	63	3.14	2.400	*0.000
Error	262	1.33		

*Significant at 5% level of significance.

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TABLE 9

REGRESSION OF TREATMENT MEANS (Y) ON ENVIRONMENTAL MEANS (X) OF CORN GRAIN YIELDS FOR EACH TREATMENT AND THE TEST FOR EQUIVALENCE OF THE FOUR REGRESSION EQUATIONS DURING LIQUID AND DEWATERED BIOSOLIDS APPLICATIONS (1973 TO 1995)

Treatment Y	Intercept a	Slope b	R^2	P Value
Control	0.0000	0.8777	0.9371	0.000
1/4 Max	0.0000	0.8666	0.9481	
1/2 Max	0.0000	1.0369	0.9830	
Max	0.0000	1.2181	0.9541	

Regression Equation: $Y = a + bX$.

yearly environmental means is shown in Figure 4. Grain yields during both liquid and dewatered biosolids applications were the highest in the maximum treatment followed by the one-half maximum treatment. Yields for the one-fourth maximum and control treatments were essentially the same as indicated by the similar slopes for the two regression lines in Table 9. Liquid and dewatered biosolids applications from 1973 through 1995 resulted in higher corn grain yields in both the maximum and one-half maximum treatments as compared to the control and one-fourth maximum treatments.

Corn grain yields on the biosolids-amended mine spoil plots were influenced by a variety of factors. The impact of the mine spoil physical properties on grain yields is discussed later in this paper. During liquid biosolids applications, multiple regression analysis (Table 10) showed that there were 10 significant independent variables that influenced grain yields. The most important of these variables were leaf K, biosolids applied NH_4-N, annual rainfall, and biosolids applied P.

Multiple regression analysis to evaluate the impact of independent variables affecting grain yields during applications of dewatered biosolids (Table 11) showed 6 significant variables affecting the grain yields, as compared to 10 during liquid biosolids applications. The most important of these

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FIGURE 4

STABILITY ANALYSIS FOR TREATMENT MEANS OF GRAIN
YIELDS DURING LIQUID AND DEWATERED BIOSOLIDS APPLICATIONS

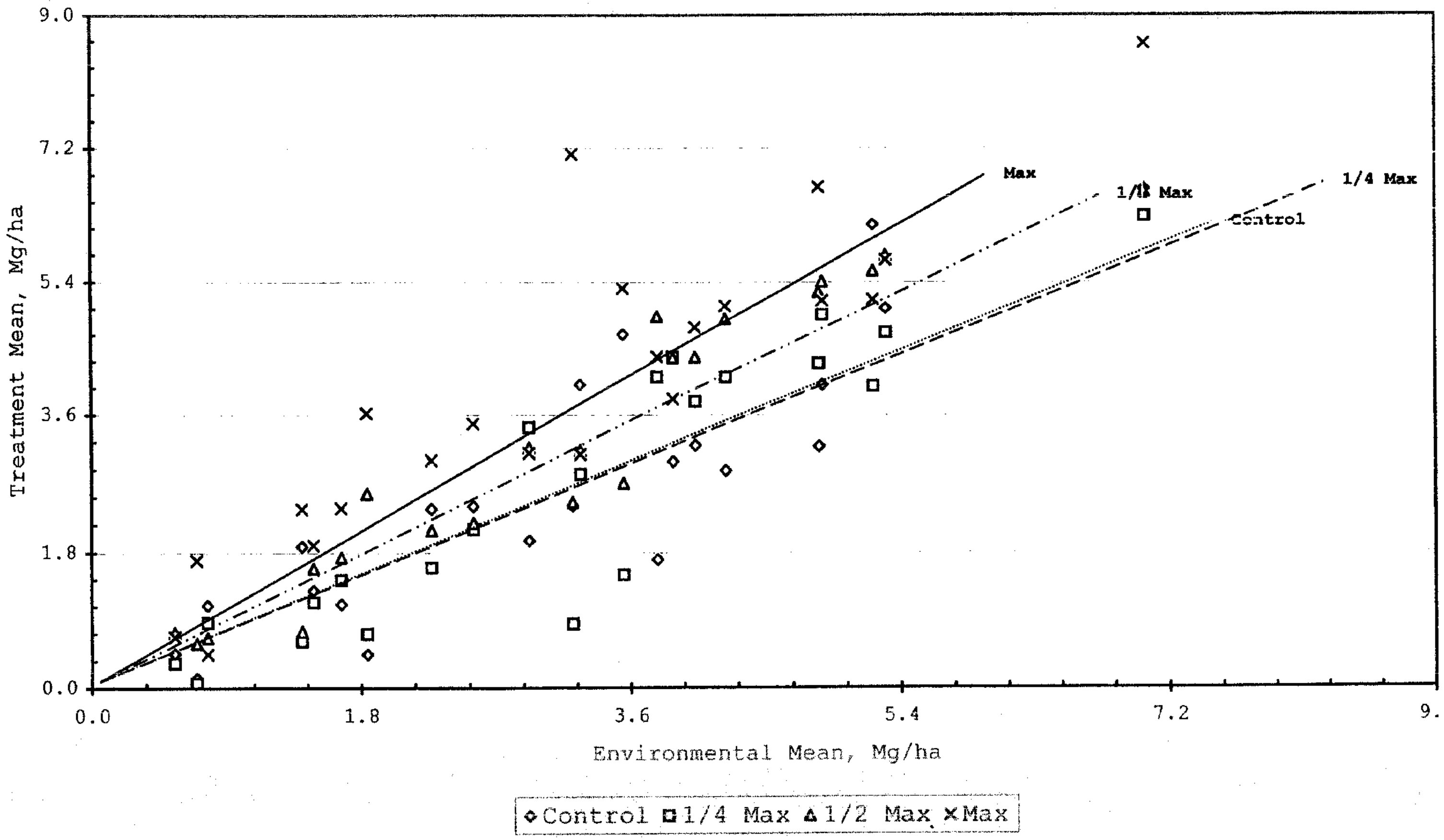

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TABLE 10

MULTIPLE REGRESSION OF GRAIN YIELDS[1]
ON SIGNIFICANT INDEPENDENT VARIABLES DURING
LIQUID BIOSOLIDS APPLICATION (1973 TO 1984)

Independent Variable	Coeff Est	Mean Square Error	T Value	P Value 134*	R^2
Leaf Nitrogen	-0.049670	0.393011271600	2.61	0.010	0.975
Leaf Potassium	-0.099942	0.393011271600	6.68	0.000	
Total Nitrogen Uptake	0.017374	0.393011271600	4.75	0.000	
Total Phosphorus Uptake	0.092882	0.393011271600	3.31	0.001	
Total Potassium Uptake	0.007759	0.393011271600	2.43	0.017	
Annual Rainfall	0.032033	0.393011271600	6.28	0.000	
Biosolids Applied Total Kjeldahl Nitrogen	-0.001386	0.393011271600	5.03	0.000	
Biosolids Applied NH_4-N	-0.002512	0.393011271600	6.61	0.000	
Biosolids Applied PAN[3]	0.003742	0.393011271600	4.64	0.000	
Biosolids Applied Phosphorus	0.001045	0.393011271600	5.80	0.000	

[1]Grain yields are equal to sum of the product of the coefficient in column 2 multiplied by the concentration of corresponding independent variable in column 1. There is no intercept in the model.

*Error degrees of freedom used for evaluation of P Value.

[2]R-Square of fitted regression.

[3]Plant available nitrogen.

TABLE 11

MULTIPLE REGRESSION OF GRAIN YIELDS[1]
ON SIGNIFICANT INDEPENDENT VARIABLES DURING
DEWATERED BIOSOLIDS APPLICATION (1985 TO 1995)

Independent Variable	Coeff Est	Mean Square Error	T Value	P Value 164*	R^2
Leaf Nitrogen	-0.039518	1.005070505800	2.87	0.005	0.940
Leaf Phosphorus	-0.000357	1.005070505800	3.96	0.000	
Total Nitrogen Uptake	0.022976	1.005070505800	7.51	0.000	
Total Phosphorus Uptake	0.109393	1.005070505800	8.92	0.000	
Growing Season Rainfall	0.027256	1.005070505800	4.38	0.000	
Biosolids Applied Phosphorus	0.000464	1.005070505800	3.38	0.001	

[1]Grain yields are equal to sum of the product of the coefficient in column 2 multiplied by the concentration of corresponding independent variable in column 1. There is no intercept in the model.

*Error degrees of freedom used for evaluation of P Value.

[2]R-Square of fitted regression.

variables were total P uptake, total N uptake, and growing season rainfall. The affect of rain during the growing season on yearly grain yields during the applications of dewatered biosolids can be critical on the mine spoil because of the shallow rooting depth for corn.

Multiple regression analysis of independent variables affecting corn grain yields during both liquid and dewatered biosolids applications is shown in Table 12. There were 9 variables that significantly affected grain yields. The most significant variables were total P uptake, total N uptake, leaf P, growing season rainfall, and biosolids applied NH_4-N. Of the biosolids applied constituents, Tables 10 and 12 indicate that NH_4-N, which is readily available to plants, is important for yields on the mine spoil. Biosolids applied PAN is also important, as indicated in Table 12.

Stover yields in each of the four treatments varied considerably during the 1973 through 1995 interval of biosolids applications (Table 13). Mean yields ranged from 1.01 Mg ha^{-1} in the 1988 maximum treatment to 7.07 Mg ha^{-1} in the 1978 maximum treatment. Stover yields during liquid biosolids application, 1973 through 1984, were the lowest in 1983 and the highest in 1978. Significant differences in stover yields between treatments occurred in 1983 and 1984. During dewatered biosolids applications, stover yields were the lowest in 1988, a

TABLE 12

MULTIPLE REGRESSION OF GRAIN YIELDS[1]
ON SIGNIFICANT INDEPENDENT VARIABLES DURING
LIQUID AND DEWATERED BIOSOLIDS APPLICATION (1973 TO 1995)

Independent Variable	Coeff Est	Mean Square Error	T Value	P Value 305*	R^2
Leaf Phosphorus	-0.000465	0.856892405600	7.56	0.000	0.946
Leaf Potassium	-0.021037	0.856892405600	1.70	0.091	
Total Nitrogen Uptake	0.014349	0.856892405600	8.80	0.000	
Total Phosphorus Uptake	0.136129	0.856892405600	15.12	0.000	
Growing Season Rainfall	0.032514	0.856892405600	6.64	0.000	
Biosolids Applied Total Kjeldahl Nitrogen	-0.001191	0.856892405600	5.55	0.000	
Biosolids Applied NH_4-N	-0.003209	0.856892405600	6.49	0.000	
Biosolids Applied PAN[3]	0.004717	0.856892405600	6.05	0.000	
Biosolids Applied Phosphorus	0.000500	0.856892405600	4.15	0.000	

[1]Grain yields are equal to sum of the product of the coefficient in column 2 multiplied by the concentration of corresponding independent variable in column 1. There is no intercept in the model.

*Error degrees of freedom used for evaluation of P Value.

[2]R-Square of fitted regression.

[3]Plant available nitrogen.

TABLE 13

ANNUAL CORN STOVER YIELDS
ON BIOSOLIDS-AMENDED CALCAREOUS MINE SPOIL

Year	Treatments[1]				Prob (ANOVA)
	Control	1/4 Max	1/2 Max	Max	
	Liquid Biosolids Application (Mg/ha)				
1974	2.60	2.78	3.54	4.03	0.060
1975	4.11	3.83	3.76	3.86	0.983
1976	4.10	4.36	4.31	3.78	0.771
1977	3.28	4.01	4.15	4.50	0.141
1978	5.52	5.74	6.67	7.07	0.153
1980	4.91	4.96	4.89	4.80	0.985
1981	6.52	5.75	6.33	6.85	0.638
1982	5.64	5.92	6.54	6.64	0.688
1983	1.74	1.98	*3.0	*3.02	0.005
1984	3.60	4.17	4.83	*6.43	0.003
	Dewatered Biosolids Application (Mg/ha)				
1985	3.10	*4.77	*5.17	*5.37	0.012
1986	4.42	4.47	5.10	6.35	0.082
1987	3.80	3.68	3.52	4.04	0.699
1988	1.53	1.39	1.04	1.01	0.253
1989	3.71	3.92	4.60	3.78	0.490
1990	4.95	*2.44	*2.17	4.09	0.023
1991	1.89	1.39	1.69	3.63	0.102
1992	4.15	3.41	4.29	3.37	0.235
1993	3.87	2.32	3.53	*6.89	0.000
1994	5.49	3.00	3.75	6.19	**0.028
1995	1.89	2.12	2.15	4.14	0.418

TABLE 13 (Continued)

ANNUAL CORN STOVER YIELDS
ON BIOSOLIDS-AMENDED CALCAREOUS MINE SPOIL

Year	Treatments[1]				Prob (ANOVA)
	Control	1/4 Max	1/2 Max	Max	
	Summary of Treatment Means (Mg/ha)				
Liquid Biosolids	4.20	4.35	4.80	*5.10	0.048
Dewatered Biosolids	3.53	2.99	3.36	*4.44	0.001
All Years	3.85	3.64	4.05	*4.75	0.000

[1]Please see Appendix AI-2 for Dunnett T-value and ANOVA p-value.

*Significantly different from control at 5% level of significance by Dunnett test.

**Unable to detect significant difference from control by Dunnett test.

drought year, and the highest in 1986. Stover yields varied significantly between treatments in 1985, 1990, 1993, and 1994.

A summary of mean stover yields for each treatment during liquid biosolids applications, dewatered biosolids applications, and all years is shown in Table 13. Stover yields in the biosolids-amended treatments during liquid biosolids applications generally equaled or exceeded those in the fertilized control treatment. During the application of dewatered biosolids, only yields in the maximum-amended biosolids treatments generally equaled or exceeded those in the fertilized control treatment. For all years of biosolids applications, stover yields in the one-half maximum and maximum treatments generally equaled or exceeded those in the control treatment.

An ANOVA for corn stover yields from 1973 through 1984 during liquid biosolids applications showed significant ($P \leq 0.05$) differences for year and treatment but not for a year-by-treatment interaction (Table 14). Consequently, no regression and stability analyses were conducted on the stover yield data during liquid biosolids applications.

An ANOVA for corn stover yields from 1985 through 1995 during dewatered biosolids applications showed significant ($P \leq 0.05$) differences for year, treatment, and year-by-treatment interaction (Table 15). Regression analysis of the yearly

TABLE 14

ANALYSIS OF VARIANCE
FOR CORN STOVER YIELDS FROM 1973 TO 1984
DURING LIQUID BIOSOLIDS APPLICATIONS

Source of Variation	Degrees of Freedom	Mean Square Error	F Ratio	P Value
Year	9	28.59	31.418	*0.000
Treatment	3	6.79	7.462	*0.000
Year x Treatment	27	0.91	1.000	0.495
Error	120	0.92		

*Significant at 5% level of significance.

TABLE 15

ANALYSIS OF VARIANCE
FOR CORN STOVER YIELDS FROM 1985 TO 1995
DURING DEWATERED BIOSOLIDS APPLICATIONS

Source of Variation	Degrees of Freedom	Mean Square Error	F Ratio	P Value
Year	10	21.57	6.657	*0.000
Treatment	3	16.67	5.145	*0.000
Year x Treatment	30	3.24	2.500	*0.000
Error	132	1.29		

*Significant at 5% level of significance.

treatment mean stover yields on the environmental means is shown in Table 16. The slopes for the treatments were significantly different. Stability analysis showed that stover yields during dewatered biosolids applications were the lowest in the one-fourth maximum treatment and the highest in the maximum treatment (Figure 5). Yields for the control and one-half maximum treatments were similar, as indicated by Figure 5 and the slopes of the regression lines in Table 16.

An ANOVA for corn stover yields from 1973 through 1995 during both liquid and dewatered biosolids applications showed significant ($P \leq 0.05$) differences for year, treatment, and year-by-treatment interaction (Table 17). Regression analysis of the yearly treatment mean stover yields on the environmental means showed significant differences between the slopes of the treatments (Table 18). Stability analysis (Figure 6) showed that during both liquid and dewatered biosolids applications, corn stover yields were the highest in the maximum treatment followed by the one-half maximum, control, and one-fourth maximum treatments. As a comparison, stability analysis showed that corn grain yields were the highest in the maximum and one-half maximum treatments, respectively, with the yields in the control and one-fourth maximum treatments being similar (Figure 4).

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TABLE 16

REGRESSION OF TREATMENT MEANS (Y) ON ENVIRONMENTAL MEANS (X) OF CORN STOVER YIELDS FOR EACH TREATMENT AND THE TEST FOR EQUIVALENCE OF THE FOUR REGRESSION EQUATIONS DURING DEWATERED BIOSOLIDS APPLICATIONS (1985 TO 1995)

Treatment Y	Intercept a	Slope b	R^2	P Value
Control	0.0000	0.9751	0.9566	0.000
1/4 Max	0.0000	0.8355	0.9634	
1/2 Max	0.0000	0.9543	0.9741	
Max	0.0000	1.2352	0.9628	

Regression Equation: $Y = a + bX$.

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FIGURE 5

STABILITY ANALYSIS FOR TREATMENT MEANS OF STOVER YIELDS DURING DEWATERED BIOSOLIDS APPLICATIONS

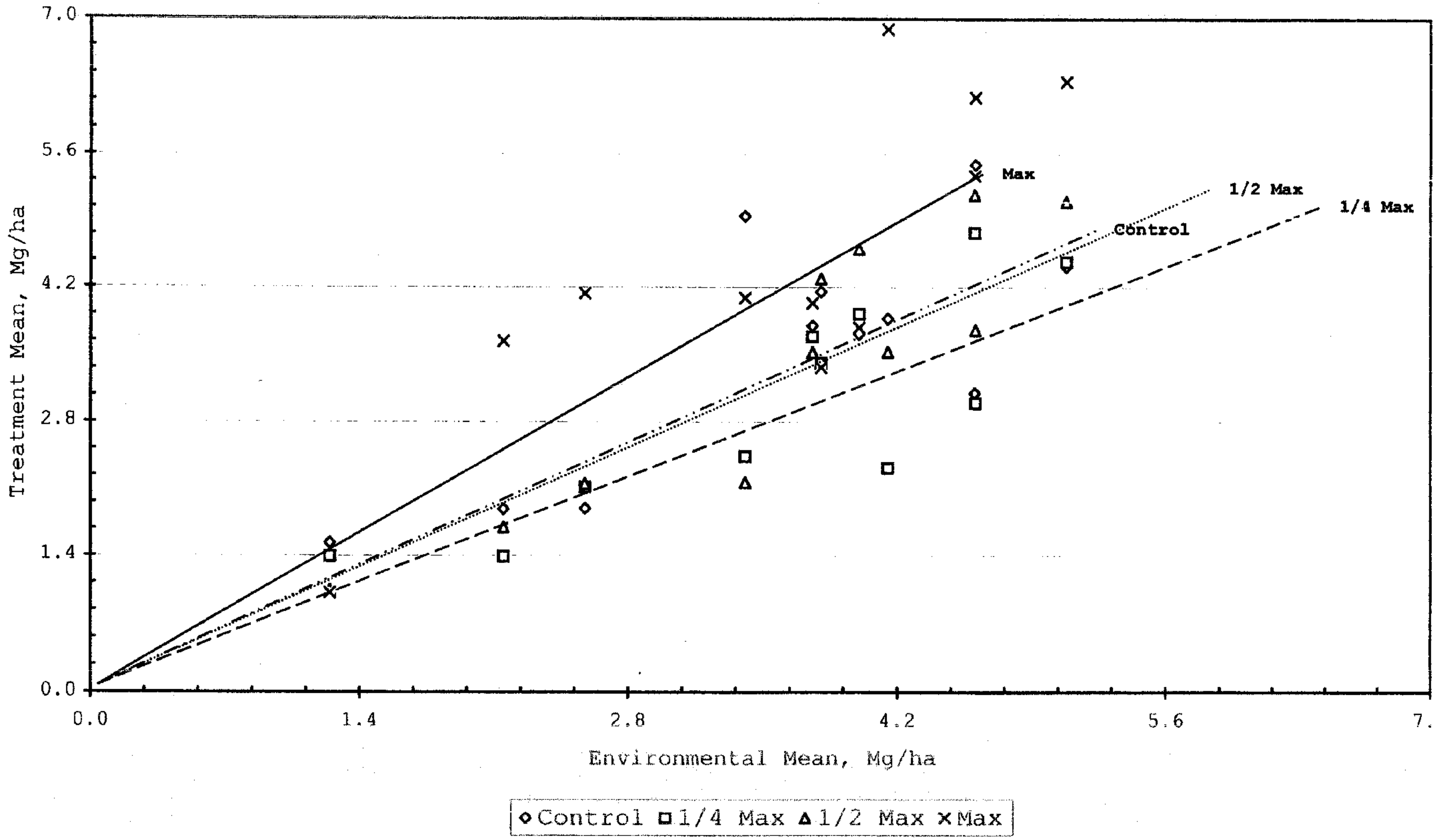

TABLE 17

ANALYSIS OF VARIANCE
FOR CORN STOVER YIELDS FROM 1973 TO 1995
DURING LIQUID AND DEWATERED BIOSOLIDS APPLICATIONS

Source of Variation	Degrees of Freedom	Mean Square Error	F Ratio	P Value
Year	20	28.11	12.719	*0.000
Treatment	3	19.70	8.914	*0.000
Year x Treatment	60	2.21	2.000	*0.000
Error	252	1.12		

*Significant at 5% level of significance.

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TABLE 18

REGRESSION OF TREATMENT MEANS (Y) ON ENVIRONMENTAL MEANS (X) OF CORN STOVER YIELDS FOR EACH TREATMENT AND THE TEST FOR EQUIVALENCE OF THE FOUR REGRESSION EQUATIONS DURING LIQUID AND DEWATERED BIOSOLIDS APPLICATIONS (1973 TO 1995)

Treatment Y	Intercept a	Slope b	R^2	P Value
Control	0.0000	0.9424	0.9739	0.000
1/4 Max	0.0000	0.8999	0.9811	
1/2 Max	0.0000	1.0028	0.9876	
Max	0.0000	1.1549	0.9738	

Regression Equation: Y = a + bX.

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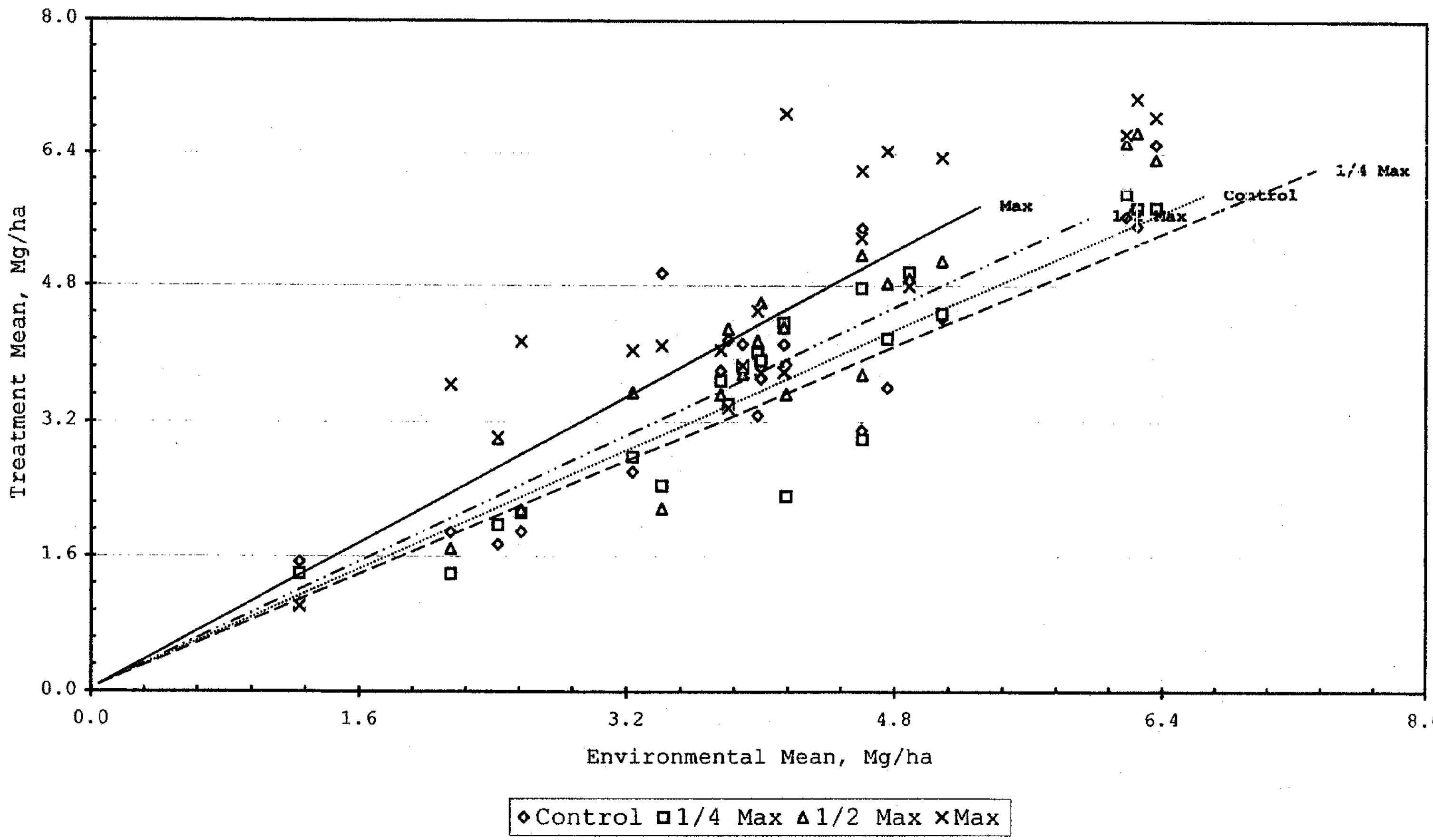
FIGURE 6

STABILITY ANALYSIS FOR TREATMENT MEANS OF STOVER YIELDS DURING LIQUID AND DEWATERED BIOSOLIDS APPLICATIONS



The increases in corn grain and stover yields with increasing rates of biosolids application in this study agrees with that reported by other researchers in field studies conducted on productive agricultural soils. Hinesly and Hansen (1983), Giordano et al. (1975), Kelling et al. (1977), and Lutrick et al. (1975) reported corn yield increases with biosolids applications on productive agricultural soils. Clapp et al. (1994), in a 20-year field study on productive agricultural soils, observed that corn yields on biosolids-amended plots equaled or exceeded those of control plots receiving commercial fertilizer.

Obtaining consistent corn yields with biosolids applications on mine spoils generated prior to the enactment of the 1977 Federal Surface Mining and Control Act, such as those at the District's Fulton County site, presents difficult problems. The mine spoil is extremely heterogeneous, has a bulk density greater than 1.60 g cm^{-3}, and the rooting depth is often limited to the zone of tillage. Fehrenbacher et al. (1982) reported that on regraded spoil with no topsoil or B horizon added, as in these research plots, the corn root penetration was generally confined to the zone of tillage (20-30 cm). In these situations, deep rooted crops such as corn often have limited plant available moisture.

Regression analysis for variables affecting corn grain yields (Tables 10 through 12) showed that annual and growing season rainfall were significant factors. The shallow rooting depth and lack of moisture during dry summer months can often affect yield responses (Pietz et al., 1982). Power et al. (1981) indicate that 90 cm of soil material is needed to obtain maximum production of most crops for mine land reclamation in semiarid regions.

Element Concentrations

LEAF NITROGEN

Mean corn leaf N concentrations in the four treatments varied yearly (Table 19). Mean leaf N concentrations ranged from 10.1 g N kg^{-1} in the 1992 one-fourth maximum treatment to 34.9 g N kg^{-1} in the 1978 maximum treatment. Corn leaf N during liquid biosolids applications was the lowest in 1983 and the highest in 1978. Significant variations in leaf N concentrations between treatments occurred in 1973, 1974, and 1977. During dewatered biosolids applications, corn leaf N levels were the lowest in 1992 and the highest in 1986. Significant differences in leaf N concentrations between treatments occurred in 1988, 1990, 1991, 1993, and 1994.

A summary of mean corn leaf N concentrations for each treatment during liquid biosolids applications, dewatered

TABLE 19

ANNUAL CONCENTRATIONS OF CORN LEAF NITROGEN
ON BIOSOLIDS-AMENDED CALCAREOUS MINE SPOIL

Year	Treatments[1]				Prob (ANOVA)
	Control	1/4 Max	1/2 Max	Max	
	Liquid Biosolids Application (g/kg)				
1973	30.6	30.0	30.2	*33.8	0.005
1974	27.2	*28.9	*29.4	*29.5	0.001
1975	29.4	29.2	29.4	29.6	0.971
1976	29.3	28.2	28.5	28.5	0.757
1977	30.5	30.1	31.1	*33.9	0.030
1978	34.3	32.8	32.1	34.9	***0.391
1979	27.7	28.1	27.8	32.0	0.352
1980	29.9	28.6	29.0	31.0	0.270
1981	30.6	28.7	30.1	32.4	0.465
1982	30.0	25.0	29.1	31.7	0.067
1983	27.2	24.9	25.9	25.9	0.191
1984	31.8	30.2	30.1	30.8	0.726
	Dewatered Biosolids Application (g/kg)				
1985	27.1	27.5	27.3	28.2	0.790
1986	30.7	27.9	29.7	28.9	0.559
1987	26.7	23.9	23.4	25.3	0.247
1988	24.8	23.5	*21.5	22.5	0.046
1989	29.6	28.2	29.4	28.7	0.344
1990	25.8	*16.7	20.0	24.7	0.008
1991	18.3	*12.6	15.6	15.6	0.010
1992	14.3	10.1	12.8	13.6	0.188
1993	16.3	13.8	17.4	20.5	**0.035
1994	25.1	*13.4	*16.4	*19.2	0.000
1995	28.5	28.3	26.4	27.2	0.691

TABLE 19 (Continued)

ANNUAL CONCENTRATIONS OF CORN LEAF NITROGEN
ON BIOSOLIDS-AMENDED CALCAREOUS MINE SPOIL

Year	Treatments[1]				Prob (ANOVA)
	Control	1/4 Max	1/2 Max	Max	
	Summary of Treatment Means (g/kg)				
Liquid Biosolids	29.9	28.7	29.4	31.2	**0.001
Dewatered Biosolids	24.3	*20.5	21.8	23.1	0.030
All Years	27.2	*24.8	25.8	27.3	0.012

[1]Please see Appendix AI-3 for Dunnett T-value and ANOVA p-value.

*Significantly different from control at 5% level of significance by Dunnett Test.

**Unable to detect significant difference from control by Dunnett test.

***ANOVA and Dunnett tests are based on rank.

biosolids applications, and all years is shown in Table 19. During liquid biosolids applications, leaf N concentrations in the one-half and maximum treatments either equaled or exceeded those of the control treatment. However, during the applications of dewatered biosolids, leaf N levels in all biosolids treatments were generally lower than those of the control treatment. Mean leaf N for the one-fourth maximum treatment was significantly lower than that of the control treatment (Table 19). For all years, only leaf N in the maximum treatment was comparable to that of the control treatment. Mean leaf N in the one-fourth maximum treatment was significantly lower then that of the control treatment (Table 19).

Leaf N concentrations in Table 19 give an indication of the N sufficiency status in each of the four treatments. Jones (1967) suggested an N sufficiency range for corn leaves of 27.6 - 35.0 g kg^{-1}, and a critical N value of 29.0 g kg^{-1} was recommended by Gallo et al. (1968) and Tyner (1946). Leaf N concentrations during the applications of liquid biosolids were generally within the N sufficiency range, and leaf N levels during the applications of dewatered biosolids were below the N sufficiency range, except for 1985, 1986, and 1989 (Table 19).

An ANOVA for corn leaf N during liquid biosolids applications showed significant ($P \leq 0.05$) differences for year and treatment, but not for the year-by-treatment variation (Table 20). Consequently, no regression analysis of the treatment means on the environmental means was done to test for the equivalence of the treatment regression equations, and no stability analysis of the leaf N treatment means on the environment mean was conducted.

An ANOVA for leaf N concentrations during dewatered biosolids applications showed significant ($P \leq 0.05$) differences for year, treatment, and year-by-treatment interaction (Table 21). Regression of the yearly treatment means on the environmental means showed that the regression slopes of the four treatments were significantly ($P \leq 0.05$) different (Table 22). Stability analysis showed that leaf N concentrations were the highest in the control and maximum treatments, respectively (Figure 7). Leaf N levels in the one-half maximum treatment were slightly higher than those of the one-fourth maximum treatment which had the lowest leaf N concentrations.

An ANOVA for leaf N concentrations during both liquid and dewatered biosolids applications showed significant ($P \leq 0.05$) differences for year, treatment, and year-by-treatment interaction (Table 23). A regression of the yearly treatment means on the environmental means showed that the slopes of the regression equations for the treatments were significantly different (Table 24). Stability analysis (Figure 8) for all

TABLE 20

ANALYSIS OF VARIANCE[1]
FOR LEAF NITROGEN CONCENTRATIONS FROM 1973 TO 1984
DURING LIQUID BIOSOLIDS APPLICATIONS

Source of Variation	Degrees of Freedom	Mean Square Error	F Ratio	P Value
Year	11	0.06	6.000	*0.000
Treatment	3	0.06	6.000	*0.000
Year x Treatment	33	0.01	0.900	0.565
Error	144	0.01		

[1]Analysis of variance is based on log(leaf nitrogen concentrations).

*Significant at 5% level of significance.

TABLE 21

ANALYSIS OF VARIANCE[1]
FOR LEAF NITROGEN CONCENTRATIONS FROM 1985 TO 1995
DURING DEWATERED BIOSOLIDS APPLICATIONS

Source of Variation	Degrees of Freedom	Mean Square Error	F Ratio	P Value
Year	10	1.35	27.000	*0.000
Treatment	3	0.36	7.200	*0.000
Year x Treatment	30	0.05	2.800	*0.000
Error	132	0.02		

[1]Analysis of variance is based on log(leaf nitrogen concentrations).

*Significant at 5% level of significance.

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TABLE 22

REGRESSION OF TREATMENT MEANS(Y) ON ENVIRONMENTAL MEANS[1](X) OF LEAF NITROGEN CONCENTRATIONS BY TREATMENT AND THE TEST FOR EQUIVALENCE OF THE FOUR REGRESSION EQUATIONS DURING DEWATERED BIOSOLIDS APPLICATIONS (1985 TO 1995)

Treatment Y	Intercept a	Slope b	R^2	P Value
Control	0.0000	1.0288	0.9989	0.000
1/4 Max	0.0000	0.9656	0.9983	
1/2 Max	0.0000	0.9919	0.9998	
Max	0.0000	1.0137	0.9995	

[1]Regression is based on mean of log(leaf nitrogen).
Regression Equation: $Y = a + bX$.

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FIGURE 7

STABILITY ANALYSIS FOR TREATMENT MEANS OF LOG(LEAF N) CONCENTRATIONS DURING DEWATERED BIOSOLIDS APPLICATIONS

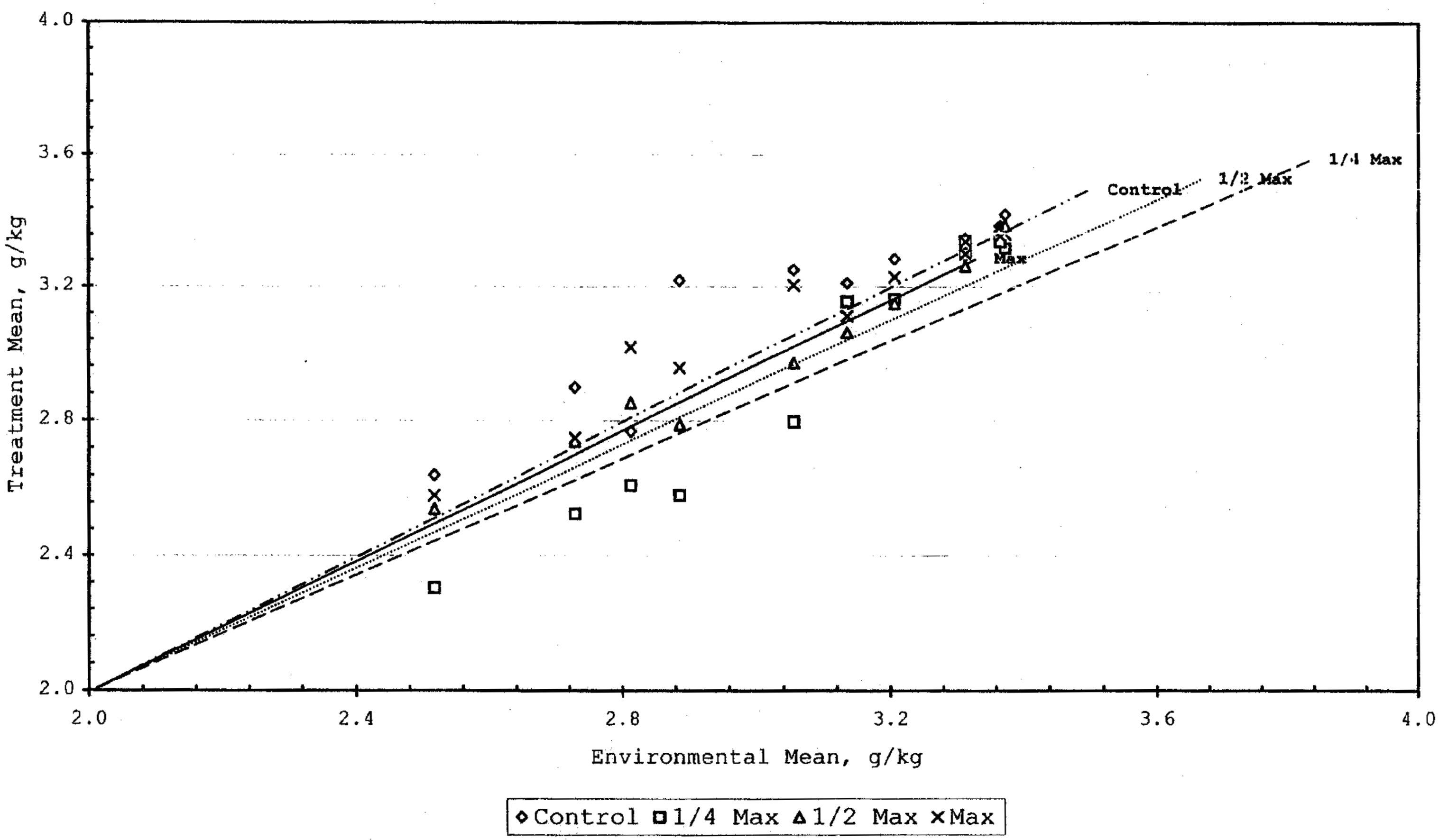

TABLE 23

ANALYSIS OF VARIANCE[1]
FOR LEAF NITROGEN CONCENTRATIONS FROM 1973 TO 1995
DURING LIQUID AND DEWATERED BIOSOLIDS APPLICATIONS

Source of Variation	Degrees of Freedom	Mean Square Error	F Ratio	P Value
Year	22	1.09	36.333	*0.000
Treatment	3	0.31	10.333	*0.000
Year x Treatment	66	0.03	2.600	*0.000
Error	276	0.01		

[1]Analysis of variance is based on log(leaf nitrogen concentrations).

*Significant at 5% level of significance.

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TABLE 24

REGRESSION OF TREATMENT MEANS(Y) ON ENVIRONMENTAL MEANS[1](X) OF LEAF NITROGEN CONCENTRATIONS BY TREATMENT AND THE TEST FOR EQUIVALENCE OF THE FOUR REGRESSION EQUATIONS DURING LIQUID AND DEWATERED BIOSOLIDS APPLICATIONS (1973 TO 1995)

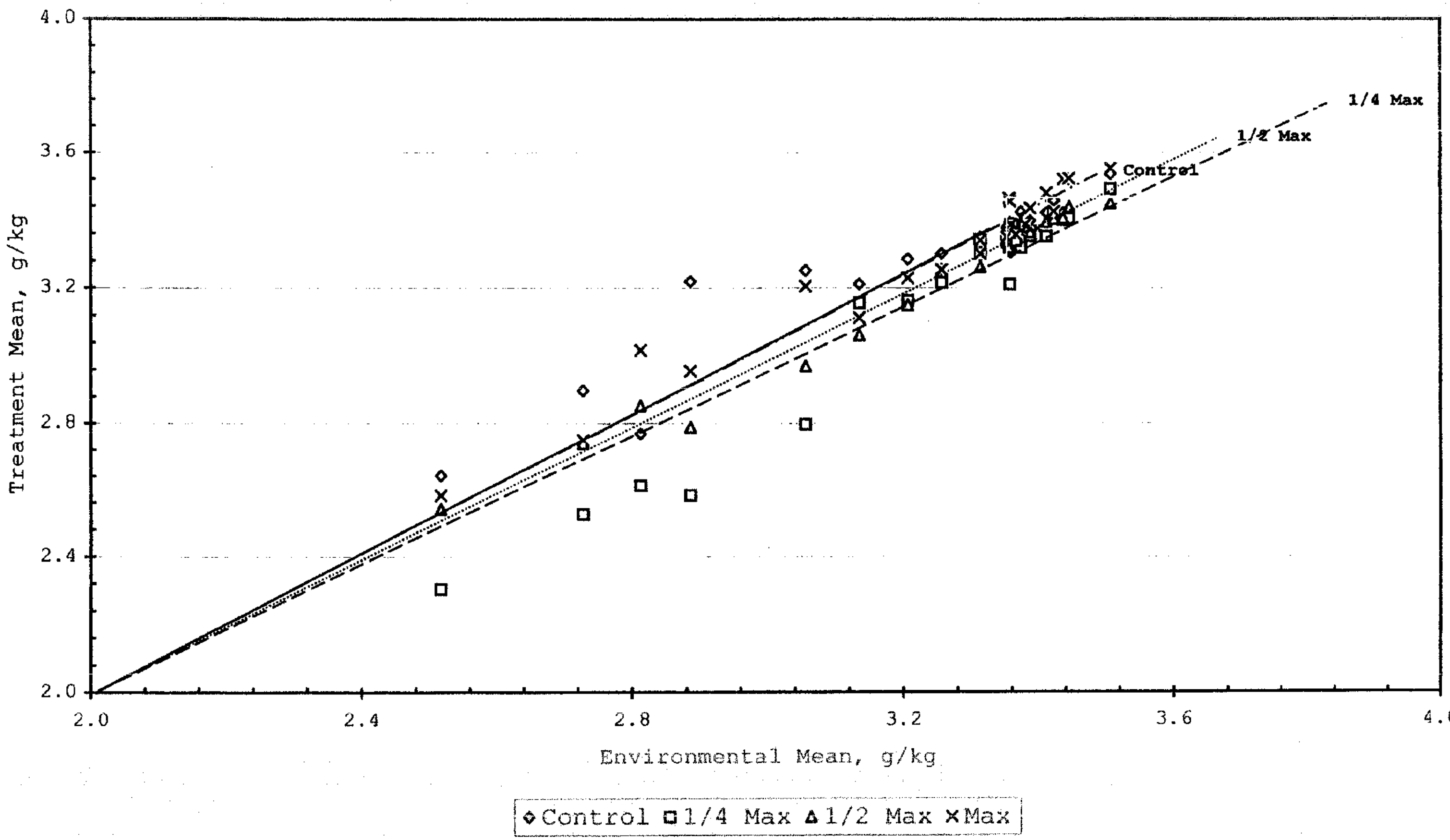
Treatment Y	Intercept a	Slope b	R^2	P Value
Control	0.0000	1.0130	0.9993	0.000
1/4 Max	0.0000	0.9791	0.9991	
1/2 Max	0.0000	0.9943	0.9999	
Max	0.0000	1.0137	0.9997	

[1]Regression is based on mean of log(leaf nitrogen).
Regression Equation: Y = a + bX.

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

FIGURE 8

STABILITY ANALYSIS FOR TREATMENT MEANS OF LOG(LEAF N) CONCENTRATIONS DURING LIQUID AND DEWATERED BIOSOLIDS APPLICATIONS



years, during both liquid and dewatered biosolids applications, showed that leaf N concentrations were the highest in the maximum and control treatments, respectively, followed by the one-half and one-fourth maximum treatments.

The corn leaf N concentrations in Table 19 and the stability analysis shown in Figures 7 and 8 indicate that N was a more limiting nutrient during the applications of dewatered biosolids, as compared to liquid biosolids. During the applications of dewatered biosolids, the lower amount of total Kjeldahl-N and NH_4-N in the biosolids (Table 1), the lower amounts of N applied (Table 2), and the lower mineralization rate of the aged, dewatered biosolids were factors contributing to N being a more limiting nutrient than during the applications of liquid biosolids.

LEAF PHOSPHORUS

Mean corn leaf P concentrations in the four treatments from 1973 through 1995 (Table 25) showed a more consistent yearly response than leaf N levels. Mean leaf P concentrations varied from 2,005 mg P kg^{-1} in the 1988 one-half maximum treatment to 5,778 mg P kg^{-1} in the 1974 control treatment. Corn leaf P during liquid biosolids application was the lowest in 1982 and the highest in 1974. Leaf P concentrations were significantly different between treatments in 1974, 1979, and

TABLE 25

ANNUAL CONCENTRATIONS OF CORN LEAF PHOSPHORUS
ON BIOSOLIDS-AMENDED CALCAREOUS MINE SPOIL

Year	Treatments[1]				Prob (ANOVA)
	Control	1/4 Max	1/2 Max	Max	
	Liquid Biosolids Application (mg/kg)				
1973	3207	2783	2749	3139	0.096
1974	5778	*3461	*3597	*3527	0.001
1975	3065	3035	2623	2748	0.078
1976	2924	2689	2638	2671	0.218
1977	3204	3081	3250	2985	0.530
1978	3128	3141	3058	3023	0.781
1979	3030	*2333	*2440	2898	0.010
1980	2910	2801	2875	3159	0.079
1981	3184	3131	3267	3393	0.434
1982	2572	2362	2815	2906	0.119
1983	3105	*2642	*2735	2939	0.010
1984	2985	2806	2775	3050	0.459
	Dewatered Biosolids Application (mg/kg)				
1985	2566	2571	2594	2639	0.935
1986	2595	2493	2527	2756	0.419
1987	2401	2171	2072	2284	0.071
1988	2208	2032	2005	2124	0.490
1989	2845	2673	2759	2687	0.235
1990	2614	3066	3149	2556	**0.022
1991	2794	3166	2616	2457	**0.027
1992	2681	2210	2353	2588	0.280
1993	3559	3496	2292	2705	0.687
1994	3313	3272	3085	4135	0.434
1995	5704	6579	6338	5216	**0.039

TABLE 25 (Continued)

ANNUAL CONCENTRATIONS OF CORN LEAF PHOSPHORUS ON BIOSOLIDS-AMENDED CALCAREOUS MINE SPOIL

Year	Treatments[1]				Prob (ANOVA)
	Control	1/4 Max	1/2 Max	Max	
	Summary of Treatment Means (mg/kg)				
Liquid Biosolids	3258	*2855	*2902	3036	***0.000
Dewatered Biosolids	3025	3066	2890	2922	0.889
All Years	3147	2956	2896	2982	0.291

[1]Please see Appendix AI-4 for Dunnett T-value and ANOVA p-value.

*Significantly different from control at 5% level of significance by Dunnett Test.

**Unable to detect significant difference from control by Dunnett test.

***ANOVA and Dunnett tests are based on rank.

1983. During applications of dewatered biosolids, corn leaf P was the lowest in 1988, a drought year, and the highest in 1995. Leaf P levels varied significantly between treatments in 1990, 1991, and 1995.

A summary of mean corn leaf P concentrations during liquid biosolids applications, dewatered biosolids applications, and all years is shown in Table 25. The mean leaf P concentration in the control treatment during liquid biosolids applications was higher than the levels observed in the biosolids-amended treatments. Mean leaf P concentrations in the biosolids-amended treatments during dewatered biosolids applications were generally lower than the control treatment. The exception was the one-fourth maximum-amended treatment, where the mean leaf P level was a little higher than the control treatment. For all years mean leaf P was the highest in the control treatment.

Leaf P concentrations in Table 25 give an indication of the corn P sufficiency status in each of the four treatments. Jones (1967) suggested a corn leaf P sufficiency range of 2,500-5,000 mg P kg^{-1}, and Melstead et al. (1969) reported 2,500 mg P kg^{-1} as the critical value for leaf P. Leaf P levels in Table 25 were generally within the nutrient sufficiency range and above the critical level during liquid biosolids applications, except for 1979 and 1982. During applications of dewatered biosolids, leaf P concentrations were within the nutrient sufficiency range and above the critical level for all years except 1987, 1988, and 1992. A drought occurred in 1987 and 1988 (Figure 1), and this appeared to have affected the leaf P levels in all treatments during those years.

An ANOVA for corn leaf P from 1973 through 1984 showed significant ($P \leq 0.05$) sources of variation for year, treatment, and the year-by-treatment interaction (Table 26). Regression analysis based on the log of the yearly treatment means on the log of the environmental means showed that the regression slopes of the four treatments were significantly different (Table 27). The slopes of the control and maximum treatments were similar as were those of the one-fourth and one-half maximum treatments. Stability analysis using the log of treatment mean leaf P and the log of environmental mean leaf P showed that leaf P concentrations were the highest in the control and maximum treatments, respectively, during liquid biosolids applications (Figure 9). The regression lines for the one-fourth and one-half maximum treatments in Figure 9 were similar, as shown by the coefficients for the slopes in Table 27.

An ANOVA for corn leaf P concentrations during dewatered biosolids applications shows only a significant ($P \leq 0.05$) source of variation for year (Table 28). The variations in

TABLE 26

ANALYSIS OF VARIANCE[1]
FOR LEAF PHOSPHORUS CONCENTRATIONS FROM 1973 TO 1984
DURING LIQUID BIOSOLIDS APPLICATIONS

Source of Variation	Degrees of Freedom	Mean Square Error	F Ratio	P Value
Year	11	0.190	6.333	*0.000
Treatment	3	0.140	4.667	*0.000
Year x Treatment	33	0.030	3.200	*0.000
Error	144	0.010		

[1]Analysis of variance is based on log(leaf phosphorus concentrations).

*Significant at 5% level of significance.

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TABLE 27

REGRESSION OF TREATMENT MEANS(Y) ON ENVIRONMENTAL MEANS[1](X) OF LEAF PHOSPHORUS CONCENTRATIONS BY TREATMENT AND THE TEST FOR EQUIVALENCE OF THE FOUR REGRESSION EQUATIONS DURING LIQUID BIOSOLIDS APPLICATIONS (1973 TO 1984)

Treatment Y	Intercept a	Slope b	R^2	P Value
Control	0.0000	1.0085	0.9998	0.001
1/4 Max	0.0000	0.9938	1.0000	
1/2 Max	0.0000	0.9957	1.0000	
Max	0.0000	1.0020	0.9999	

[1]Regression is based on mean of log(leaf phosphorus).
Regression Equation: Y = a + bX.

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FIGURE 9

STABILITY ANALYSIS FOR TREATMENT MEANS OF LOG(LEAF P) CONCENTRATIONS DURING LIQUID BIOSOLIDS APPLICATIONS

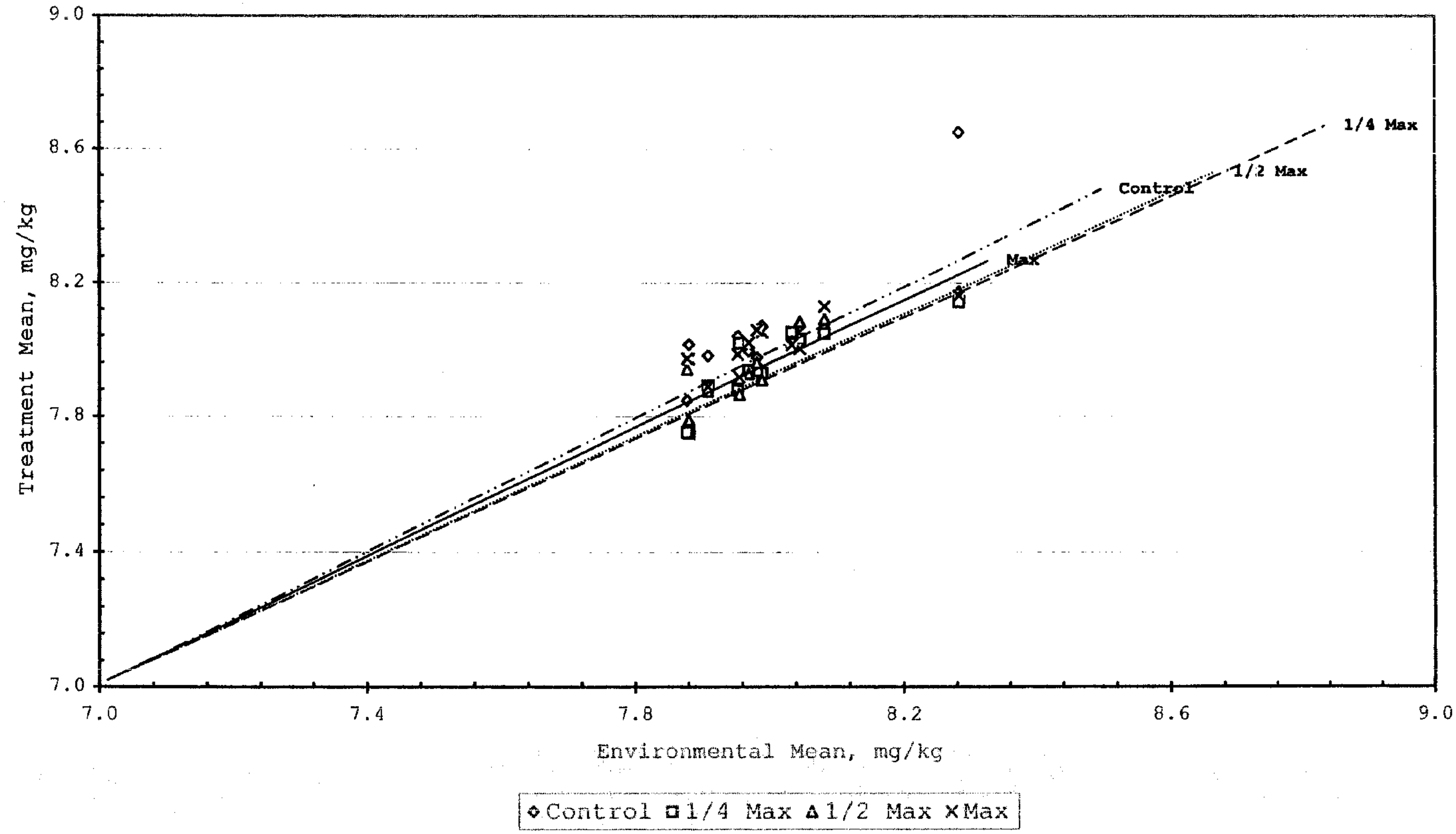

TABLE 28

ANALYSIS OF VARIANCE[1]
FOR LEAF PHOSPHORUS CONCENTRATIONS FROM 1985 TO 1995
DURING DEWATERED BIOSOLIDS APPLICATIONS

Source of Variation	Degrees of Freedom	Mean Square Error	F Ratio	P Value
Year	10	1.230	24.600	*0.000
Treatment	3	0.050	1.000	0.243
Year x Treatment	30	0.050	1.300	0.134
Error	132	0.040		

[1]Analysis of variance is based on log(leaf phosphorus concentrations).

*Significant at 5% level of significance.

leaf P with treatment and the year-by-treatment interaction were not significant. Consequently, the regression of treatment means on the environmental means and stability analysis were not done. This implies that leaf P concentrations during the applications of dewatered biosolids were fairly consistent in the treatments, as indicated by the summary of treatment means and the high, non-significant ANOVA probability value in Table 25.

An ANOVA for leaf P concentrations for all years showed significant ($P \leq 0.05$) differences between year, treatment, and the year-by-treatment interaction (Table 29). A regression analysis using the log of leaf P concentrations against the log of the environmental means showed that there was a significant difference between the slopes of the treatments even though the slopes of the biosolids treatments were essentially the same (Table 30). This is reflected in the stability analysis of the log of the treatment means on the log of the environmental means (Figure 10). Leaf P concentrations were the highest in the control treatment and leaf P levels in the biosolids treatments were clustered together, as shown by the regression slopes in Table 30.

Multiple regression analysis to evaluate the variables influencing corn grain yields showed that leaf P was a significant variable during the applications of dewatered

TABLE 29

ANALYSIS OF VARIANCE[1]
FOR LEAF PHOSPHORUS CONCENTRATIONS FROM 1973 TO 1995
DURING LIQUID AND DEWATERED BIOSOLIDS APPLICATIONS

Source of Variation	Degrees of Freedom	Mean Square Error	F Ratio	P Value
Year	22	0.670	16.750	*0.000
Treatment	3	0.110	2.750	*0.002
Year x Treatment	66	0.040	1.800	*0.001
Error	276	0.020		

[1]Analysis of variance is based on log(leaf phosphorus concentrations).

*Significant at 5% level of significance.

TABLE 30

REGRESSION OF TREATMENT MEANS (Y) ON ENVIRONMENTAL MEANS[1] (X) OF LEAF PHOSPHORUS CONCENTRATIONS BY TREATMENT AND THE TEST FOR EQUIVALENCE OF THE FOUR REGRESSION EQUATIONS DURING LIQUID AND DEWATERED BIOSOLIDS APPLICATIONS (1973 TO 1995)

Treatment Y	Intercept a	Slope b	R^2	P Value
Control	0.0000	1.0063	0.9999	0.013
1/4 Max	0.0000	0.9984	0.9999	
1/2 Max	0.0000	0.9960	0.9999	
Max	0.0000	0.9993	0.9999	

[1]Regression is based on mean of log(leaf phosphorus).
Regression Equation: Y = a + bX.

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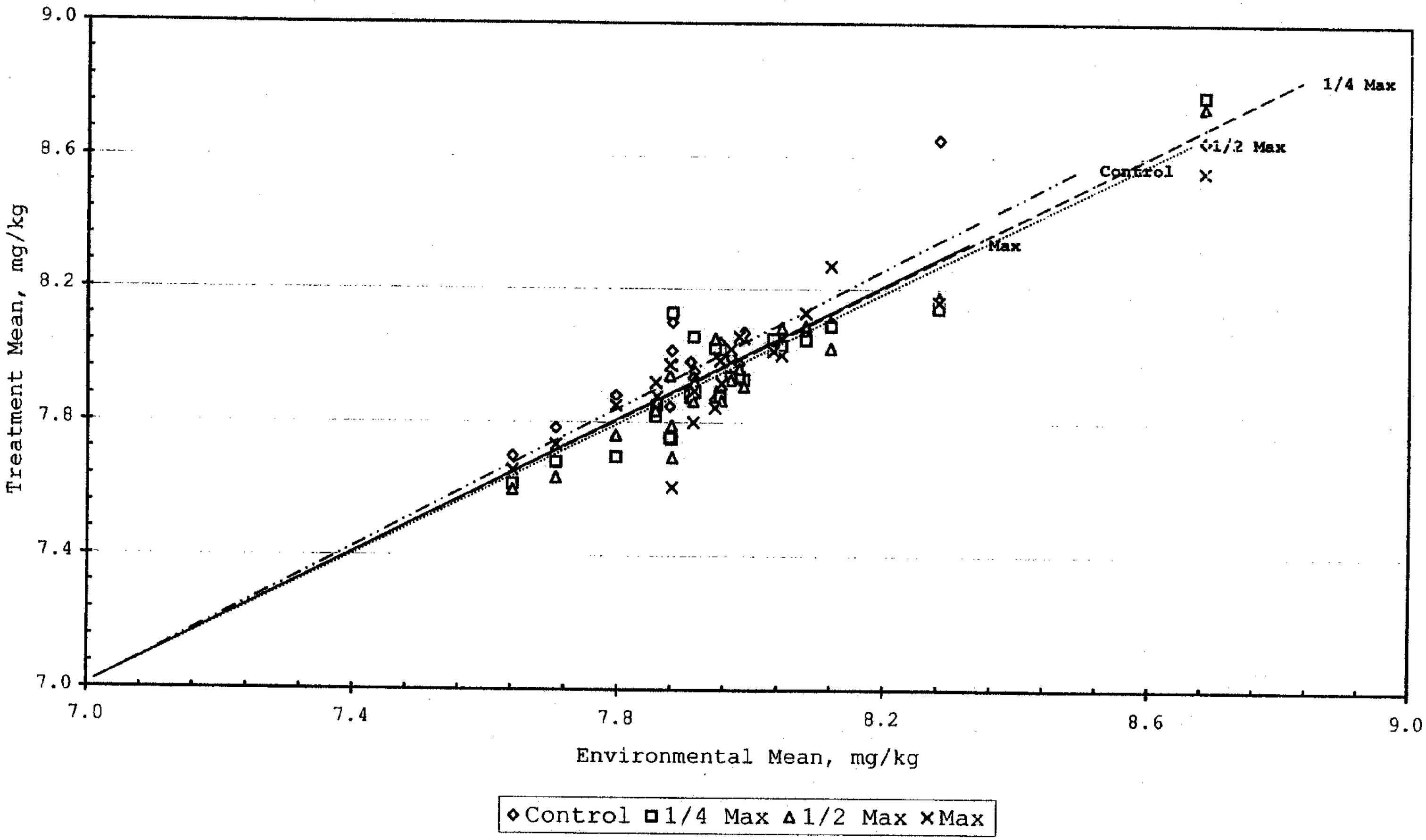
FIGURE 10

STABILITY ANALYSIS FOR TREATMENT MEANS OF LOG(LEAF P) CONCENTRATIONS DURING LIQUID AND DEWATERED BIOSOLIDS APPLICATIONS



biosolids (Table 11), and for the applications of both liquid and dewatered biosolids (Table 12).

Phosphate forms in biosolids are variable depending on the wastewater treatment processes (Cavallaro et al., 1993; McCoy et al., 1986; McLaughlin and Champion, 1987). District biosolids are waste-activated, anaerobically digested. The major forms of P in biosolids can be Ca, Fe, and Al phosphates along with organic and water-soluble forms (Chang et al., 1983). In liquid biosolids treated soils, Chang et al. (1983) observed a significant elevation in soluble P. Maguire et al. (2000) in an on-farm survey of biosolids use found increases in the bioavailable forms of soil P from biosolids applications. Leaf P concentrations in Table 25, the regression analysis of leaf P concentrations in Table 27 and 30, and the stability analysis in Figures 9 and 10 suggests that there was little difference in leaf P levels under liquid versus dewatered biosolids applications.

LEAF POTASSIUM

Mean leaf K concentrations in the four treatments during the 1973 through 1995 interval showed yearly fluctuations (Table 31). Mean leaf K levels varied from 11.8 g K kg^{-1} in the 1991 one-fourth maximum treatment to 29.4 g K kg^{-1} in the 1981 maximum treatment. During liquid biosolids applications, corn

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TABLE 31

ANNUAL CONCENTRATIONS OF CORN LEAF POTASSIUM ON BIOSOLIDS-AMENDED CALCAREOUS MINE SPOIL

Year	Treatments[1]				Prob (ANOVA)
	Control	1/4 Max	1/2 Max	Max	
	Liquid Biosolids Application (g/kg)				
1973	19.2	24.1	22.2	23.9	0.279
1974	25.5	24.4	24.8	27.0	**0.040
1975	17.0	16.4	16.3	15.1	0.792
1976	17.9	18.0	17.2	18.5	0.662
1977	20.4	19.3	19.4	18.6	0.446
1980	15.6	16.6	17.5	17.4	0.270
1981	28.2	27.9	27.5	29.4	0.309
1982	19.2	18.1	18.5	19.5	0.653
1983	21.6	21.3	21.0	23.7	0.294
1984	20.2	19.2	21.0	22.7	**0.042
	Dewatered Biosolids Application (g/kg)				
1985	17.8	18.7	18.1	18.0	0.506
1986	20.2	19.1	19.3	19.8	0.622
1987	22.7	21.6	22.0	23.7	0.061
1988	18.8	18.3	20.1	21.4	0.297
1989	17.8	17.1	16.8	17.9	**0.033
1990	18.2	18.9	18.1	18.0	0.522
1991	17.6	*11.8	14.8	16.5	0.013
1992	21.3	20.1	22.6	21.5	0.364
1993	19.1	20.4	20.3	*21.9	0.012
1994	19.1	19.5	18.9	20.8	0.517
1995	19.3	18.4	18.6	20.1	0.742

TABLE 31 (Continued)

ANNUAL CONCENTRATIONS OF CORN LEAF POTASSIUM ON BIOSOLIDS-AMENDED CALCAREOUS MINE SPOIL

Year	Treatments[1]				Prob (ANOVA)
	Control	1/4 Max	1/2 Max	Max	
	Summary of Treatment Means (g/kg)				
Liquid Biosolids	20.5	20.5	20.5	21.6	0.594
Dewatered Biosolids	19.3	18.5	19.0	20.0	0.066
All Years	19.8	19.5	19.8	20.7	0.114

[1]Please see Appendix AI-5 for Dunnett T-value and ANOVA p-value.

*Significantly different from control at 5% level of significance by Dunnett test.

**Unable to detect significant difference from control by Dunnett test.

leaf K was the lowest in all treatments in 1975 and the highest in 1981. Significant variations in leaf K occurred between treatments in 1974 and 1984. Corn leaf K during applications of dewatered biosolids was the lowest in all treatments in 1991 and the highest in 1987. Significant variations in leaf K between treatments occurred in 1989, 1991, and 1993 (Table 31).

A summary of mean corn leaf K concentrations for each treatment during liquid biosolids applications, dewatered biosolids applications, and all years is shown in Table 31. Mean leaf K levels were generally the same in all treatments during liquid biosolids applications, dewatered biosolids applications, and all years. Leaf K concentrations in the maximum-amended treatment were slightly higher than the levels in the control treatment, but these differences were not significant as shown in Table 31.

The mean leaf K levels in Table 31 give an indication of the corn K sufficiency status in each of the four treatments. Jones (1967) gave a corn leaf K sufficiency range of 17.1 to 25.0 g K kg^{-1}, and Melstead et al. (1969) reported 19.0 g K kg^{-1} as the critical value. The mean leaf K concentrations for the treatments in Table 31 were all usually within the nutrient sufficiency range and above the critical value. However, Table 31 shows that there were some years (1975, 1980, 1989, and

1991) when leaf K levels in all four treatments were at or below the critical level. The leaf K concentrations in Table 31 suggest that K was not a limiting nutrient in most years.

An ANOVA for corn leaf K during liquid biosolids applications showed only significant ($P \leq 0.05$) differences for year, and not for treatment and the year-by-treatment interaction (Table 32). Consequently, the regression of treatment means on the environmental means and stability analysis were not done. This implies that leaf K concentrations during the applications of liquid biosolids were fairly consistent in the treatments, as indicated by the summary of treatment means in Table 31 and the lack of a significant difference between the treatment means.

An ANOVA for leaf K concentrations during dewatered biosolids applications showed significant ($P \leq 0.05$) sources of variation for year, treatment, and the year-by-treatment interaction (Table 33). Regression of the log of leaf K treatment means on the log of the leaf K environmental means showed significant differences in the slopes of the regression equations (Table 34). Stability analysis showed that the leaf K concentrations were the highest in the maximum and control treatments, respectively, during the applications of dewatered biosolids (Figure 11). Leaf K concentrations in the one-fourth and one-half maximum treatments were essentially the

TABLE 32

ANALYSIS OF VARIANCE[1]
FOR LEAF POTASSIUM CONCENTRATIONS FROM 1973 TO 1984
DURING LIQUID BIOSOLIDS APPLICATIONS

Source of Variation	Degrees of Freedom	Mean Square Error	F Ratio	P Value
Year	9	0.510	51.000	*0.000
Treatment	3	0.020	2.000	0.176
Year x Treatment	27	0.010	1.100	0.315
Error	120	0.010		

[1]Analysis of variance is based on log(leaf potassium concentrations).

*Significant at 5% level of significance.

TABLE 33

ANALYSIS OF VARIANCE[1]
FOR LEAF POTASSIUM CONCENTRATIONS FROM 1985 TO 1995
DURING DEWATERED BIOSOLIDS APPLICATIONS

Source of Variation	Degrees of Freedom	Mean Square Error	F Ratio	P Value
Year	10	0.190	9.500	*0.000
Treatment	3	0.050	2.500	*0.001
Year x Treatment	30	0.020	2.000	*0.005
Error	132	0.010		

[1]Analysis of variance is based on log(leaf potassium concentrations).

*Significant at 5% level of significance.

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TABLE 34

REGRESSION OF TREATMENT MEANS(Y) ON ENVIRONMENTAL MEANS[1](X) OF LEAF POTASSIUM CONCENTRATIONS BY TREATMENT AND THE TEST FOR EQUIVALENCE OF THE FOUR REGRESSION EQUATIONS DURING DEWATERED BIOSOLIDS APPLICATIONS (1985 TO 1995)

Treatment Y	Intercept a	Slope b	R^2	P Value
Control	0.0000	1.0021	0.9996	0.017
1/4 Max	0.0000	0.9871	0.9994	
1/2 Max	0.0000	0.9973	0.9999	
Max	0.0000	1.0135	0.9998	

[1]Regression is based on mean of log(leaf potassium).
Regression Equation: Y = a + bX.

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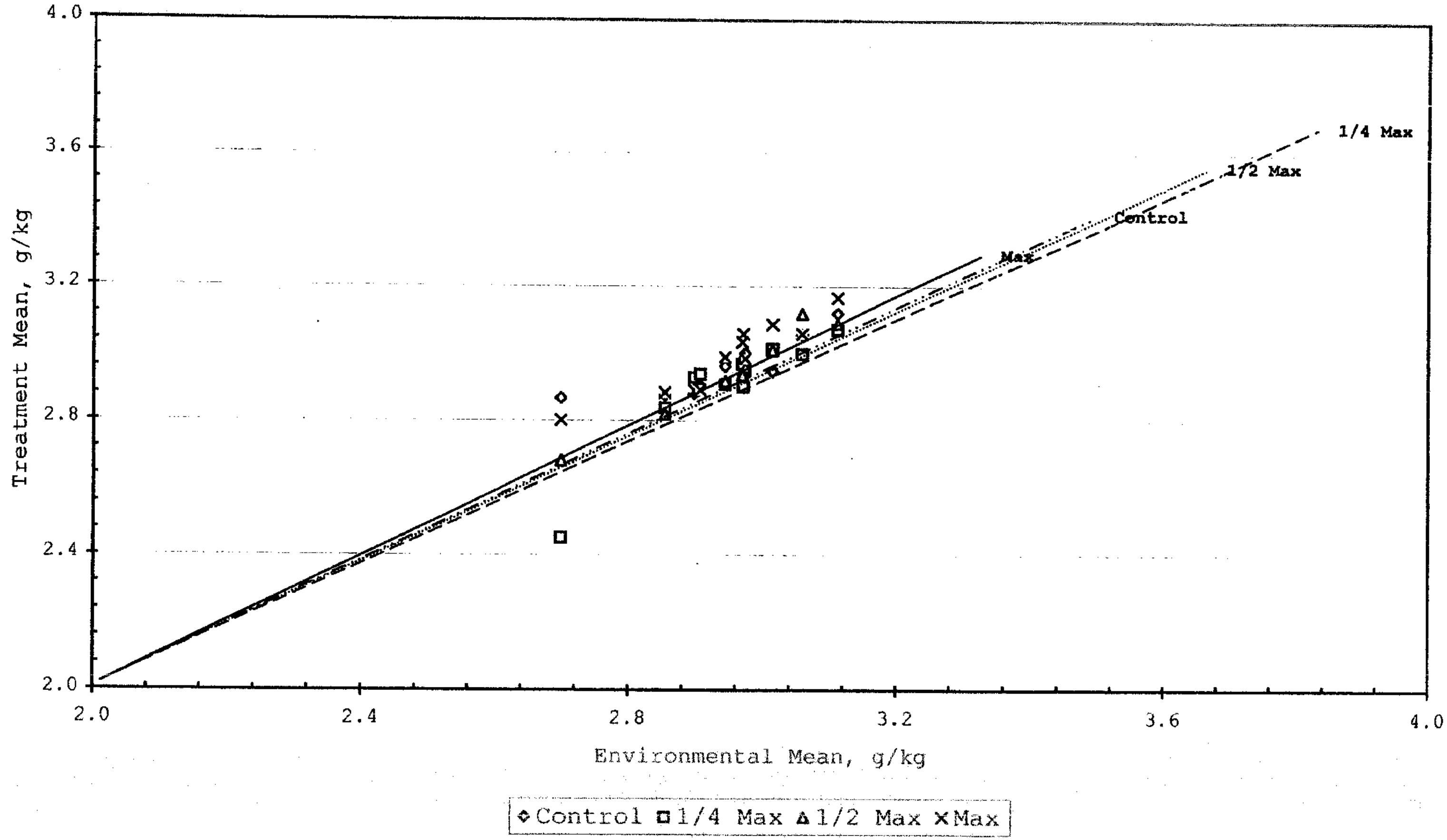
FIGURE 11

STABILITY ANALYSIS FOR TREATMENT MEANS OF LOG(LEAF K) CONCENTRATIONS DURING DEWATERED BIOSOLIDS APPLICATIONS



same, as indicated by the coefficients for the slopes in Table 34.

An ANOVA for leaf K levels during both liquid and dewatered biosolids applications showed significant ($P \leq 0.05$) differences for year, treatment, and the year-by-treatment interaction (Table 35). Regression of the log of leaf K treatment means on the log of the leaf K environmental means showed a significant difference between the slopes of the treatments (Table 36). Stability analysis showed that the maximum treatment had the highest leaf K concentrations, and the leaf K concentrations in the other treatments were essentially the same (Figure 12). This is also reflected in the regression equation slopes for the control, one-fourth maximum, and one-half maximum treatments in Table 36.

Total Element Uptake

NITROGEN UPTAKE

Total N uptake by corn (grain and stover) from 1974 through 1995 varied considerably in each of the four treatments (Table 37). Mean N uptake by corn ranged from 13 kg N ha^{-1} in the 1991 one-fourth maximum treatment to 265 kg N ha^{-1} in the 1984 maximum treatment. During liquid biosolids applications, total N uptake by corn was the lowest in 1983 and the highest in 1984. Total N uptake varied significantly between

TABLE 35

ANALYSIS OF VARIANCE[1]
FOR LEAF POTASSIUM CONCENTRATIONS FROM 1973 TO 1995
DURING LIQUID AND DEWATERED BIOSOLIDS APPLICATIONS

Source of Variation	Degrees of Freedom	Mean Square Error	F Ratio	P Value
Year	20	0.350	35.000	*0.000
Treatment	3	0.060	6.000	*0.001
Year x Treatment	60	0.010	1.500	*0.018
Error	252	0.010		

[1]Analysis of variance is based on log(leaf potassium concentrations).

*Significant at 5% level of significance.

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TABLE 36

REGRESSION OF TREATMENT MEANS(Y) ON ENVIRONMENTAL MEANS[1](X) OF LEAF POTASSIUM CONCENTRATIONS BY TREATMENT AND THE TEST FOR EQUIVALENCE OF THE FOUR REGRESSION EQUATIONS DURING LIQUID AND DEWATERED BIOSOLIDS APPLICATIONS (1973 TO 1995)

Treatment Y	Intercept a	Slope b	R^2	P Value
Control	0.0000	0.9988	0.9996	0.002
1/4 Max	0.0000	0.9920	0.9996	
1/2 Max	0.0000	0.9971	0.9999	
Max	0.0000	1.0122	0.9998	

[1]Regression is based on mean of log(leaf potassium).
Regression Equation: $Y = a + bX$.

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FIGURE 12

STABILITY ANALYSIS FOR TREATMENT MEANS OF LOG(LEAF K) CONCENTRATIONS DURING LIQUID AND DEWATERED BIOSOLIDS APPLICATIONS

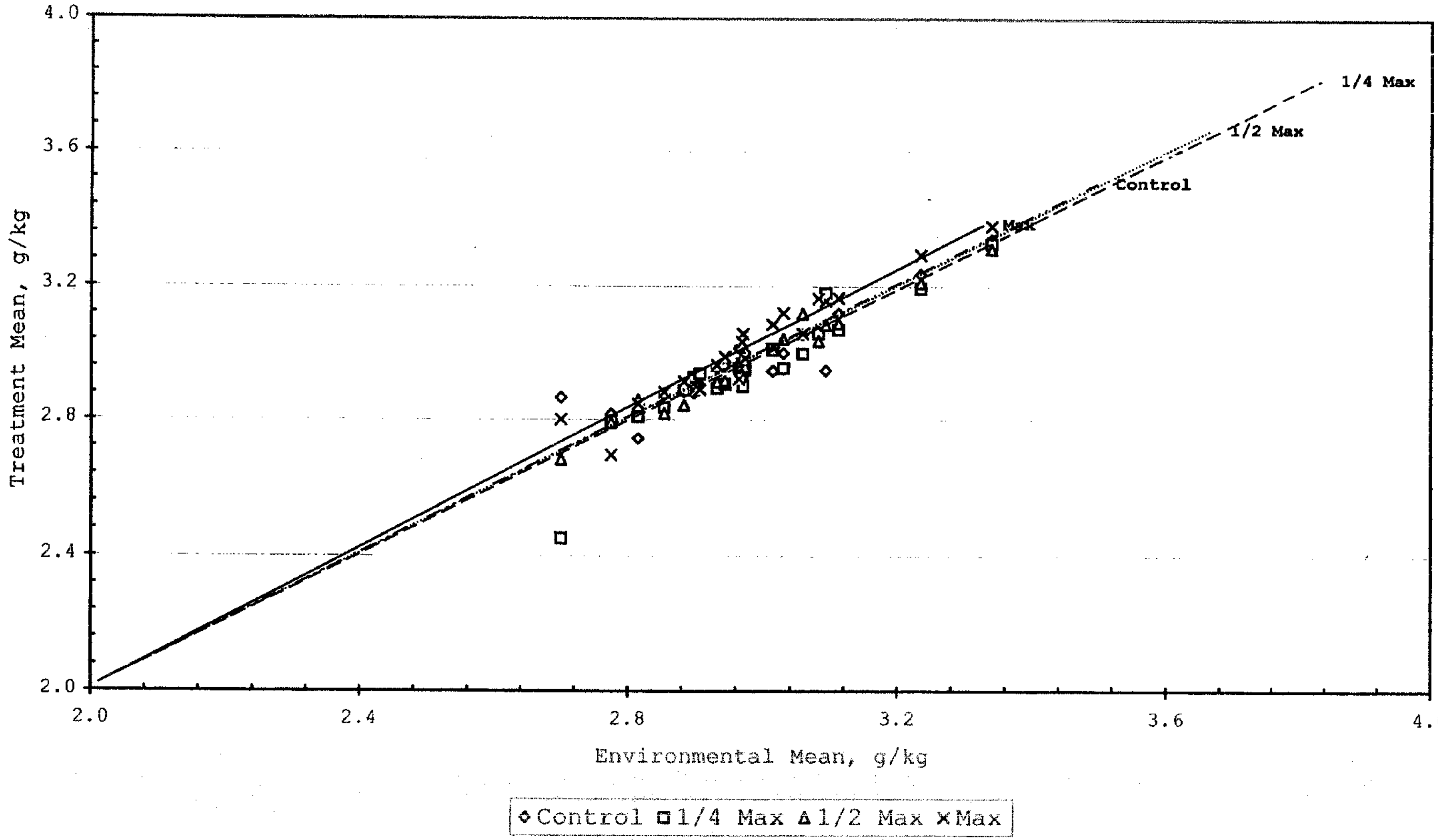

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TABLE 37

ANNUAL TOTAL NITROGEN UPTAKE BY CORN
ON BIOSOLIDS-AMENDED CALCAREOUS MINE SPOIL

Year	Treatments[1]				Prob (ANOVA)
	Control	1/4 Max	1/2 Max	Max	
	Liquid Biosolids Application (kg/ha)				
1974	53.1	69.5	72.0	*109.1	0.006
1975	112.5	110.0	116.0	123.2	0.808
1976	74.7	96.7	91.6	87.7	0.271
1977	96.7	102.7	109.6	128.8	0.220
1978	126.1	107.1	140.3	167.5	**0.035
1980	117.9	135.6	144.3	*166.5	0.015
1981	161.3	135.7	177.0	191.4	0.177
1982	112.1	113.7	151.5	167.7	**0.047
1983	37.5	38.0	60.3	*78.4	0.004
1984	118.7	148.9	*194.4	*265.2	0.000
	Dewatered Biosolids Application (kg/ha)				
1985	87.4	117.7	*164.4	*165.2	0.000
1986	162.4	146.7	153.7	208.5	0.352
1987	92.0	63.3	73.9	91.4	0.082
1988	47.0	29.5	27.5	24.5	0.101
1989	84.1	93.9	114.7	109.3	0.076
1990	68.8	*24.4	*19.3	55.3	0.002
1991	19.2	13.2	13.9	*38.6	0.007
1992	80.6	*36.3	53.3	61.9	0.044
1993	43.3	26.9	49.9	*120.1	0.001
1994	101.7	*29.8	45.7	90.9	0.017
1995	52.5	39.8	71.2	84.1	0.607

TABLE 37 (Continued)

ANNUAL TOTAL NITROGEN UPTAKE BY CORN
ON BIOSOLIDS-AMENDED CALCAREOUS MINE SPOIL

Year	Treatments[1]				Prob (ANOVA)
	Control	1/4 Max	1/2 Max	Max	
	Summary of Treatment Means (kg/ha)				
Liquid Biosolids	101.1	105.8	*125.7	*148.5	0.000
Dewatered Biosolids	78.8	57.9	71.6	95.4	**0.009
All Years	89.8	81.3	97.7	*120.7	***0.000

[1]Please see Appendix AI-6 for Dunnett T-value and ANOVA p-value.

*Significantly different from control at 5% level of significance by Dunnett Test.

**Unable to detect significant difference from control by Dunnett test.

***ANOVA and Dunnett tests are based on rank.

treatments in 1974, 1978, 1980, 1982, 1983, and 1984. Total N uptake by corn during dewatered biosolids applications was the lowest in 1991 and the highest in 1986. Significant variations in total N uptake occurred between treatments in 1985, 1990, 1991, 1992, 1993, and 1994 (Table 37).

A summary of mean total N uptake by corn for each treatment during liquid biosolids applications, dewatered biosolids applications, and all years is shown in Table 37. The ANOVAs for the summary of treatment means in Table 37 showed that there were significant ($P \leq 0.05$) differences between treatment means for liquid biosolids, dewatered biosolids, and all years. Total N uptake by corn on biosolids-amended plots was the lowest during applications of dewatered biosolids and the highest during applications of liquid biosolids. Increasing the rate of biosolids applications increased the total N uptake for both forms of biosolids applied. Total N uptake in the one-half maximum and maximum-amended treatments during liquid biosolids applications was significantly ($P \leq 0.05$) higher than the control treatment. During applications of dewatered biosolids, only total N uptake in the maximum-amended treatments was higher than the control treatment. For all years of biosolids applications, only total N uptake in the maximum treatment was significantly ($P \leq 0.05$) higher than the control treatment.

An ANOVA for total N uptake by corn during liquid biosolids applications showed significant ($P \leq 0.05$) variations for year and treatment, but not for the year-by-treatment interaction (Table 38). Consequently, the regression of treatment means on the environmental means and stability analysis were not done.

An ANOVA for total N uptake by corn during the applications of dewatered biosolids showed significant ($P \leq 0.05$) sources of variation for year, treatment, and the-year-by treatment interaction (Table 39). A regression of the log of treatment means on the log of the environmental means during dewatered biosolids applications showed that the regression equations for the treatments were significantly ($P \leq 0.05$) different (Table 40). Stability analysis showed that total N uptake was the highest in the maximum treatment followed by the control, one-half maximum, and one-fourth maximum treatments (Figure 13).

An ANOVA for total N uptake during both liquid and dewatered biosolids applications showed significant ($P \leq 0.05$) differences for year, treatment, and the year-by-treatment interaction (Table 41). A regression of the log of the treatment means on the log of the environmental means showed that there were significant differences in the regression equations for the treatments (Table 42). Stability analysis showed that

TABLE 38

ANALYSIS OF VARIANCE[1]
FOR TOTAL NITROGEN UPTAKE BY CORN FROM 1973 TO 1984
DURING LIQUID BIOSOLIDS APPLICATIONS

Source of Variation	Degrees of Freedom	Mean Square Error	F Ratio	P Value
Year	9	2.440	30.500	*0.000
Treatment	3	1.440	18.000	*0.000
Year x Treatment	27	0.080	1.500	0.067
Error	120	0.050		

[1]Analysis of variance is based on log(total nitrogen uptake).

*Significant at 5% level of significance.

TABLE 39

ANALYSIS OF VARIANCE[1]
FOR TOTAL NITROGEN UPTAKE BY CORN FROM 1985 TO 1995
DURING DEWATERED BIOSOLIDS APPLICATIONS

Source of Variation	Degrees of Freedom	Mean Square Error	F Ratio	P Value
Year	10	6.440	13.417	*0.000
Treatment	3	3.740	7.792	*0.000
Year x Treatment	30	0.480	2.100	*0.002
Error	126	0.220		

[1]Analysis of variance is based on log(total nitrogen uptake).

*Significant at 5% level of significance.

TABLE 40

REGRESSION OF TREATMENT MEANS(Y) ON ENVIRONMENTAL MEANS[1](X) OF TOTAL NITROGEN UPTAKE BY CORN BY TREATMENT AND THE TEST FOR EQUIVALENCE OF THE FOUR REGRESSION EQUATIONS DURING DEWATERED BIOSOLIDS APPLICATIONS (1985 TO 1995)

Treatment Y	Intercept a	Slope b	R^2	P Value
Control	0.0000	1.0253	0.9928	0.000
1/4 Max	0.0000	0.9157	0.9947	
1/2 Max	0.0000	0.9790	0.9962	
Max	0.0000	1.0757	0.9948	

[1]Regression is based on mean of log(total nitrogen uptake).
Regression Equation: Y = a + bX.

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FIGURE 13

STABILITY ANALYSIS FOR TREATMENT MEANS OF LOG(TOTAL N) UPTAKE DURING DEWATERED BIOSOLIDS APPLICATIONS

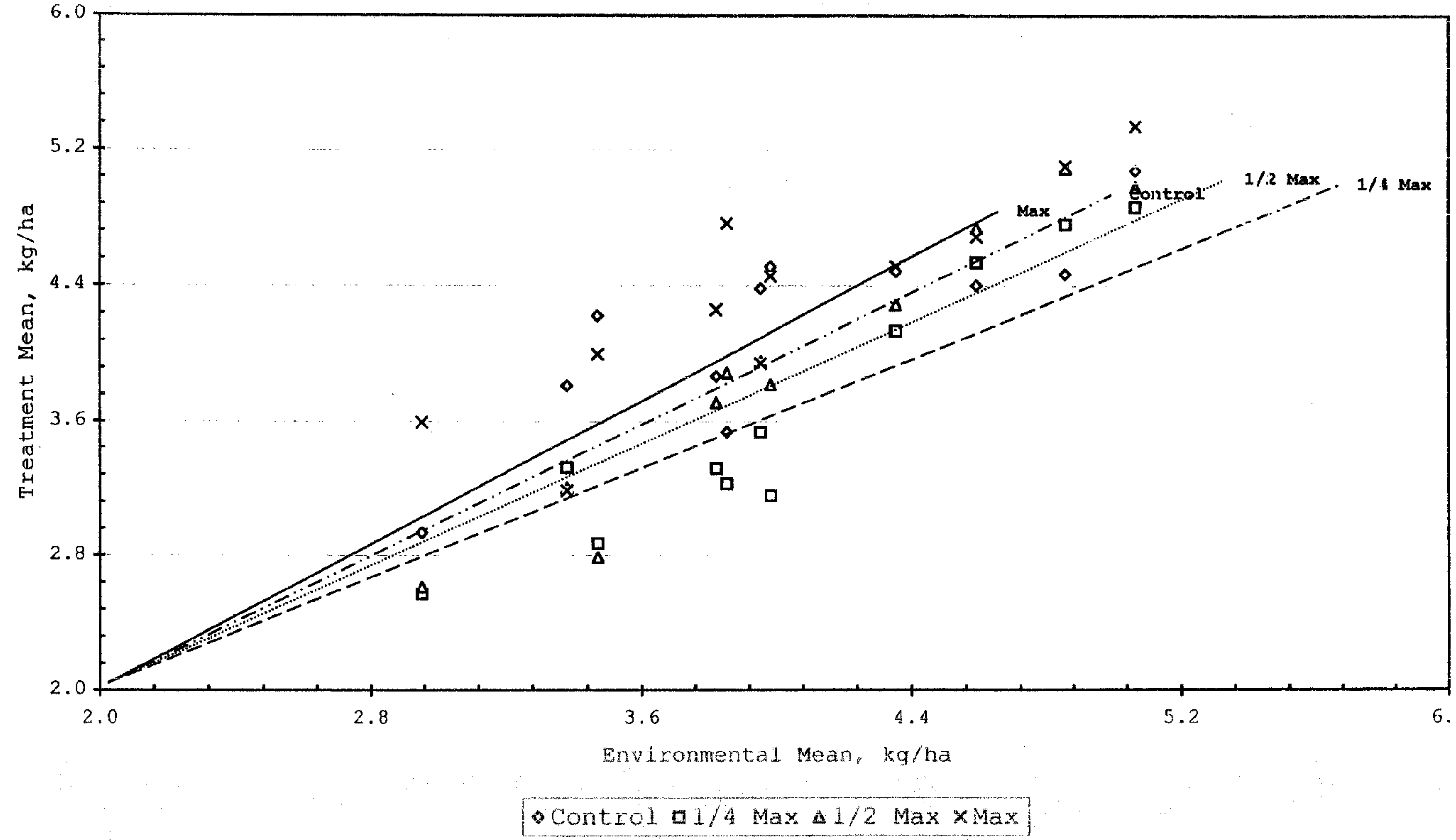

TABLE 41

ANALYSIS OF VARIANCE[1]
FOR TOTAL NITROGEN UPTAKE BY CORN FROM 1973 TO 1995
DURING LIQUID AND DEWATERED BIOSOLIDS APPLICATIONS

Source of Variation	Degrees of Freedom	Mean Square Error	F Ratio	P Value
Year	20	6.070	17.853	*0.000
Treatment	3	3.860	11.353	*0.000
Year x Treatment	60	0.340	2.500	*0.000
Error	246	0.140		

[1]Analysis of variance is based on log(total nitrogen uptake).

*Significant at 5% level of significance.

TABLE 42

REGRESSION OF TREATMENT MEANS (Y) ON ENVIRONMENTAL MEANS[1] (X) OF TOTAL NITROGEN UPTAKE BY CORN BY TREATMENT AND THE TEST FOR EQUIVALENCE OF THE FOUR REGRESSION EQUATIONS DURING LIQUID AND DEWATERED BIOSOLIDS APPLICATIONS (1973 TO 1995)

Treatment Y	Intercept a	Slope b	R^2	P Value
Control	0.0000	0.9900	0.9949	0.000
1/4 Max	0.0000	0.9494	0.9964	
1/2 Max	0.0000	0.9972	0.9980	
Max	0.0000	1.0615	0.9969	

[1]Regression is based on mean of log(total nitrogen uptake).
Regression Equation: $Y = a + bX$.

total N uptake was the highest in the maximum treatment followed by the one-half maximum treatment, control treatment, and one-fourth maximum treatment (Figure 14).

Nitrogen uptake by corn on calcareous mine spoil was usually less than that observed on productive agricultural soils receiving biosolids. Clapp et al. (1994) reported mean N uptakes varying from 183 to 223 kg ha^{-1} on biosolids-amended agricultural soil during a 20-year study. Using the same experimental design as used in this study, Hinesly and Hansen (1983) on a Blount silt loam observed N uptakes by corn of 191 to 240 kg ha^{-1} in the maximum biosolids-amended plots.

The mean percent recovery of N by corn, total N uptake divided by total N applied, during the 1974-1995 period varied with the treatments. On the control treatment receiving commercial fertilizer, the mean N recovery was 26.2 percent. In the biosolids-amended treatments, the N recovery was 14.9 percent for the one-fourth maximum, 9.1 percent for the one-half maximum, and 5.6 percent for the maximum.

Kelling et al. (1977) reported that the lower biosolids treatment rates showed the highest recoveries of biosolids-applied N, and that the amount of N recovered decreased with higher biosolids application rates. The lower N recoveries in the biosolids-amended treatments in this study probably reflects the losses of N through volatilization, denitrification,

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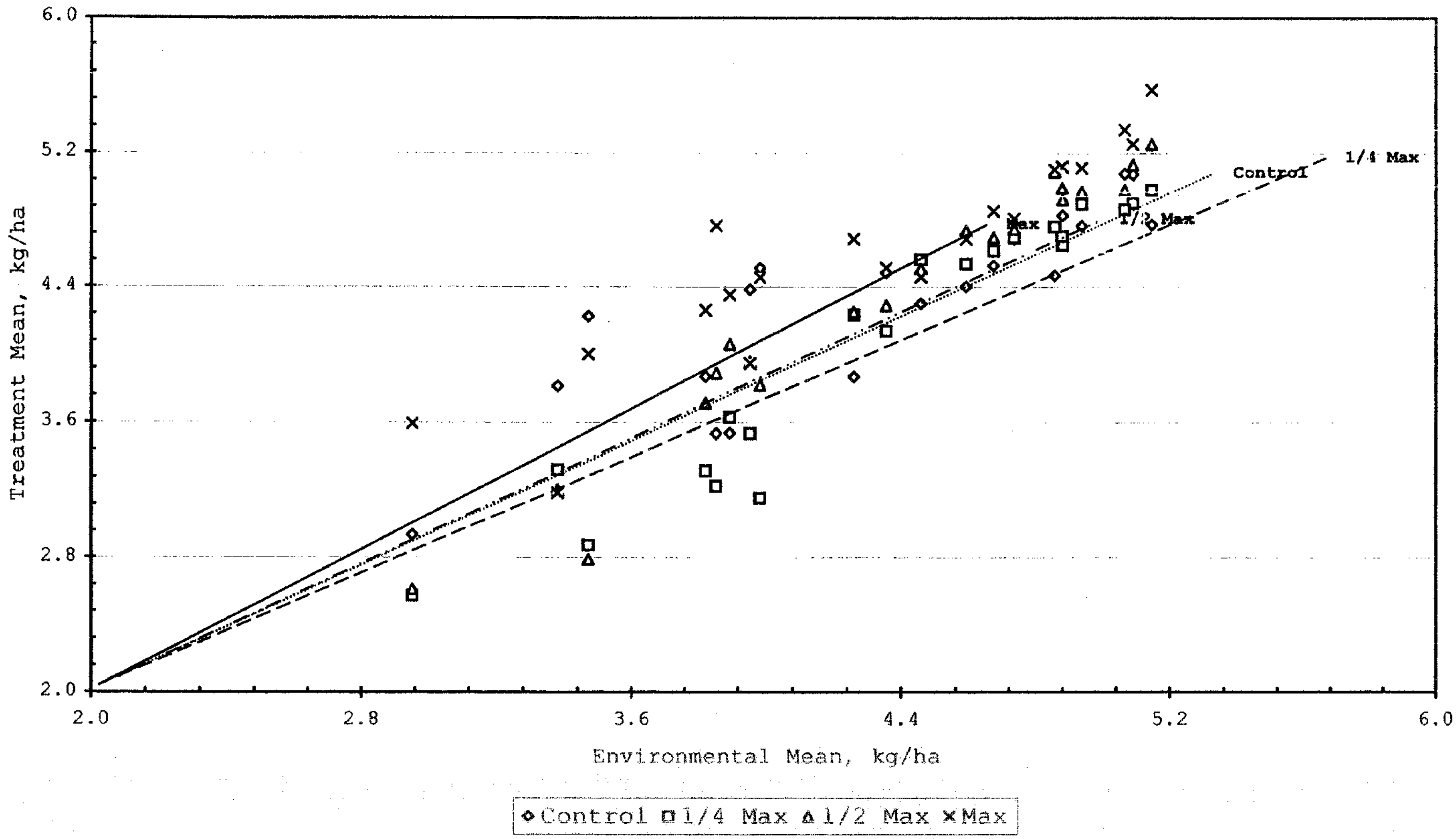
FIGURE 14

STABILITY ANALYSIS FOR TREATMENT MEANS OF LOG(TOTAL N) UPTAKE DURING LIQUID AND DEWATERED BIOSOLIDS APPLICATIONS



and leaching; the low mineralization rate of organic N from aged, anaerobically digested biosolids; and the high amounts of total N applied, especially during liquid biosolids applications (Table 2).

PHOSPHORUS UPTAKE

Total P uptake by corn in the four treatments varied yearly (Table 43). Mean P uptake by corn ranged from 2.7 kg P ha^{-1} in the 1988 maximum treatment to 41.1 kg P ha^{-1} in the 1994 maximum treatment. Mean total P uptake during liquid biosolids applications was the lowest in 1983 and the highest for most treatments in 1981. Significant differences in total P uptake between treatments occurred from 1980 through 1984. During dewatered biosolids applications, mean total P uptake was the lowest in 1988 and the highest in 1994. Significant variations in total P uptake between treatments occurred in 1985, 1988, 1989, 1990, 1991, and 1993 (Table 43).

A summary of mean total P uptake by corn for each treatment during liquid biosolids applications, dewatered biosolids applications, and all years is shown in Table 43. Total P uptake in the one-half maximum and maximum plots was higher than that obtained in the control treatment during liquid and dewatered biosolids applications and for all

TABLE 43

ANNUAL TOTAL PHOSPHORUS UPTAKE BY CORN
ON BIOSOLIDS-AMENDED CALCAREOUS MINE SPOIL

Year	Treatments[1]				Prob (ANOVA)
	Control	1/4 Max	1/2 Max	Max	
	Liquid Biosolids Application (kg/ha)				
1974	9.3	8.8	10.3	11.8	0.330
1975	19.6	17.5	17.8	18.7	0.829
1976	13.4	16.4	14.0	12.9	0.260
1977	12.4	11.0	11.4	14.3	0.373
1978	18.1	15.3	18.7	22.4	0.108
1980	14.4	15.3	17.0	*23.4	0.003
1981	19.6	19.8	23.8	*27.5	0.035
1982	17.1	17.7	22.4	*28.3	0.025
1983	4.3	3.8	6.5	*8.0	0.017
1984	13.7	17.0	*23.4	*32.1	0.000
	Dewatered Biosolids Application (kg/ha)				
1985	11.1	*15.1	*21.1	*22.7	0.000
1986	24.9	23.2	25.0	31.8	0.375
1987	10.3	8.6	9.4	10.5	0.565
1988	6.1	3.5	3.5	*2.7	0.038
1989	10.9	*15.5	*18.0	*15.9	0.006
1990	9.8	*5.1	*5.7	9.3	0.009
1991	4.0	3.4	4.3	*9.0	0.028
1992	21.4	13.8	16.6	17.3	0.203
1993	15.9	9.9	18.1	*36.0	0.000
1994	26.2	19.2	21.2	41.1	0.087
1995	17.6	15.8	27.3	32.1	0.610

TABLE 43 (Continued)

ANNUAL TOTAL PHOSPHORUS UPTAKE BY CORN
ON BIOSOLIDS-AMENDED CALCAREOUS MINE SPOIL

Year	Treatments[1]				Prob (ANOVA)
	Control	1/4 Max	1/2 Max	Max	
	Summary of Treatment Means (kg/ha)				
Liquid Biosolids	14.2	14.3	16.5	*19.9	0.000
Dewatered Biosolids	14.5	*12.2	15.2	*20.8	***0.000
All Years	14.3	13.2	15.8	*20.4	***0.000

[1]Please see Appendix AI-7 for Dunnett T-value and ANOVA p-value.

*Significantly different from control at 5% level of significance by Dunnett test.

***ANOVA and Dunnett tests are based on rank.

years. On the biosolids-amended treatments, total P uptake in the one-fourth and one-half maximum treatments was the highest during liquid biosolids applications. The lowest total P uptake occurred in the one-fourth maximum treatment during applications of dewatered biosolids (Table 43).

An ANOVA for total P uptake by corn during liquid biosolids applications showed significant ($P \leq 0.05$) variations for year, treatment, and the year-by-treatment interaction (Table 44). A regression analysis of the log of treatment means on the log of the environmental means showed significant ($P \leq 0.05$) differences between the slopes of the treatments (Table 45). Stability analysis showed that the maximum treatment had the highest P uptake followed by the one-half maximum treatment (Figure 15). The regression lines for the one-fourth maximum and control treatments were essentially the same as shown by the slope coefficients in Table 45.

An ANOVA for total P uptake by corn during applications of dewatered biosolids showed significant ($P \leq 0.05$) differences for year and treatment, but not for the year-by-treatment interaction (Table 46). Consequently, the regression of treatment means on the environmental means and stability analysis were not done.

TABLE 44

ANALYSIS OF VARIANCE[1]
FOR TOTAL PHOSPHORUS UPTAKE BY CORN FROM 1973 TO 1984
DURING LIQUID BIOSOLIDS APPLICATIONS

Source of Variation	Degrees of Freedom	Mean Square Error	F Ratio	P Value
Year	9	3.160	35.111	*0.000
Treatment	3	1.120	12.444	*0.000
Year x Treatment	27	0.090	1.700	*0.030
Error	120	0.050		

[1]Analysis of variance is based on log(total phosphorus uptake).

*Significant at 5% level of significance.

TABLE 45

REGRESSION OF TREATMENT MEANS (Y) ON ENVIRONMENTAL MEANS[1] (X) OF TOTAL PHOSPHORUS UPTAKE BY CORN BY TREATMENT AND THE TEST FOR EQUIVALENCE OF THE FOUR REGRESSION EQUATIONS DURING LIQUID BIOSOLIDS APPLICATIONS (1973 TO 1984)

Treatment Y	Intercept a	Slope b	R^2	P Value
Control	0.0000	0.9514	0.9973	0.000
1/4 Max	0.0000	0.9570	0.9978	
1/2 Max	0.0000	1.0122	0.9993	
Max	0.0000	1.0794	0.9967	

[1]Regression is based on mean of log(total phosphorus uptake).
Regression Equation: Y = a + bX.

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FIGURE 15

STABILITY ANALYSIS FOR TREATMENT MEANS OF LOG(TOTAL P)
UPTAKE DURING LIQUID BIOSOLIDS APPLICATIONS

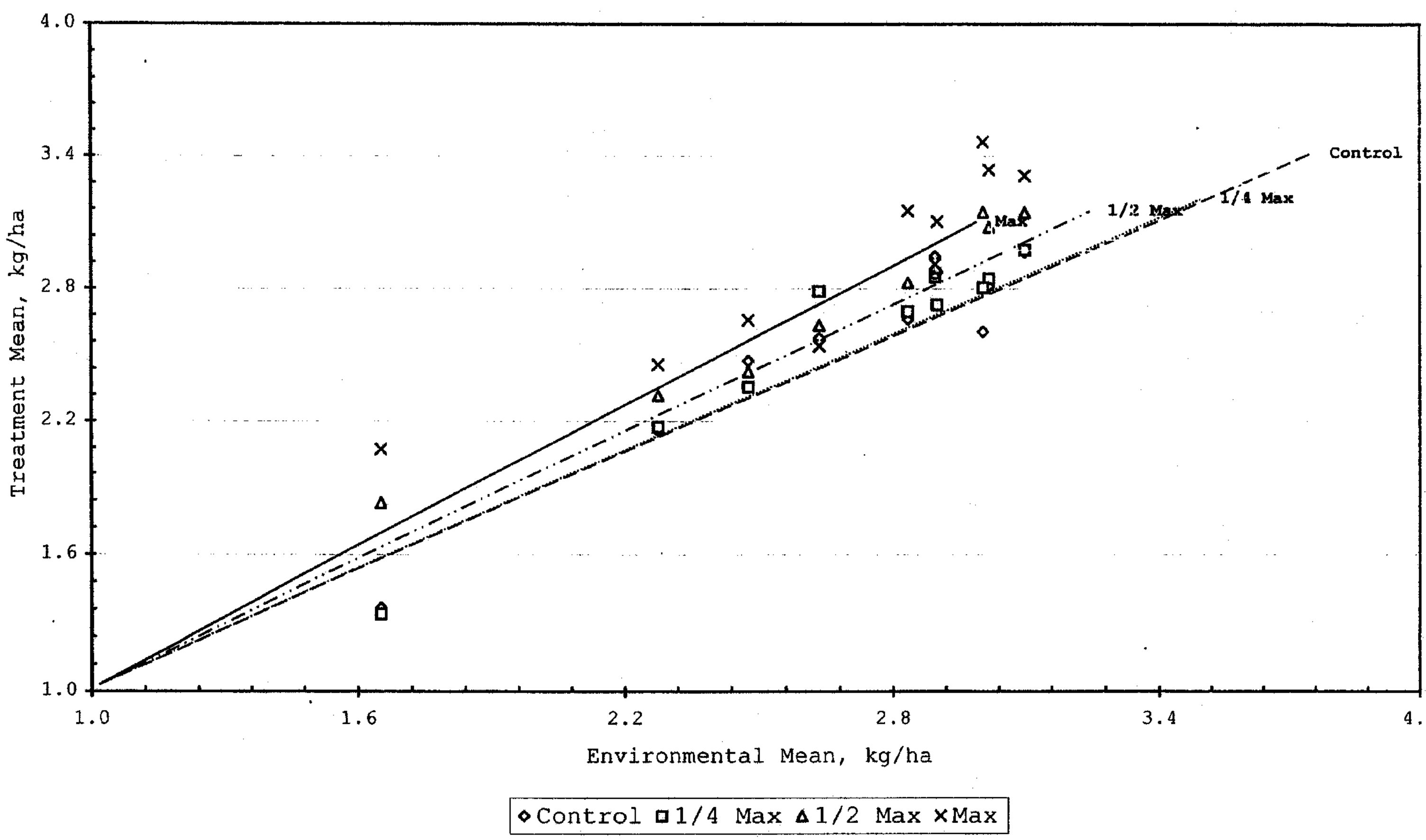

TABLE 46

ANALYSIS OF VARIANCE[1]
FOR TOTAL PHOSPHORUS UPTAKE BY CORN FROM 1985 TO 1995
DURING DEWATERED BIOSOLIDS APPLICATIONS

Source of Variation	Degrees of Freedom	Mean Square Error	F Ratio	P Value
Year	10	6.630	20.719	*0.000
Treatment	3	2.340	7.313	*0.000
Year x Treatment	30	0.320	1.400	0.090
Error	126	0.220		

[1]Analysis of variance is based on log(total phosphorus uptake).

*Significant at 5% level of significance.

An ANOVA for total P uptake by corn during the applications of both liquid and dewatered biosolids showed significant ($P \leq 0.05$) differences for year, treatment, and the year-by-treatment interaction (Table 47). Regression analysis of the log of treatment means on the log of the environmental means showed that the treatment regression equations were significantly different (Table 48). Stability analysis showed that total P uptake was the highest in the maximum treatment followed by the one-half maximum, control, and one-fourth maximum treatments (Figure 16).

Multiple regression analysis to evaluate the variables affecting corn yields showed that total P uptake was the major variable influencing corn yields during the applications of dewatered biosolids (Table 11) and during the applications of both liquid and dewatered biosolids (Table 12).

Phosphorus uptake by corn on calcareous mine spoil was lower than that observed on productive agricultural soils receiving biosolids. Clapp et al. (1994) reported mean P uptakes by corn of 36 to 38 kg ha^{-1} on biosolids-amended agricultural soils. On a biosolids-amended Blount silt loam, Hinesly and Hansen (1983) observed P uptakes of 38 to 52 kg ha^{-1} in the maximum-amended treatment.

The mean recovery of P during the 1974 to 1995 interval varied with the treatments. In the control treatment 6.6

TABLE 47

ANALYSIS OF VARIANCE[1]
FOR TOTAL PHOSPHORUS UPTAKE BY CORN FROM 1973 TO 1995
DURING LIQUID AND DEWATERED BIOSOLIDS APPLICATIONS

Source of Variation	Degrees of Freedom	Mean Square Error	F Ratio	P Value
Year	20	4.910	22.318	*0.000
Treatment	3	3.090	14.045	*0.000
Year x Treatment	60	0.220	1.600	*0.011
Error	246	0.140		

[1]Analysis of variance is based on log(total phosphorus uptake).

*Significant at 5% level of significance.

TABLE 48

REGRESSION OF TREATMENT MEANS(Y) ON ENVIRONMENTAL MEANS[1](X) OF TOTAL PHOSPHORUS UPTAKE BY CORN BY TREATMENT AND THE TEST FOR EQUIVALENCE OF THE FOUR REGRESSION EQUATIONS DURING LIQUID AND DEWATERED BIOSOLIDS APPLICATIONS (1973 TO 1995)

Treatment Y	Intercept a	Slope b	R^2	P Value
Control	0.0000	0.9706	0.9929	0.000
1/4 Max	0.0000	0.9251	0.9928	
1/2 Max	0.0000	1.0018	0.9981	
Max	0.0000	1.0970	0.9929	

[1]Regression is based on mean of log(total phosphorus uptake).
Regression Equation: $Y = a + bX$.

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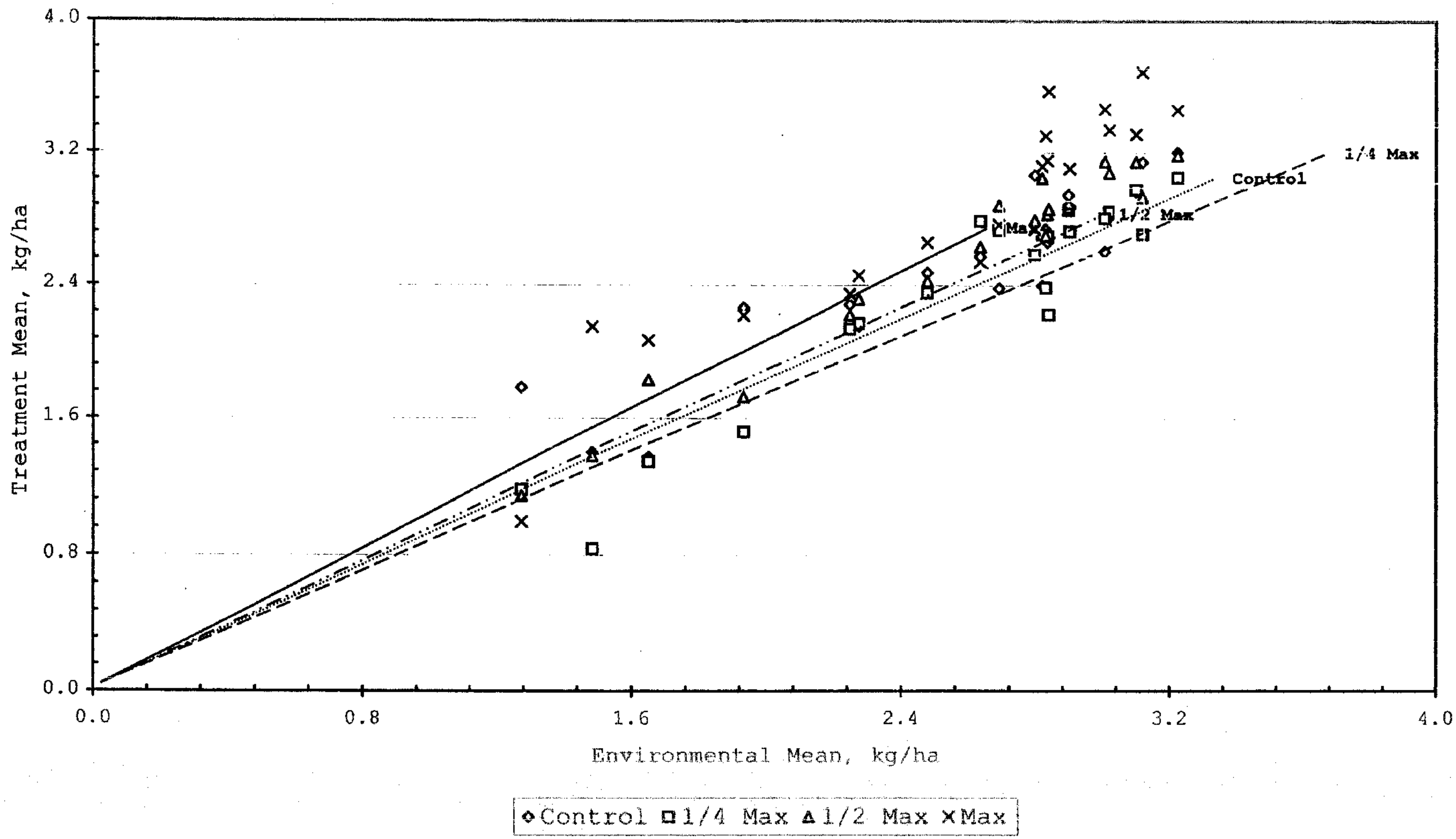
FIGURE 16

STABILITY ANALYSIS FOR TREATMENT MEANS OF LOG(TOTAL P) UPTAKE DURING LIQUID AND DEWATERED BIOSOLIDS APPLICATIONS



percent of the applied P was recovered by corn. The mean recovery of P in the biosolids treatments was 3.2 percent for one-fourth maximum, 1.9 percent for one-half maximum, and 1.2 percent for the maximum.

Kelling et al. (1977) reported that the recovery of biosolids-applied P was less than 5 percent in the first crops after a low rate biosolids application, and about 1 percent on the first crops after a high rate biosolids application. They also observed that P recovery by crops decreased with increasing biosolids application rates.

POTASSIUM UPTAKE

Total K uptake by corn in the four treatments varied yearly (Table 49). Mean total K uptake ranged from 12.5 kg ha^{-1} in the 1991 one-fourth maximum treatments to 176 kg ha^{-1} in the 1994 one-half maximum treatments. Mean total K uptake during liquid biosolids applications was the lowest in 1977 and the highest in 1981. Significant differences in total K uptake between treatments occurred in 1974, 1983, and 1984. During applications of dewatered biosolids, mean total K uptake was the lowest in 1991 and the highest in 1994. Significant differences between treatments in total K uptake were observed in 1985, 1990, 1992, and 1993 (Table 49).

TABLE 49

ANNUAL TOTAL POTASSIUM UPTAKE BY CORN
ON BIOSOLIDS-AMENDED CALCAREOUS MINE SPOIL

Year	Treatments[1]				Prob (ANOVA)
	Control	1/4 Max	1/2 Max	Max	
	Liquid Biosolids Application (kg/ha)				
1974	41.5	37.3	55.7	*74.1	0.001
1975	59.7	66.8	62.3	68.9	0.874
1976	73.6	85.8	92.8	71.8	0.313
1977	34.7	34.7	38.8	50.9	0.052
1980	73.5	60.5	67.5	87.8	0.162
1981	99.4	80.6	105.8	133.6	0.141
1982	90.1	88.1	90.3	133.6	0.089
1983	21.1	21.9	30.3	*43.7	0.005
1984	56.1	67.5	*84.4	*119.3	0.000
	Dewatered Biosolids Application (kg/ha)				
1985	46.9	58.7	*79.5	*87.3	0.001
1986	90.0	84.9	81.0	122.4	0.183
1987	70.7	55.5	61.9	75.9	0.465
1988	28.4	22.7	18.1	17.3	0.173
1989	104.8	91.2	135.2	118.9	0.192
1990	66.6	*24.7	*25.7	69.7	0.003
1991	15.6	12.5	15.9	29.9	0.126
1992	48.5	36.6	50.5	37.5	**0.018
1993	58.8	31.8	60.2	*149.9	0.000
1994	93.4	42.3	176.4	99.4	***0.138
1995	40.8	32.9	58.1	66.8	0.627

TABLE 49 (Continued)

ANNUAL TOTAL POTASSIUM UPTAKE BY CORN
ON BIOSOLIDS-AMENDED CALCAREOUS MINE SPOIL

Year	Treatments[1]				Prob (ANOVA)
	Control	1/4 Max	1/2 Max	Max	
	Summary of Treatment Means (kg/ha)				
Liquid Biosolids	61.1	60.3	69.8	*87.1	0.001
Dewatered Biosolids	62.5	*45.9	69.6	79.5	***0.000
All Years	61.8	*52.6	69.7	*82.9	***0.000

[1]Please see Appendix AI-8 for Dunnett T-value and ANOVA p-value.

*Significantly different from control at 5% level of significance by Dunnett Test.

**Unable to detect significant difference from control by Dunnett test.

***ANOVA and Dunnett tests are based on rank.

A summary of mean total K uptake by corn for each treatment during liquid biosolids applications, dewatered biosolids applications, and all years is shown in Table 49. Total K uptake in the one-half maximum and maximum treatments was higher than that observed in the control treatment during liquid and dewatered biosolids applications and for all years. The total uptake of K in the one-fourth maximum treatment was significantly lower than that observed in the control treatment during dewatered biosolids applications and for all years (Table 49).

An ANOVA for total K uptake by corn during liquid biosolids applications showed significant ($P \leq 0.05$) differences for year and treatment, but not for the year-by-treatment interaction (Table 50). Because of this, the regression of treatment means on the environmental means and stability analysis were not done.

An ANOVA for total K uptake by corn during dewatered biosolids applications showed significant ($P \leq 0.05$) differences for year, treatment, and the year-by-treatment interaction (Table 51). Regression of the log of the treatment means on the log of the environmental means indicated that the regression equations for the treatments were significantly different (Table 52). Stability analysis in Figure 17 showed that the

TABLE 50

ANALYSIS OF VARIANCE[1]
FOR TOTAL POTASSIUM UPTAKE BY CORN FROM 1973 TO 1984
DURING LIQUID BIOSOLIDS APPLICATIONS

Source of Variation	Degrees of Freedom	Mean Square Error	F Ratio	P Value
Year	8	3.010	33.444	*0.000
Treatment	3	1.340	14.889	*0.000
Year x Treatment	24	0.090	1.300	0.194
Error	108	0.070		

[1]Analysis of variance is based on log(total potassium uptake).

*Significant at 5% level of significance.

TABLE 51

ANALYSIS OF VARIANCE[1]
FOR TOTAL POTASSIUM UPTAKE BY CORN FROM 1985 TO 1995
DURING DEWATERED BIOSOLIDS APPLICATIONS

Source of Variation	Degrees of Freedom	Mean Square Error	F Ratio	P Value
Year	10	5.230	12.452	*0.000
Treatment	3	3.080	7.333	*0.000
Year x Treatment	30	0.420	1.700	*0.026
Error	126	0.250		

[1]Analysis of variance is based on log(total potassium uptake).

*Significant at 5% level of significance.

TABLE 52

REGRESSION OF TREATMENT MEANS (Y) ON ENVIRONMENTAL MEANS[1] (X) OF TOTAL POTASSIUM UPTAKE BY CORN BY TREATMENT AND THE TEST FOR EQUIVALENCE OF THE FOUR REGRESSION EQUATIONS DURING DEWATERED BIOSOLIDS APPLICATIONS (1985 TO 1995)

Treatment Y	Intercept a	Slope b	R^2	P Value
Control	0.0000	1.0117	0.9964	0.000
1/4 Max	0.0000	0.9085	0.9922	
1/2 Max	0.0000	1.0007	0.9970	
Max	0.0000	1.0746	0.9951	

[1]Regression is based on mean of log(total potassium uptake).
Regression Equation: $Y = a + bX$.

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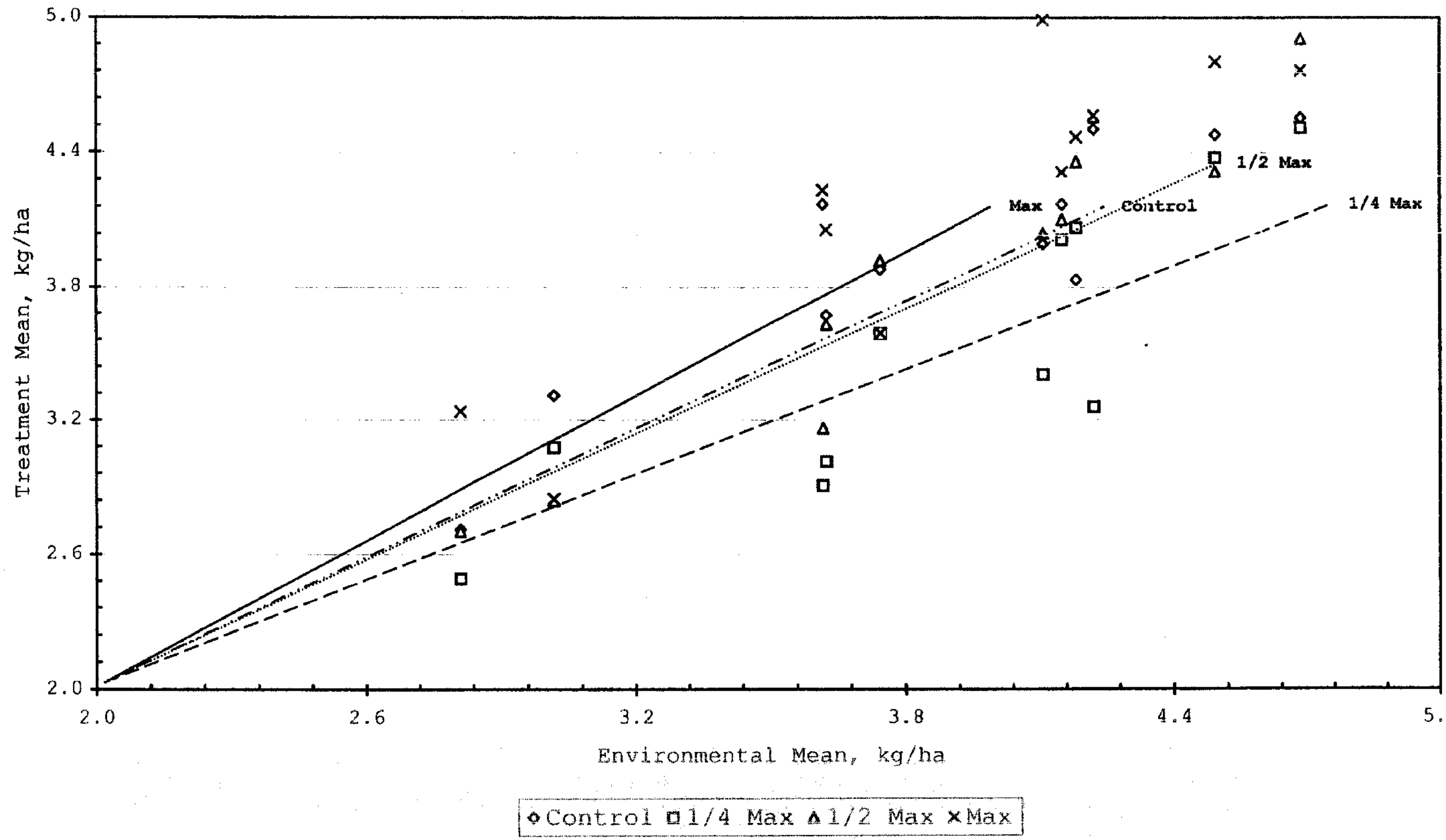
FIGURE 17

STABILITY ANALYSIS FOR TREATMENT MEANS OF LOG(TOTAL K)
UPTAKE DURING DEWATERED BIOSOLIDS APPLICATIONS



highest total K uptake occurred in the maximum treatment, followed by the control, one-half maximum, and one-fourth maximum treatments. The slopes for the control and one-half maximum treatments in Figure 17 were very similar, as indicated by the coefficients for the slopes in Table 52.

An ANOVA for total K uptake during applications of both liquid and dewatered biosolids in Table 53 showed that there were significant ($P \leq 0.05$) differences for year, treatment, and the year-by-treatment interaction. A regression of the log of the treatment means on the log of the environmental means in Table 54 showed that the regression equations for the treatments were significantly different. Stability analysis showed that during the applications of liquid and dewatered biosolids, total K uptake was the highest in the maximum treatment (Figure 18). The uptake of K in the one-half maximum and control treatments were essentially the same followed by the one-fourth maximum treatment. This is reflected in the slopes of the regression equations shown in Table 54.

The total K uptake by corn on calcareous mine spoil was lower than that observed on productive agricultural soils receiving biosolids. Clapp et al. (1994) reported mean K uptakes of 104 to 165 kg ha^{-1} on biosolids-amended agricultural soils. Hinesly and Hansen (1983) on a biosolids-amended Blount

TABLE 53

ANALYSIS OF VARIANCE[1]
FOR TOTAL POTASSIUM UPTAKE BY CORN FROM 1973 TO 1995
DURING LIQUID AND DEWATERED BIOSOLIDS APPLICATIONS

Source of Variation	Degrees of Freedom	Mean Square Error	F Ratio	P Value
Year	19	4.230	14.586	*0.000
Treatment	3	3.860	13.310	*0.000
Year x Treatment	57	0.290	1.700	*0.003
Error	234	0.170		

[1]Analysis of variance is based on log(total potassium uptake).

*Significant at 5% level of significance.

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TABLE 54

REGRESSION OF TREATMENT MEANS (Y) ON ENVIRONMENTAL MEANS[1] (X) OF TOTAL POTASSIUM UPTAKE BY CORN BY TREATMENT AND THE TEST FOR EQUIVALENCE OF THE FOUR REGRESSION EQUATIONS DURING LIQUID AND DEWATERED BIOSOLIDS APPLICATIONS (1973 TO 1995)

Treatment Y	Intercept a	Slope b	R^2	P Value
Control	0.0000	0.9897	0.9971	0.000
1/4 Max	0.0000	0.9365	0.9947	
1/2 Max	0.0000	1.0030	0.9982	
Max	0.0000	1.0684	0.9965	

[1]Regression is based on mean of log(total potassium uptake).
Regression Equation: Y = a + bX.

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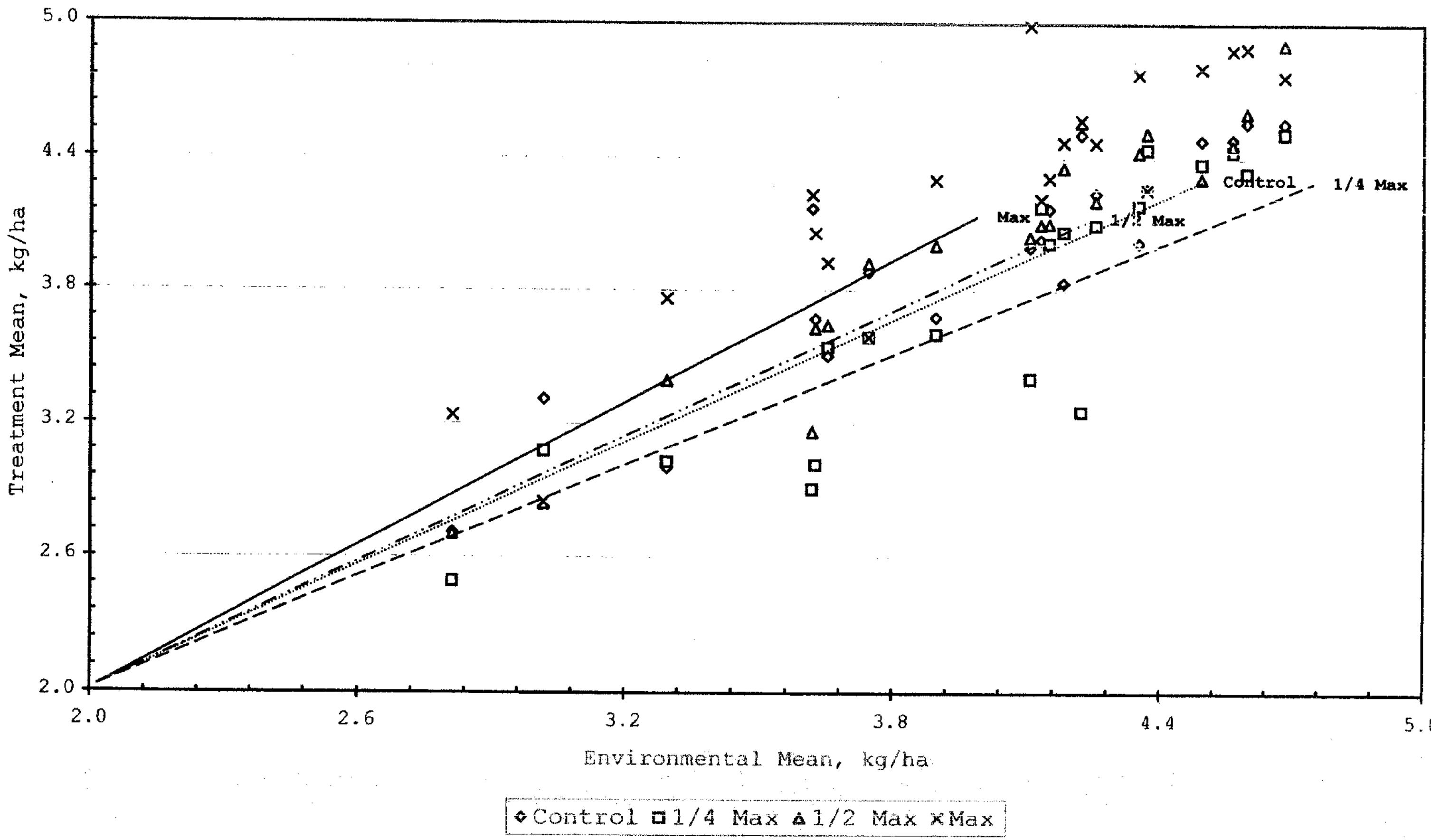
FIGURE 18

STABILITY ANALYSIS FOR TREATMENT MEANS OF LOG(TOTAL K)
UPTAKE DURING LIQUID AND DEWATERED BIOSOLIDS APPLICATIONS



silt loam observed K uptakes of 120 to 305 kg ha^{-1} in the maximum-amended treatment.

The mean recovery of K during the 1974 to 1995 interval varied with the treatments. The amount recovered by the various treatments reflects the 112 kg K ha^{-1} applied annually to all four treatments and the amounts applied by biosolids. Additional amounts of plant utilizable K were in the mine spoil, which contained approximately 28 percent clay. The major components of clay fraction were illite (54 percent), chlorite (8 percent) and vermiculite (11 percent) (Pietz et al., 1982). Potassium recovery in the control treatment was 48.9 percent. In the biosolids-amended treatments, the K recovery was 28.3 percent in one-fourth maximum, 29.4 percent in one-half maximum, and 23.3 percent in the maximum.

Mine Spoil, Biosolids, and Climatic Factors

Many factors affected corn yields and nutrient composition during the 1973 through 1995 interval. Major factors playing a significant role in corn production on biosolids-amended mine spoil were the physical characteristics of mine spoil, the nutrient composition of the applied biosolids, and growing season rainfall. A mine spoil physical factor that most limits crop yields and nutrient uptake, as discussed previously, is the shallow rooting depth resulting from compaction during strip-mining activities. A major biosolids factor, as indicated by leaf N content and total N uptake, was the amount of biosolids-applied N available for plant uptake as shown in Tables 10 and 12. Biosolids applied P was also important, as indicated in Tables 10 through 12. Growing season rainfall was a major climatic factor affecting grain yields, as indicated by the regression analysis in Tables 11 and 12.

Of these factors, the amount of PAN is the most easily managed variable for crop production on mine spoil. The Illinois Environmental Protection Agency (IEPA) (State of Illinois, 1984) recommends that the PAN be calculated as 80 percent of biosolids-applied NH_4-N and 20 percent of organic N. There was a considerable difference in PAN under liquid versus dewatered biosolids applications (Table 1). The mean yearly PAN applied to the maximum treatments under liquid biosolids application was 1,355 kg N ha^{-1} (1,210 lb N $acre^{-1}$), as compared to 253 kg N ha^{-1} (226 lb N $acre^{-1}$) with dewatered biosolids applications.

The average corn grain yield for productive soils in Fulton County, Illinois, from 1984 through 1993 was 7.78 Mg ha^{-1} (124 bu $acre^{-1}$) (Illinois Register, 1998). The amount of biosolids required to obtain a corn yield of 7.78 Mg ha^{-1} (124 bu $acre^{-1}$) on productive agricultural soils in Fulton County, Illinois was 8.6

Mg ha^{-1} (3.8 tons $acre^{-1}$) for liquid biosolids applications and 47.5 Mg ha^{-1} (21.2 tons $acre^{-1}$) for dewatered biosolids applications (Illinois Register, 1998). Yearly corn yield data (Table 3) show that biosolids applications to mine spoil, which met or exceeded the proposed PAN requirements for both liquid and dewatered biosolids, did not result in grain yields higher than 7.78 Mg ha^{-1} except in 1986.

Leaf N data (Table 19) and stability analysis for leaf N (Figure 7) indicate that N was a limiting nutrient during most years of dewatered biosolids applications, even with the previous residual biosolids applications and an annual application rate of 67.2 Mg ha^{-1} (30 tons $acre^{-1}$) to the maximum treatment. The low amounts of NH_4-N and the reduced mineralization of the organic N in the aged, dewatered biosolids were major factors affecting the supply of PAN. Regression analysis during both liquid and dewatered biosolids applications (Table 12) shows that PAN along with biosolids applied total Kjeldahl-N and NH_4-N were significant variables that affected corn grain yields.

The actual amounts of PAN in the mine spoil with dewatered biosolids applications were much less than the calculated amount required to reach desired corn yields on productive agricultural soils based on IEPA's criteria. Mineralization of organic N in the aged, dewatered, anaerobically digested biosolids was considerably less than the proposed mineralization rates of 20 percent the first year, 10 percent the second year, 5 percent the third year, 2.5 percent the fourth year, and 1.25 percent the fifth year (State of Illinois, 1984).

Computer simulation of PAN, based on a seven-day test to predict long-term decomposition for biosolids (Gilmour et al., 1996), was conducted on a sample of the dewatered biosolids from the experiment. The estimated PAN of the biosolids sample from the experiment based on the computer simulation was 63.8 kg ha^{-1} (57 lb $acre^{-1}$) (J. T. Gilmour, 1997, personal communication). The computer simulated PAN was 25 percent of the 253 kg N ha^{-1} (226 lb N $acre^{-1}$) PAN calculated for the composition of dewatered biosolids using the formula established by the IEPA. The estimated mineralization rate of organic N in the aged, dewatered, anaerobically digested biosolids based on computer simulation was about 5 percent, and this is an important factor which needs to be assessed in determining appropriate biosolids application rates for crop production on agricultural land and in more stressful situations such as mine spoil and other disturbed lands.

The extremely heterogeneous mine spoil imposes physical and chemical factors on plant growth not normally observed in productive agricultural soils. Applying biosolids in amounts greater than the PAN requirements to mine spoil, as done in this study, will not result in grain yields projected for productive agricultural soils unless other mine spoil and environmental factors are not limiting.

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APPENDIX

ASSUMPTION OF VALIDITY TESTS AND ANALYSIS OF VARIANCE (ANOVA) FOR EQUAL TREATMENT MEANS AND DUNNETT STATISTICS OF TREATMENTS FROM CONTROL FOR CORN GRAIN AND STOVER YIELDS; CORN LEAF NITROGEN, PHOSPHORUS, AND POTASSIUM CONCENTRATIONS; AND TOTAL NITROGEN, PHOSPHORUS, AND POTASSIUM UPTAKE BY CORN

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TABLE AI-1

ASSUMPTION VALIDITY TESTS AND ANALYSIS OF VARIANCE (ANOVA) FOR EQUAL TREATMENT MEANS AND DUNNETT STATISTICS OF TREATMENTS FROM CONTROL ON ANNUAL CORN GRAIN YIELDS ON BIOSOLIDS-AMENDED CALCAREOUS MINE SOIL

		Dunnett's Statistic (T) (Calculated from control)			**Assumption Test**		P Value ANOVA		
Year	$D_\alpha(E,V)$[1]	T 1/4 Max	T 1/2 Max	T Max	**P Value Normal**	**P Value Bartlett**	Actual Values	Rank	Applied
				Liquid Biosolids Application (Mg/ha)					
1973	2.68 (12,3)	1.85	1.51	1.42	**1.00**	**0.74**	0.31	0.54	0.31
1974	2.68 (12,3)	0.98	1.86	*3.76	**0.94**	**0.54**	0.02	0.01	0.02
1975	2.68 (12,3)	1.62	2.37	1.94	**0.96**	**0.85**	0.15	0.18	0.15
1976	2.68 (12,3)	*2.94	*2.92	1.73	**0.99**	**0.92**	0.04	0.05	0.04
1977	2.68 (12,3)	1.57	0.57	1.30	**1.00**	**0.37**	0.08	0.05	0.08
1978	2.68 (12,3)	*2.72	1.99	2.12	**0.81**	**0.50**	0.08	0.28	0.08
1980	2.68 (12,3)	0.54	0.40	1.95	**0.96**	**0.32**	0.09	0.15	0.10
1981	2.68 (12,3)	0.31	0.68	0.62	**0.73**	**0.40**	0.71	0.89	0.71
1982	2.68 (12,3)	0.92	1.87	2.51	**0.98**	**0.96**	0.12	0.12	0.12
1983	2.68 (12,3)	0.57	1.18	0.96	**0.74**	**0.07**	0.29	0.13	0.29
1984	2.68 (12,3)	1.76	*3.31	*5.54	**0.98**	**0.64**	0.00	0.00	0.00
				Dewatered Biosolids Application (Mg/ha)					
1985	2.68 (12,3)	*3.28	*5.37	*5.82	**0.90**	**0.92**	0.00	0.00	0.00
1986	2.68 (12,3)	0.26	0.03	1.37	**0.25**	**0.22**	0.39	0.47	0.39
1987	2.68 (12,3)	0.29	0.58	1.17	**1.00**	**0.96**	0.50	0.53	0.50
1988	2.68 (12,3)	1.03	2.01	*2.98	**0.94**	**0.55**	0.06	0.03	0.06
1989	2.68 (12,3)	*4.92	*6.59	*5.47	**0.95**	**0.98**	0.00	0.00	0.00
1990	2.68 (12,3)	2.64	2.37	1.03	**0.79**	**0.98**	0.01	0.01	0.01
1991	2.76 (10,3)	0.18	1.19	*4.06	**0.24**	**0.05**	0.01	0.01	0.01
1992	2.68 (12,3)	1.59	0.45	0.73	**0.45**	**0.42**	0.47	0.58	0.47
1993	2.68 (12,3)	1.34	0.04	*4.06	**0.47**	**0.34**	0.00	0.00	0.00
1994	2.68 (12,3)	2.37	1.48	0.48	**1.00**	**0.89**	0.05	0.06	0.05
1995	2.68 (12,3)	0.17	1.36	2.03	**0.61**	**0.15**	0.19	0.23	0.18
				Summary of Treatment Means (Mg/ha)					
Liquid Biosolids	2.36 (172,3)	0.81	1.93	*2.82	**0.82**	**0.88**	0.03	0.00	0.03
Dewatered Biosolids	2.36 (170,3)	0.90	0.59	*2.72	**0.00**	**0.77**	0.00	0.00	0.00
All Years	2.36 (346,3)	0.28	1.54	*3.84	**0.06**	**0.73**	0.00	0.00	0.00

[1]Dunnett's tabular value at $\alpha = 0.05$
(E = error DF, V = number of treatments compared with control).
*Corresponding treatment mean is significantly different from control mean.

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TABLE AI-2

ASSUMPTION VALIDITY TESTS AND ANALYSIS OF VARIANCE (ANOVA) FOR EQUAL TREATMENT MEANS AND DUNNETT STATISTICS OF TREATMENTS FROM CONTROL ON ANNUAL CORN STOVER YIELDS ON BIOSOLIDS-AMENDED CALCAREOUS MINE SOIL

Year	$D_\alpha(E,V)$[1]	Dunnett's Statistic (T) (Calculated from control)			**Assumption Test**		P Value ANOVA		
		T 1/4 Max	T 1/2 Max	T Max	**P Value Normal**	**P Value Bartlett**	Actual Values	Rank	Applied
				Liquid Biosolids Application (Mg/ha)					
1974	2.68 (12,3)	0.34	1.79	*2.73	**1.00**	**0.83**	0.06	0.06	0.06
1975	2.68 (12,3)	0.30	0.38	0.27	**0.93**	**0.34**	0.98	0.68	0.98
1976	2.68 (12,3)	0.43	0.35	0.53	**1.00**	**0.42**	0.77	0.84	0.77
1977	2.68 (12,3)	1.49	1.78	2.49	**0.85**	**0.42**	0.14	0.25	0.14
1978	2.68 (12,3)	0.31	1.60	2.15	**0.79**	**0.53**	0.15	0.11	0.15
1980	2.68 (12,3)	0.11	0.04	0.25	**1.00**	**0.44**	0.99	0.94	0.98
1981	2.68 (12,3)	0.90	0.22	0.39	**0.99**	**0.59**	0.64	0.63	0.64
1982	2.68 (12,3)	0.29	0.93	1.03	**0.95**	**0.13**	0.69	0.83	0.69
1983	2.68 (12,3)	0.67	*3.53	*3.59	**1.00**	**0.87**	0.00	0.00	0.00
1984	2.68 (12,3)	0.96	2.06	*4.75	**0.99**	**0.14**	0.00	0.00	0.00
				Dewatered Biosolids Application (Mg/ha)					
1985	2.68 (12,3)	*2.73	*3.38	*3.71	**1.00**	**0.90**	0.01	0.01	0.01
1986	2.68 (12,3)	0.07	0.90	2.56	**0.99**	**0.77**	0.08	0.07	0.08
1987	2.68 (12,3)	0.27	0.64	0.55	**0.98**	**0.64**	0.70	0.83	0.70
1988	2.68 (12,3)	0.48	1.67	1.77	**0.90**	**0.33**	0.25	0.14	0.25
1989	2.68 (12,3)	0.34	1.42	0.11	**0.88**	**0.12**	0.49	0.14	0.49
1990	2.68 (12,3)	*2.86	*3.17	0.98	**1.00**	**0.46**	0.02	0.04	0.02
1991	2.68 (12,3)	0.56	0.23	1.96	**0.42**	**0.38**	0.10	0.31	0.10
1992	2.68 (12,3)	1.38	0.26	1.45	**1.00**	**0.50**	0.23	0.18	0.24
1993	2.68 (12,3)	2.24	0.49	*4.36	**0.98**	**0.65**	0.00	0.00	0.00
1994	2.68 (12,3)	2.47	1.72	0.69	**1.00**	**0.63**	0.03	0.02	0.03
1995	2.68 (12,3)	0.16	0.18	1.53	**0.96**	**0.98**	0.42	0.52	0.42
				Summary of Treatment Means (Mg/ha)					
Liquid Biosolids	2.36 (156,3)	0.42	1.69	*2.54	**0.80**	**0.83**	0.05	0.00	0.05
Dewatered Biosolids	2.36 (172,3)	1.51	0.48	*2.55	**0.71**	**0.53**	0.00	0.00	0.00
All Years	2.36 (332,3)	0.79	0.76	*3.40	**0.56**	**0.94**	0.00	0.00	0.00

[1]Dunnett's tabular value at $\alpha = 0.05$
(E = error DF, V = number of treatments compared with control).
*Corresponding treatment mean is significantly different from control mean.

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TABLE AI-3

ASSUMPTION VALIDITY TESTS AND ANALYSIS OF VARIANCE (ANOVA) FOR EQUAL TREATMENT MEANS AND DUNNETT STATISTICS OF TREATMENTS FROM CONTROL ON ANNUAL LEAF NITROGEN ON BIOSOLIDS-AMENDED CALCAREOUS MINE SOIL

		Dunnett's Statistic (T) (Calculated from control)			**Assumption Test**		P Value ANOVA		
Year	$D_{\alpha}(E,V)$[1]	T 1/4 Max	T 1/2 Max	T Max	**P Value Normal**	**P Value Bartlett**	Actual Values	Rank	Applied
				Liquid Biosolids Application (g/ha)					
1973	2.68 (12,3)	0.63	0.42	*3.34	**0.96**	**0.31**	0.00	0.01	0.00
1974	2.68 (12,3)	*3.71	*4.80	*5.02	**0.99**	**0.78**	0.00	0.00	0.00
1975	2.68 (12,3)	0.25	0.00	0.25	**1.00**	**0.67**	0.97	1.00	0.97
1976	2.68 (12,3)	1.02	0.74	0.74	**0.83**	**0.47**	0.76	0.69	0.76
1977	2.68 (12,3)	0.34	0.51	*2.89	**0.97**	**0.90**	0.03	0.07	0.03
1978	2.68 (12,3)	1.09	0.37	0.56	**0.42**	**0.05**	0.70	0.39	**0.39
1979	2.68 (12,3)	0.15	0.04	1.63	**0.75**	**0.74**	0.35	0.48	0.35
1980	2.68 (12,3)	1.05	0.73	0.89	**0.92**	**0.70**	0.27	0.16	0.27
1981	2.68 (12,3)	0.83	0.22	0.79	**1.00**	**0.44**	0.47	0.44	0.46
1982	2.68 (12,3)	2.20	0.40	0.75	**0.95**	**0.55**	0.07	0.02	0.07
1983	2.68 (12,3)	2.39	1.35	1.35	**0.98**	**0.37**	0.19	0.17	0.19
1984	2.68 (12,3)	0.99	1.05	0.62	**1.00**	**0.99**	0.73	0.89	0.73
				Dewatered Biosolids Application (g/ha)					
1985	2.68 (12,3)	0.35	0.18	0.96	**0.99**	**0.12**	0.79	0.71	0.79
1986	2.68 (12,3)	1.44	0.51	0.92	**0.82**	**0.28**	0.56	0.56	0.56
1987	2.68 (12,3)	1.64	1.93	0.82	**0.94**	**0.61**	0.25	0.19	0.25
1988	2.68 (12,3)	1.22	*3.08	2.15	**0.73**	**0.26**	0.05	0.05	0.05
1989	2.68 (12,3)	1.69	0.24	1.09	**0.99**	**0.46**	0.34	0.33	0.34
1990	2.68 (12,3)	*3.82	2.43	0.46	**0.72**	**0.19**	0.01	0.03	0.01
1991	2.68 (12,3)	*4.24	2.01	2.01	**1.00**	**0.48**	0.01	0.01	0.01
1992	2.68 (12,3)	2.24	0.80	0.37	**0.52**	**0.70**	0.19	0.20	0.19
1993	2.68 (12,3)	1.27	0.56	2.13	**0.99**	**0.85**	0.04	0.05	0.04
1994	2.68 (12,3)	*6.97	*5.18	*3.51	**0.97**	**0.86**	0.00	0.00	0.00
1995	2.68 (12,3)	0.10	1.04	0.64	**1.00**	**0.64**	0.69	0.78	0.69
				Summary of Treatment Means (g/ha)					
Liquid Biosolids	2.36 (188,3)	2.02	0.84	2.19	**0.57**	**0.94**	0.00	0.00	0.00
Dewatered Biosolids	2.36 (172,3)	*2.88	1.89	0.91	**0.01**	**0.21**	0.03	0.00	0.03
All Years	2.36 (364,3)	*2.70	1.57	0.11	**0.00**	**0.09**	0.01	0.00	0.01

[1]Dunnett's tabular value at $\alpha = 0.05$
(E = error DF, V = number of treatments compared with control).
*Corresponding treatment mean is significantly different from control mean.
**ANOVA and Dunnett tests are based on rank.

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

TABLE AI-4

ASSUMPTION VALIDITY TESTS AND ANALYSIS OF VARIANCE (ANOVA) FOR EQUAL TREATMENT MEANS AND DUNNETT STATISTICS OF TREATMENTS FROM CONTROL ON ANNUAL LEAF PHOSPHORUS ON BIOSOLIDS-AMENDED CALCAREOUS MINE SOIL

		Dunnett's Statistic (T) (Calculated from control)			**Assumption Test**		P Value ANOVA[2]		
Year	$D_\alpha(E,V)$[1]	T 1/4 Max	T 1/2 Max	T Max	**P Value Normal**	**P Value Bartlett**	Actual Values	Rank	Applied
		Liquid Biosolids Application (mg/kg)							
1973	2.68 (12,3)	2.06	2.23	0.33	**0.78**	**0.29**	0.10	0.04	0.10
1974	2.68 (12,3)	*4.89	*4.60	*4.75	**0.26**	**0.69**	0.00	0.01	0.00
1975	2.68 (12,3)	0.17	2.46	1.76	**0.49**	**0.18**	0.08	0.06	0.08
1976	2.68 (12,3)	1.66	2.02	1.79	**0.95**	**0.38**	0.22	0.08	0.22
1977	2.68 (12,3)	0.64	0.24	1.14	**0.95**	**0.22**	0.53	0.46	0.53
1978	2.68 (12,3)	0.10	0.53	0.79	**0.78**	**0.56**	0.78	0.75	0.78
1979	2.68 (12,3)	*3.53	*2.99	0.67	**0.97**	**0.66**	0.01	0.00	0.01
1980	2.68 (12,3)	0.85	0.27	1.93	**1.00**	**0.79**	0.08	0.04	0.08
1981	2.68 (12,3)	0.33	0.51	1.28	**1.00**	**0.97**	0.43	0.36	0.43
1982	2.68 (12,3)	0.94	1.08	1.49	**0.88**	**0.78**	0.12	0.12	0.12
1983	2.68 (12,3)	*3.82	*3.06	1.37	**0.95**	**0.81**	0.01	0.00	0.01
1984	2.68 (12,3)	0.91	1.06	0.33	**0.84**	**0.31**	0.46	0.44	0.46
		Dewatered Biosolids Application (mg/kg)							
1985	2.68 (12,3)	0.04	0.22	0.58	**0.93**	**0.06**	0.94	0.84	0.94
1986	2.68 (12,3)	0.62	0.42	0.98	**1.00**	**0.65**	0.42	0.35	0.42
1987	2.68 (12,3)	1.99	*2.85	1.01	**1.00**	**1.00**	0.07	0.05	0.07
1988	2.68 (12,3)	1.25	1.44	0.60	**0.98**	**0.91**	0.49	0.63	0.49
1989	2.68 (12,3)	1.96	0.98	1.80	**1.00**	**0.79**	0.23	0.28	0.24
1990	2.68 (12,3)	2.27	2.68	0.29	**0.53**	**0.20**	0.02	0.05	0.02
1991	2.68 (12,3)	1.80	0.86	1.63	**0.94**	**0.88**	0.03	0.03	0.03
1992	2.68 (12,3)	1.85	1.29	0.37	**0.76**	**0.74**	0.28	0.28	0.28
1993	2.68 (12,3)	0.05	1.03	0.69	**0.82**	**0.48**	0.69	0.25	0.69
1994	2.68 (12,3)	0.06	0.34	1.24	**0.59**	**0.15**	0.43	0.64	0.43
1995	2.68 (12,3)	1.96	1.42	1.09	**0.91**	**0.55**	0.04	0.05	0.04
		Summary of Treatment Means (mg/kg)							
Liquid Biosolids	2.36 (188,3)	*4.91	*3.69	1.36	**0.00**	**0.00**	0.00	0.00	**0.00
Dewatered Biosolids	2.36 (172,3)	0.16	0.53	0.40	**0.00**	**0.69**	0.89	0.24	0.89
All Years	2.36 (364,3)	1.41	1.85	1.22	**0.00**	**0.79**	0.29	0.00	0.29

[1]Dunnett's tabular value at α = 0.05
(E = error DF, V = number of treatments compared with control).
[2]All statistics and ANOVA are based on log of yields.
*Corresponding treatment mean is significantly different from control mean.
**ANOVA and Dunnett tests are based on rank.

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

TABLE AI-5

ASSUMPTION VALIDITY TESTS AND ANALYSIS OF VARIANCE (ANOVA) FOR EQUAL TREATMENT MEANS AND DUNNETT STATISTICS OF TREATMENTS FROM CONTROL ON ANNUAL LEAF POTASSIUM ON BIOSOLIDS-AMENDED CALCAREOUS MINE SOIL

		Dunnett's Statistic (T) (Calculated from control)			Assumption Test		P Value ANOVA[2]		
Year	$D_{\alpha}(E,V)$[1]	T 1/4 Max	T 1/2 Max	T Max	**P Value Normal**	**P Value Bartlett**	Actual Values	Rank	Applied
				Liquid Biosolids Application (g/kg)					
1973	2.68 (12,3)	1.82	1.11	1.75	**0.99**	**0.52**	0.28	0.10	0.28
1974	2.68 (12,3)	1.35	0.86	1.84	**0.71**	**0.71**	0.04	0.02	0.04
1975	2.68 (12,3)	0.32	0.37	1.00	**0.99**	**0.48**	0.79	0.93	0.79
1976	2.68 (12,3)	0.10	0.72	0.62	**1.00**	**0.88**	0.66	0.80	0.66
1977	2.68 (12,3)	1.02	0.93	1.67	**0.92**	**0.92**	0.45	0.42	0.45
1980	2.68 (12,3)	0.96	1.83	1.73	**1.00**	**0.29**	0.27	0.17	0.27
1981	2.68 (12,3)	0.30	0.69	1.19	**0.80**	**1.00**	0.31	0.48	0.31
1982	2.68 (12,3)	0.91	0.58	0.25	**0.99**	**0.58**	0.65	0.76	0.65
1983	2.68 (12,3)	0.20	0.41	1.42	**1.00**	**0.58**	0.29	0.23	0.29
1984	2.68 (12,3)	0.93	0.74	2.31	**0.83**	**0.51**	0.04	0.04	0.04
				Dewatered Biosolids Application (g/kg)					
1985	2.68 (12,3)	1.50	0.50	0.33	**1.00**	**0.41**	0.51	0.79	0.51
1986	2.68 (12,3)	1.30	1.07	0.47	**0.89**	**0.76**	0.62	0.80	0.62
1987	2.68 (12,3)	1.48	0.94	1.34	**0.70**	**0.86**	0.06	0.01	0.06
1988	2.68 (12,3)	0.30	0.77	1.53	**1.00**	**0.89**	0.30	0.36	0.30
1989	2.68 (12,3)	1.85	2.65	0.26	**0.92**	**0.55**	0.03	0.01	0.03
1990	2.68 (12,3)	1.07	0.15	0.31	**1.00**	**0.46**	0.52	0.70	0.52
1991	2.68 (12,3)	*3.82	1.85	0.72	**0.99**	**0.79**	0.01	0.01	0.01
1992	2.68 (12,3)	0.89	0.97	0.15	**0.97**	**0.41**	0.36	0.25	0.36
1993	2.68 (12,3)	1.88	1.73	*4.04	**1.00**	**0.59**	0.01	0.01	0.01
1994	2.68 (12,3)	0.29	0.15	1.23	**1.00**	**0.65**	0.52	0.64	0.52
1995	2.68 (12,3)	0.55	0.43	0.49	**1.00**	**0.30**	0.74	0.82	0.74
				Summary of Treatment Means (g/kg)					
Liquid Biosolids	2.36 (156,3)	0.00	0.00	1.18	**0.03**	**0.42**	0.59	0.05	0.59
Dewatered Biosolids	2.36 (172,3)	1.50	0.56	1.31	**0.44**	**0.17**	0.07	0.00	0.07
All Years	2.36 (332,3)	0.56	0.00	1.67	**0.01**	**0.27**	0.11	0.00	0.11

[1]Dunnett's tabular value at $\alpha = 0.05$
(E = error DF, V = number of treatments compared with control).
[2]All statistics and ANOVA are based on log of yields.
*Corresponding treatment mean is significantly different from control mean.

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

TABLE AI-6

ASSUMPTION VALIDITY TESTS AND ANALYSIS OF VARIANCE (ANOVA) FOR EQUAL TREATMENT MEANS AND DUNNETT STATISTICS OF TREATMENTS FROM CONTROL ON ANNUAL TOTAL NITROGEN UPTAKE BY CORN ON BIOSOLIDS-AMENDED CALCAREOUS MINE SOIL

Year	$D_\alpha(E,V)$[1]	Dunnett's Statistic (T) (Calculated from control)			**Assumption Test**		P Value ANOVA[2]		
		T 1/4 Max	T 1/2 Max	T Max	**P Value Normal**	**P Value Bartlett**	Actual Values	Rank	Applied
				Liquid Biosolids Application (kg/ha)					
1974	2.68 (12,3)	1.28	1.48	*4.38	**1.00**	**0.72**	0.01	0.01	0.01
1975	2.68 (12,3)	0.18	0.25	0.75	**0.89**	**0.67**	0.81	0.75	0.81
1976	2.68 (12,3)	2.01	1.55	1.19	**1.00**	**0.99**	0.27	0.34	0.27
1977	2.68 (12,3)	0.40	0.85	2.13	**0.99**	**0.38**	0.22	0.31	0.22
1978	2.68 (12,3)	1.05	0.79	2.29	**1.00**	**0.91**	0.04	0.03	0.04
1980	2.68 (12,3)	1.41	2.11	*3.88	**1.00**	**0.80**	0.01	0.01	0.02
1981	2.68 (12,3)	1.06	0.65	1.24	**1.00**	**0.28**	0.18	0.06	0.18
1982	2.68 (12,3)	0.08	1.90	2.68	**1.00**	**0.69**	0.05	0.01	0.05
1983	2.68 (12,3)	0.05	2.28	*4.09	**0.99**	**0.52**	0.00	0.00	0.00
1984	2.68 (12,3)	1.33	*3.34	*6.47	**0.97**	**0.64**	0.00	0.00	0.00
				Dewatered Biosolids Application (kg/ha)					
1985	2.68 (12,3)	2.07	*5.25	*5.30	**1.00**	**0.47**	0.00	0.00	0.00
1986	2.68 (12,3)	0.44	0.24	1.28	**0.36**	**0.12**	0.35	0.27	0.35
1987	2.68 (12,3)	2.44	1.54	0.05	**1.00**	**0.50**	0.08	0.04	0.08
1988	2.68 (12,3)	1.97	2.19	2.53	**0.93**	**0.57**	0.10	0.09	0.10
1989	2.68 (12,3)	0.85	2.64	2.18	**1.00**	**0.78**	0.08	0.08	0.08
1990	2.68 (12,3)	*3.90	*4.35	1.19	**0.50**	**0.56**	0.00	0.00	0.00
1991	2.76 (10,3)	0.98	0.87	*3.18	**0.57**	**0.16**	0.01	0.00	0.01
1992	2.68 (12,3)	*3.25	2.01	1.37	**1.00**	**0.41**	0.04	0.03	0.04
1993	2.68 (12,3)	0.92	0.37	*4.30	**0.59**	**0.37**	0.00	0.00	0.00
1994	2.68 (12,3)	*3.30	2.57	0.50	**0.29**	**0.12**	0.02	0.01	0.02
1995	2.88 (8,3)	0.41	0.60	1.01	**1.00**	**0.95**	0.61	0.59	0.61
				Summary of Treatment Means (kg/ha)					
Liquid Biosolids	2.36 (156,3)	0.45	*2.37	*4.57	**0.66**	**0.07**	0.00	0.00	0.00
Dewatered Biosolids	2.36 (166,3)	1.90	0.66	1.51	**0.13**	**0.32**	0.01	0.00	0.01
All Years	2.36 (326,3)	2.36	1.35	*6.87	**0.39**	**0.01**	0.00	0.00	**0.00

[1]Dunnett's tabular value at $\alpha = 0.05$
(E = error DF, V = number of treatments compared with control).
[2]All statistics and ANOVA are based on log of yields.
*Corresponding treatment mean is significantly different from control mean.
**ANOVA and Dunnett tests are based on rank.

TABLE AI-7

ASSUMPTION VALIDITY TESTS AND ANALYSIS OF VARIANCE (ANOVA) FOR EQUAL TREATMENT MEANS AND DUNNETT STATISTICS OF TREATMENTS FROM CONTROL ON ANNUAL TOTAL PHOSPHORUS UPTAKE BY CORN ON BIOSOLIDS-AMENDED CALCAREOUS MINE SOIL

Year	$D_{\alpha}(E,V)$[1]	Dunnett's Statistic (T) (Calculated from control)			Assumption Test		P Value ANOVA[2]		
		T 1/4 Max	T 1/2 Max	T Max	**P Value Normal**	**P Value Bartlett**	Actual Values	Rank	Applied
				Liquid Biosolids Application (kg/ha)					
1974	2.68 (12,3)	0.30	0.61	1.52	**1.00**	**0.45**	0.33	0.41	0.33
1975	2.68 (12,3)	0.83	0.71	0.36	**0.98**	**0.71**	0.83	0.63	0.83
1976	2.68 (12,3)	1.69	0.34	0.28	**1.00**	**0.72**	0.26	0.27	0.26
1977	2.68 (12,3)	0.71	0.50	0.96	**1.00**	**0.41**	0.37	0.20	0.37
1978	2.68 (12,3)	1.09	0.23	1.67	**1.00**	**0.46**	0.11	0.14	0.11
1980	2.68 (12,3)	0.45	1.31	*4.54	**1.00**	**0.58**	0.00	0.01	0.00
1981	2.68 (12,3)	0.08	1.59	*2.98	**0.99**	**0.63**	0.04	0.01	0.04
1982	2.68 (12,3)	0.17	1.52	*3.22	**1.00**	**0.89**	0.03	0.03	0.02
1983	2.68 (12,3)	0.40	1.78	*2.99	**0.94**	**0.37**	0.02	0.02	0.02
1984	2.68 (12,3)	1.30	*3.83	*7.26	**1.00**	**0.93**	0.00	0.00	0.00
				Dewatered Biosolids Application (kg/ha)					
1985	2.68 (12,3)	*3.11	*7.77	*9.02	**1.00**	**0.94**	0.00	0.00	0.00
1986	2.68 (12,3)	0.34	0.02	1.36	**0.55**	**0.35**	0.38	0.42	0.38
1987	2.68 (12,3)	1.13	0.60	0.13	**1.00**	**0.36**	0.56	0.39	0.56
1988	2.68 (12,3)	2.46	2.46	*3.22	**0.65**	**0.52**	0.04	0.08	0.04
1989	2.68 (12,3)	*2.87	*4.43	*3.12	**1.00**	**0.92**	0.01	0.00	0.01
1990	2.68 (12,3)	*3.44	*3.00	0.37	**0.94**	**0.72**	0.01	0.01	0.01
1991	2.76 (10,3)	0.37	0.18	*3.07	**0.95**	**0.38**	0.03	0.03	0.03
1992	2.68 (12,3)	2.27	1.43	1.22	**0.91**	**0.12**	0.20	0.16	0.20
1993	2.68 (12,3)	1.46	0.53	*4.88	**0.54**	**0.88**	0.00	0.00	0.00
1994	2.68 (12,3)	0.83	0.60	1.78	**0.94**	**0.99**	0.09	0.15	0.09
1995	2.88 (8,3)	0.15	0.79	1.18	**1.00**	**0.90**	0.61	0.59	0.61
				Summary of Treatment Means (kg/ha)					
Liquid Biosolids	2.36 (156,3)	0.07	1.59	*3.93	**0.77**	**0.06**	0.00	0.00	0.00
Dewatered Biosolids	2.36 (166,3)	*2.37	0.00	*3.24	**0.02**	**0.01**	0.00	0.00	**0.00
All Years	2.36 (326,3)	1.76	1.42	*6.56	**0.06**	**0.00**	0.00	0.00	**0.00

[1]Dunnett's tabular value at $\alpha = 0.05$
(E = error DF, V = number of treatments compared with control).
[2]All statistics and ANOVA are based on log of yields.
*Corresponding treatment mean is significantly different from control mean.
**ANOVA and Dunnett tests are based on rank.

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

TABLE AI-8

ASSUMPTION VALIDITY TESTS AND ANALYSIS OF VARIANCE (ANOVA) FOR EQUAL TREATMENT MEANS AND DUNNETT STATISTICS OF TREATMENTS FROM CONTROL ON ANNUAL TOTAL POTASSIUM UPTAKE BY CORN ON BIOSOLIDS-AMENDED CALCAREOUS MINE SOIL

		Dunnett's Statistic (T) (Calculated from control)			Assumption Test		P Value ANOVA[2]		
Year	$D_\alpha(E,V)$[1]	T 1/4 Max	T 1/2 Max	T Max	**P Value Normal**	**P Value Bartlett**	Actual Values	Rank	Applied
				Liquid Biosolids Application (kg/ha)					
1974	2.68 (12,3)	0.57	1.94	*4.45	**0.95**	**0.81**	0.00	0.00	0.00
1975	2.68 (12,3)	0.57	0.21	0.75	**0.99**	**0.98**	0.87	0.97	0.87
1976	2.68 (12,3)	0.99	1.56	0.15	**0.99**	**0.93**	0.31	0.21	0.31
1977	2.68 (12,3)	0.00	0.70	*2.77	**0.96**	**0.62**	0.05	0.07	0.05
1980	2.68 (12,3)	1.13	0.52	1.24	**1.00**	**0.23**	0.16	0.14	0.16
1981	2.68 (12,3)	0.90	0.31	1.63	**1.00**	**0.81**	0.14	0.07	0.14
1982	2.68 (12,3)	0.11	0.01	2.31	**1.00**	**0.95**	0.09	0.14	0.09
1983	2.68 (12,3)	0.15	1.67	*4.11	**0.96**	**0.99**	0.00	0.01	0.00
1984	2.68 (12,3)	1.09	*2.71	*6.06	**0.94**	**0.86**	0.00	0.00	0.00
				Dewatered Biosolids Application (kg/ha)					
1985	2.68 (12,3)	1.52	*4.19	*5.19	**1.00**	**0.35**	0.00	0.00	0.00
1986	2.68 (12,3)	0.26	0.46	1.67	**0.86**	**0.76**	0.18	0.10	0.18
1987	2.68 (12,3)	1.13	0.65	0.39	**0.93**	**0.19**	0.47	0.26	0.46
1988	2.68 (12,3)	1.11	2.00	2.16	**0.75**	**0.41**	0.17	0.16	0.17
1989	2.68 (12,3)	0.69	1.55	0.72	**1.00**	**0.07**	0.19	0.15	0.19
1990	2.68 (12,3)	*3.44	*3.35	0.25	**0.80**	**0.82**	0.00	0.01	0.00
1991	2.76 (10,3)	0.45	0.04	2.10	**0.91**	**0.45**	0.13	0.56	0.13
1992	2.68 (12,3)	2.60	0.44	2.40	**0.90**	**0.17**	0.02	0.00	0.02
1993	2.68 (12,3)	1.52	0.08	*5.13	**0.66**	**0.69**	0.00	0.00	0.00
1994	2.68 (12,3)	1.99	0.75	0.41	**0.08**	**0.01**	0.53	0.14	**0.14
1995	2.88 (8,3)	0.31	0.69	1.03	**1.00**	**0.92**	0.63	0.63	0.63
				Summary of Treatment Means (kg/ha)					
Liquid Biosolids	2.36 (140,3)	0.11	1.20	*3.58	**0.45**	**0.54**	0.00	0.00	0.00
Dewatered Biosolids	2.36 (166,3)	*3.87	0.30	1.91	**0.01**	**0.00**	0.03	0.00	**0.00
All Years	2.36 (310,3)	*3.03	1.66	*5.39	**0.02**	**0.00**	0.00	0.00	**0.00

[1]Dunnett's tabular value at $\alpha = 0.05$
(E = error DF, V = number of treatments compared with control).
[2]All statistics and ANOVA are based on log of yields.
*Corresponding treatment mean is significantly different from control mean.
**ANOVA and Dunnett tests are based on rank.