AN ABSTRACT OF THE THESIS OF

___Mark Edward Mellbye___ for the degree of ___Master of Science___

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Title: ___Incinerated Sewage Sludge Use as a Soil Amendment for Sweet Corn___

___(Zea mays L.)___

Redacted for Privacy

Abstract approved: _____ _____
V. V. Volk

Field and greenhouse experiments were conducted to determine the
suitability of using incinerated sewage sludge ash as a soil amendment
for sweet corn production on Willamette silt loam.

In 1977, field plots were treated with 0, 11, 22, and 43 mt/ha of
ash containing lime, in factorial combination with a P fertilizer vari-
able (0 or 90 kg/ha P). In 1978, additional ash containing alum was
applied to P fertilized plots only, resulting in cumulative ash rates
of 27, 53, and 106 mt/ha. Sweet corn was grown both years and NH_4NO_3
and NH_4SO_4 fertilizer was applied to provide N.

Ash samples contained between 9 and 18% P_2O_5 and from 2 to 34%
$CaCO_3$ equivalence. Elements assayed for in the waste and found in
excess of 1% included Ca, P, Fe, and Al. Metals found in concentra-
tions ranging from 0.1 to 1% were Mg, K, Na, Zn, Pb, Mn, Cu, and Cr;
while Ni, B, Cd, and Mo concentrations were less than 300 µg/g.

Soil pH increased from 5.3 to 6.0 with the highest ash application.
Exchangeable Ca and available P; total P, Zn, Cd, Cu, Ni, Pb, and Cr;
and DTPA-extractable Zn, Cd, Cu, and Pb content of the surface soil

(0-15 cm) increased with ash applications. DTPA-extractable Mn decreased with waste addition while extractable Ni and Cr, and exchangeable Mg, K, and Na were not measurably affected. Water extracted a small portion (<0.5%) of the total Zn, Cd, Cu, Ni, Cr, and Pb in the surface soil and no trace metal movement below the 30 cm soil depth was detected, suggesting trace metal enrichment in the soil did not represent a source of groundwater contamination.

Silage and mature ear yield increased in 1978 from 65 and 13 mt/ha, respectively, on the P fertilized control soil, to 78 and 17 mt/ha, respectively, when 106 mt/ha of ash was applied. Mature ear yield and leaf P content increased both with ash application and with P fertilizer treatments, suggesting a P response from the ash additions.

The corn tissues contained a normal content of the elements assayed on both control and waste-treated soil. The Zn, Ca, Mg, P, B, and possibly Mo concentration in the leaves increased, while K and Mn contents decreased, with waste application. The Cd content of the leaves increased slightly with ash application in 1977 (from 0.26 to 0.35 µg/g) but not in 1978. The Cu, Cr, Pb, Na, and Ni concentration in the leaves and most elements assayed in the kernels and silage were largely unaffected by ash applications.

In a greenhouse experiment, corn was grown on two pure ashes (low and high in water extractable Cr) and on Willamette soil amended with the ashes at rates which applied 0, 280, 560, 1120, and 2240 kg/ha of Zn. All pots received 56 kg/ha/week of N applied as NH_4NO_3 and NH_4SO_4. Corn grown on the ash which contained 12.5 µg/g of water extractable Cr was severely stunted and chlorotic, while corn plants grown on pure ash with only 0.054 µg/g of extractable Cr grew comparably to plants grown

on control soils. If Cr toxicity was the cause of poor growth on the ash high in water extractable Cr, the problem was ameliorated when ash was mixed with soil, since corn plant yield on soil amended with either ash exceeded plant yield on the P fertilized control soil. Plant yields were greatest when ash was applied at rates which approximated the maximum allowable Zn addition (560 kg/ha), suggesting that for optimum corn growth, ash applications could be regulated by the USEPA (1977) guidelines for Zn addition.

Utilization of incinerated sewage sludge ash as a soil amendment for sweet corn production on Willamette silt loam was a feasible waste management alternative.

Incinerated Sewage Sludge Use as a Soil
Amendment for Sweet Corn (<u>Zea</u> <u>mays</u> L.)

by

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INTRODUCTION

Municipal wastewater treatment and sludge disposal is a major

environmental problem in the United States. Ocean dumping or discharge

of sewage into navigable rivers and lakes is no longer acceptable.

Alternatively, the Amended Federal Water Pollution Control Act of 1972

(U.S. Congress, 1972) encourages recycling of potential nutrients in

sewage on land.

Sewage sludges contain major (N, P, K, S, Ca, Mg) and minor (Zn,

Cu, Mn, Fe, Mo, B) plant nutrients, organic matter, and water. In

field and greenhouse experiments the yield of crops has increased with

application of sewage sludge to soil, the fertilizer value of the

sludges being ascribed primarily to their content of N and P (Anderson,

1955).

Accumulation of sludge trace elements (Zn, Cd, Cu, Ni, Pb, B, Se,

Cr, As, Ba, Co, Mn, V, Mo) in the soil is considered to be a potential

long-term hazard to crop productivity and/or quality from sewage sludge

applications to agricultural land (Page, 1974). Investigators in

England concluded that Zn, Cu, and Ni were the elements most likely to

cause plant toxicity problems when sewage sludge is used as a soil

additive (Webber, 1972). Cadmium is considered a serious threat to the

food chain on sludge-amended soil because it may be taken up by plants

to levels considered unsafe for human consumption (Chaney, 1973).

Sewage sludge-applied Mo and Se could accumulate in plants to levels

considered hazardous to certain foraging animals (Page, 1974). Sewage

sludge may also contain pathogenic organisms and possibly toxic organic

substances such as polychlorinated biphenyls and pesticides (USEPA,

1972). Because of possible hazards associated with sludge application

on land, or water pollution problems resulting from disposal in surface

waters, incineration was considered to be the sludge treatment and dis-

posal option with the "brightest future" in the early 1970s (Sludge

Treatment, Disposal and Utilization, 1971).

Incineration reduces sludge volume for ultimate disposal and pro-

duces a sterile ash in which pesticides and other organics have been

destroyed (USEPA, 1972). Virtually all the sludge N, S, C, Hg, and a

portion of the Pb and other trace metals are volatilized by incinera-

tion. Most sludge trace metals are more concentrated in the ash than

in the dewatered sludge, but are presumably converted by incineration

to less soluble oxides (USEPA, 1972).

Incinerated sewage sludge ashes have been described as "unique

fertilizers" which are rich in P and may contain lime (Sebastian, 1972).

However, crop growth and trace metal enrichment in soil-plant systems

on soil amended with sewage sludge ash has not been extensively studied.

Information has been published on trace element availability to

plants and mobility in soils following sewage sludge application; how-

ever, plant uptake and toxicity of trace metals applied to soils from

inorganic sources will probably be different than that applied from

sewage sludge (Cunningham et al., 1975a). Trace metals in sludge ashes

are not associated with organic matter and are probably in different

chemical forms than those in sludges. Hence, ash-applied trace metals

may also have different plant availability (and perhaps mobility) in

soil than metals found in wet sewage sludges.

OBJECTIVES

The general objective of this research project was to test the suitability of using incinerated sewage sludge ash[1] as a soil amendment for sweet corn production on Willamette silt loam. Specific objectives were:

(1) Determine the effect of ash applications on the yield and elemental composition of sweet corn;

(2) Determine the effect of ash applications on soil chemical properties and elemental content;

(3) Determine if ash constituents pose a threat to ground or surface water when incorporated with soil;

(4) Develop recommendations for suitable waste application rates.

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[1] Sewage sludge ash was provided by the Unified Sewerage Agency of Washington County, Oregon, and was produced in a multiple-hearth incinerator at the Durham facilities.

LITERATURE REVIEW

Incineration of Sewage Sludge

Anderson (1955) stated over two decades ago that removal of more organic constituents in raw sewage was essential for cleaner streams. Removed solids today, in the form of sewage sludge, still present an ultimate disposal problem. Incineration of sewage sludge was considered a plausible solution to this problem in the early 1970s, although high operation and maintenance costs today indicate incineration is the most expensive sludge treatment alternative (Ettlich, 1978).

A major motivating factor in developing incinerator technology for sewage treatment was that incineration reduced sludge volume to about 10% of the volume of dewatered sludge (Ettlich et al., 1978). Also, the remaining ash was free of pathogenic microorganisms (USEPA, 1972). Although air pollution was considered a potential problem, three test incinerators were able to achieve acceptably low emission concentrations for the common pollutants (particulates, NO_x, SO_2, and visible emissions) (USEPA, 1972).

Pesticides (aldrin, dieldrin, chlordane, DDD, DDT) and polychlorinated biphenyls (PCBs) were detected in sewage sludges by a U.S. Environmental Protection Agency Task Force, which evaluated incineration as an acceptable alternative to sea disposal (USEPA, 1972). As pesticides and PCBs were not found in the ash from incineration of these sludges, it was concluded that they were destroyed by incineration.

After measuring trace metal concentrations in sewage sludge, stack gases, and ash samples at several incinerators, it was concluded that

most trace metals would not disproportionately appear in stack gases because of volatilization, but would be converted to less soluble oxides and remain in the ash, or be removed by stack scrubbers or electrostatic precipitators and appear in the particulates (USEPA, 1972). In the Task Force study (USEPA, 1972), ash samples normally showed a higher concentration of trace metals when compared with the pre-incinerated sludges. A notable exception was Hg, which was not detectable in the ashes and presumed completely volatilzed. A portion of the Pb and other trace metals were also probably volatilized, but problems in stack emission sampling methods and analysis precluded a quantitative estimate of these losses.

In another study, Stevens et al. (1972) measured Pb contents of 49 and 15 µg/g on tree foliage surrounding two incinerators in Connecticut. Tree foliage in an adjacent rural area contained 6 µg/g of Pb, indicating that Pb volatilized during incineration of the sludge. The high figure in trees near the first incinerator reflected a closer proximity to a busy highway, since foliage of trees two miles distant along the same highway still contained 29 µg/g of Pb (attributed to exhaust from vehicles).

Chromium may be an exception to the Task Force (USEPA, 1972) conclusion that most trace metals will be converted to less soluble oxides. Olthof and Lancy (1978) state that a portion of the Cr(III) will be oxidized to the more toxic Cr(VI) during incineration of sludge. The oxide of Cr(VI) is soluble in water (Cotton and Wilkinson, 1972) and may represent a pollution hazard in landfill disposal of wastes containing Cr(VI) (Griffin et al., 1977).

The major components of sewage sludge ashes from various waste treatment plants in the United States were Si, Al, Fe, Ca, and P (Tables 1 and 2). The ashes were alkaline and mainly silt grain sized (Table 1). Minor elements at concentrations less than 1% but generally greater than 1000 µg/g in 13 sludge ashes included Zn, Mn, Pb, Cu, Cr, Ba, and Ti (Table 2, Gabler and Neyland, 1977).

Sebastian (1972) reported that some 50,000 mt of incinerated sewage sludge ash produced in Tokyo and Nagoya, Japan was auctioned to Japanese fertilizer companies at $2.42/mt. The ash contained 6.0% P_2O_5, 0.2% N, and 1.0% K_2O. Sebastian also pointed out that ash produced at the advanced waste water treatment program at South Lake Tahoe, California, is even richer in P (12.5% P_2O_5) and contains "30% lime ($CaCO_3$ equivalence) which would neutralize acid soils." Published reports evaluating sludge ash as a fertilizer are scant, although one report from Iran where Parsa and Lindsay (1972) amended a Zn deficient soil with sewage sludge ash indicated ash may serve as a Zn fertilizer. Maize yield and Zn content increased with ash application.

In summary, incineration reduces sewage sludge volume for ultimate disposal and produces a sterile ash free of organic materials and pathogens. Trace metals (except Hg) may be further concentrated in the ash compared to the dried sludge, therefore, use of sewage sludge ash as a soil amendment should include an evaluation of resultant trace metal levels in the soil-plant system. Considerable information is available on the plant availability and mobility of trace metals in soils from sewage sludge additions; however, ash trace metals are not

Table 1. Chemical composition and physical-chemical properties of sewage sludge ashes from several U.S. cities.[1]

Source of Ash	Chemical Composition											Ignition Loss
	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Free CaO	Na_2O	K_2O	B	P_2O_5	SO_3	
	%											
Pontiac (Mich.)	32.5	9.6	9.5	2.1	36.9	1.1	0.4	0.6	0.015	7.0	0.01	1.0
St. Paul (Minn.)	4.9	13.5	10.8	2.6	33.4	1.1	0.2	0.1	0.006	9.9	2.7	1.62
Kansas City (Mo.)	57.7	15.0	8.5	0.8	8.6	0.03	0.4	0.3	0.02	4.4	3.4	0.31
Saginaw (Mich.)	28.2	4.6	8.7	2.2	29.9	1.6	0.3	0.07	0.01	3.9	2.9	15.1
South Tahoe (Cal.)	23.9	16.3	3.4	2.1	29.8	1.2	0.7	0.1	0.02	6.9	2.8	2.5
Cromwell (Conn.)	14.4	4.7	24.4	1.4	26.4	0.26	0.1	0.07	0.01	8.6	1.7	14.6

Table 1. Continued

			Physical and Chemical Properties					
Source of Ash	Natural Moisture Content	Specific Gravity	Grain Size Distribution (M.I.T. Scale)			pH[2]	Water Soluble Salts	Electrical Conductivity of Ash Leachate[3]
			Sand	Silt	Clay			
	%			%			%	mmhos /cm
Pontiac (Mich.)	0.2	2.95	7	93	0	11.9		450
St. Paul (Minn.)	1.2	2.85	53	47	0	10.7	0.22	1740
Kansas City (Mo.)	0.2	2.44	24	69	7	11.3	0.07	830
South Tahoe (Cal.)	0.3	2.87	14	86	0	12.8		3620
Saginaw (Mich.)	0.8	2.77	17	82	1	10.7	0	2090
Cromwell (Conn.)	64.7	2.85	15	72	13	11.5	1.52	1700
Cuyahoga (Ohio)	0.2	2.96	6	94	0	11.5		1490
Ann Arbor (Mich.)	0.1	2.75	25	69	6		1.16	2250

[1]USEPA (1972).

[2]Measured on a settled suspension with a 1:5 ash to distilled water ratio.

[3]125 g ash leached with 2 liters of distilled water.

Table 2. Elemental analysis of sewage sludge ashes from several U.S. cities.[1]

Element	City[2]												
	A	B	C	D	E	F	G	H	I	J	K	L	M
	%												
Al	4.08	7.05	4.18	4.23	1.20	5.16	4.04	3.03	3.29	4.84	4.94	3.85	3.39
Ca	23.57	2.34	13.68	5.90	0.79	19.78	27.60	29.78	9.57	9.29	8.47	18.06	6.88
Fe	4.40	15.16	6.93	6.29	1.59	5.55	9.47	7.39	2.55	4.33	5.33	3.70	3.16
Mg	1.12	1.00	10.06	1.38	0.28	1.92	1.78	1.47	1.51	1.78	1.29	0.89	1.29
P	2.40	5.68	2.60	2.17	1.15	3.35	4.18	3.16	3.37	5.58	4.74	1.42	1.93
Si	11.24	18.26	13.66	28.37	42.01	15.21	9.77	9.29	28.15	20.57	22.04	20.46	31.79
Na	1.2	1.0	1.3	1.3	0.061	1.4	1.4	1.4	1.6	1.5	2.00	2.3	1.8
Ti	1.45	0.89	0.41	0.35	0.20	0.81	0.77	0.51	0.43	0.54	0.62	0.78	0.35
	µg/g												
Ba	2,500	6,000	3,800	7,400	1,200	7,600	5,900	5,300	8,700	8,400	5,500	7,000	6,100
Bi	76	89	71	81	39	76	77	100	81	120	110	150	58
B	3-30	ND[3]	3-30	3-30	ND	3-30	3-30	3-30	3-30	3-30	3-30	3-30	3-30
Cd	9	26	6	40	9	34	96	8	24	59	43	13	6
Cr	120	1,800	210	2,300	52	2,400	3,600	2,000	280	1,500	1,700	670	320
Co	22	37	28	38	11	42	38	58	24	290	38	15	25
Cu	470	880	430	1,500	210	2,200	2,000	1,700	1,700	7,300	1,600	810	1,000
Ga	30-300	100-1,000	30-300	ND	ND	30-300	30-300	30-300	30-300	100-1,000	100-1,000	100-1,000	10-100
Au	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Pb	320	1,800	160	1,500	280	810	520	240	930	1,500	1,700	610	550
Li	20	25	37	66	7	22	33	14	25	10	26	18	12
Mn	2,000	2,400	920	1,300	520	730	1,200	760	260	600	1,100	700	360
Mo	3-30	10-100	3-30	10-100	3-30	10-100	10-100	10-100	10-100	10-100	10-100	3-100	30-300
Ni	56	250	140	1,300	19	900	620	490	130	1,500	460	170	130
Nb	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	3-30	ND
Pd	ND	ND	ND	ND	ND	ND	ND	ND	ND	8.6	ND	ND	ND
K	5,200	12,400	13,600	14,100	1,300	5,500	3,500	2,600	9,900	11,900	13,100	7,700	9,500
Rb	100-1,100	100-1,000	300-3,000	30-300	ND	30-300	30-300	30-300	ND	30-300	30-300	30-300	ND
Ag	50	170	51	61	24	130	68	160	280	575	80	55	190
Sr	130	21	950	90	12	130	130	140	140	170	120	130	87
Sn	100-1,000	1,100	200	200	30-300	200	300	370	400	1,000	110	280	180
W	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	30-300	10-100
V	30-300	30-300	30-300	30-300	30-300	30-300	30-300	30-300	30-300	100-1,000	30-300	100-1,000	100-1,000
Zn	1,700	5,000	960	4,200	570	3,000	3,700	1,500	3,700	3,800	8,000	3,400	2,000
Zr	30-300	30-300	100-1,000	10-100	30-300	100-1,000	30-300	30-300	30-300	100-1,000	30-300	100-1,000	100-1,000

[1] Gabler and Neylan (1977).

[2] City Key:
A - Albany, N.Y.
B - Atlanta, Ga.
C - Cleveland, Ohio
D - Detroit, Mich.
E - Laurel, Md.

F - Plant 1, Minneapolis-St. Paul, Minn.
G - Plant 2, Minneapolis-St. Paul, Minn.
H - Mineapolis-St. Paul, Minn.
1 - Monterey, Calif.

J - Palo Alto, Calif.
K - St. Louis, Mo.
L - San Mateo, Calif.
N. - Savannah, Ga.

[3] Not detected.

associated with organic matter and are probably in different chemical forms than those in sewage sludge, hence their behavior in the soil may differ.

Utilization of Sewage Sludge and
Other Wastes on Agricultural Land

Current interest in recycling or conserving resources, prohibition of waste disposal in surface waters, lack of suitable landfill sites, and the rising cost of N fertilizers has made utilization of sewage sludge and other wastes on agricultural land a feasible waste management alternative.

Anderson (1955) reviewed crop response studies to sewage sludge between 1920 and 1950. These field and greenhouse experiments indicated that sludges are sources of N and P, but are deficient in K. King and Morris (1972) found both sewage sludge applied at 1.25, 2.5, and 5.0 cm/year, and chemical fertilizers (358-112-224 kg/ha of NPK), similarly increased the forage production of coastal bermudagrass, tenfold, over untreated control plots.

Sewage sludge also contains micronutrients (Fe, Zn, Cu, Mn, Mo, and B). The availability of these sludge trace elements was demonstrated some years ago. Water extracts from a Millwaukee, Wisconsin sludge produce called "Milorganite" were added to trace element deficient nutrient solutions. Corn, tomato and sunflower plants grown in the solutions resumed normal growth with an increase in their Zn, Mn, and Cu contents (Rehling and Troug, 1940).

Sludge applied micronutrients and other trace elements probably nonessential to plants (Cd, Ni, Cr, Se, Hg, Pb, and others) may accumulate in the surface soil to levels toxic to plant growth. Rhode (1962) reports such a buildup at the Berlin, Germany and Paris, France sewage farms. After measuring considerably greater concentrations in the soil of acid soluble Zn and Cu under unhealthy plants, Rhode implicated these metals as responsible for the chlorotic appearance and poor plant growth on the land. Leeper (1978) concluded from the work of French investigators that the problem at the Paris farm was probably a Zn induced Mn deficiency. Whether a toxicity or antagonism between Zn and Mn, a trace element problem was evident.

In England, poor growth of crops on soil amended with sewage sludge was related to the amount of extractable metals in the soil. Zinc, Cu, Ni, and possibly Cr were identified as being the probable causes of most of the toxicity symptoms (Webber, 1972).

An extensive literature review of the "Fate and Effects" of sewage sludge applied trace elements in soils was conducted by Page (1974). Page concluded that B, Cd, Cu, Zn, and possibly Ni, Pb, and Se were the trace elements most likely to cause plant toxicities in soils treated with large amounts of domestic sludge.

Certain elements applied with sludge, when accumulated by plants, may be hazardous to animals or humans consuming those plants. Since soil enrichment of As, Hg, Cd, and Pb could pose a threat to the food chain, Andersson and Nilsson (1972) concluded that sludge application rates should be limited by the content of potentially hazardous components. Sewage sludge applied to pastures may result in forages with

a Mo and Se content potentially hazardous to certain foraging animals (Page, 1974). For instance, molybdenosis (a disturbance of Cu metabolism) may develop in ruminant animals when their feed contains an excess of Mo or an unfavorable Cu:Mo ratio (Underwood, 1977).

Cadmium as an environmental contaminant has received considerable recent attention (Nordberg, 1974). Cadmium can be readily taken up by plants to levels considered unsafe for human consumption, as was illustrated by the itai-itai disease in Japan. This painful bone disease in certain local inhabitants resulted from the consumption of rice containing an abnormally high Cd concentration. The Cd had accumulated from a rice-field irrigated with Cd polluted water (Nordberg, 1974). Importantly, this epidemic indicated that plant growth may not be inhibited before Cd reaches concentrations harmful to humans. In contrast, the phytotoxic concentration of certain trace metals including Zn, Cu, Ni, Cr(III), and Mn (Alloway, 1968) is considerably less than dietary concentrations (Underwood, 1977) found toxic to certain mammals, thus affording some protection to the food chain.

Acute or chornic Cd poisoning to animals or humans consuming crops grown on sewage sludge or effluent treated soil has not been reported, though increasing Cd uptake by plants with sewage sludge application to agricultural land has been observed (Cunningham et al., 1975b; Hinesly et al., 1978a; Mitchell et al., 1978). Also, animals fed plants grown on sludge amended soil were found to contain elevated tissue burdens of Cd (Williams et al., 1978; Furr et al., 1976c).

Generalizations as to which trace elements are most likely to represent a hazard to plants or animals on sludge treated soil may not

apply to all sludges. The concentration of certain elements in sludge

results from specific local industries. For example, the high Sb(anti-

mony) content in sludge from the Washington, D.C. areas comes from the

printing industry. When swiss chard, which was grown on Sassafras silt

loam treated with 224 mt/ha of the sludge, was fed to guinea pigs, the

Sb concentration in the adrenal tissue of guinea pigs was greater than

tissue levels in control guinea pigs (Furr et al., 1976c).

Guidelines have been proposed to prevent sludge trace metal accumu-

lation in soils from reaching hazardous levels. The "Zn equivalence"

concept proposed by investigators in England (Chumbley, 1971) assumed

that the relative order of toxicity was Ni, Cu, Zn for these three

metals. They suggested that the sum of Zn + 2Cu + 8NI (µg/g soil)

should not exceed 250 µg/g in agricultural soils. In the U.S.

Environmental Protection Agency guidelines (USEPA, 1977) sewage sludge

use on agricultural soil is limited by cumulative added amounts of

sludge Zn, Cd, Cu, Ni, and Pb. Actual recommended limits depend on the

cation exchange capacity of the soil (Table 3). Leeper (1972) suggested

limiting toxic metal additions to 5% of the soil cation exchange capa-

city. Soil pH should be maintained at 6.5 or greater.

Sewage effluent and sludges also contain pathogenic organisms.

Wylie and Marsh (1978) have reviewed the disease hazards from sewage

addition to soils and report few cases of contamination from properly

managed waste application schemes.

Besides adding microorganisms to the soil, constituents of sewage

and other wastes may affect the natural biotic community of the soil.

Trace metal application to soil may reduce the enzymatic activity of

Table 3. Total sludge metals allowed on agricultural soil.[1]

Metal	Soil Cation Exchange Capacity, meg/100 g		
	0-5	5-15	>15
	Maximum Amount of Metal		
	kg/ha		
Pb	500	1000	2000
Zn	250	500	1000
Cu	125	250	500
Ni	50	100	200
Cd[2]	5	10	20

[1] USEPA (1977).

[2] Cd limited to 2 kg/ha/year.

soil microorganisms, resulting in reduced soil productivity through reduction in organic matter decomposition and nutrient recycling rates (Tyler, 1974; Chaney et al., 1978; Bond, 1976; Spalding, 1979).

The use of fly ash from coal burning as an agricultural soil amendment has been studied (Furr et al., 1976b). Forty-two elements were determined in seven crops grown on soil containing 10% fly ash. The As, B, Ca, Cu, Fe, Hg, I, K, Mg, Ni, Sb, and Se in the edible portion of some of the crops was increased, indicating incineration did not render these elements unavailable to plants.

Incinerated sewage sludge ash contains trace elements including Zn, Cd, Cu, Ni, Pb, Cr, Fe, Mn, Mo, B, and others (Table 2). As indicated by the studies reviewed here, some of these elements may enhance or restrict crop growth when the sludge ash is applied to soil while others may accumulate in plants to levels considered undesirable for animal or human consumption.

Trace Element Addition to Soils

To minimize through suitable management practices the potential problems associated with trace element addition to soil, an understanding of their fate in the soil matrix and availability to plants is desirable.

Fate in the Soil Matrix

Trace elements applied to soil may be removed by plant uptake, leached by infiltrating water, or be retained in the soil matrix. Trace element reactions with soil constituents include (1) association

with soil surfaces, (2) precipitates, (3) occluded in other precipi-
tates, (4) native constituents of soil minerals, (5) solid-state
diffusion into soil minerals, and (6) incorporation into biological
systems or residues (Hodgson, 1963). The relative importance and
rates of these reactions will depend on the metal, soil properties,
and environmental conditions (Keeney and Wildung, 1977).

Very little of the trace elements in the soil are removed by
plants (Allaway, 1968). Soil depletion of native trace elements has
been estimated as 10^3 to 10^4 years for Zn, Cu, Pb, Co, Ni, Mo; 10^2
years for Cd and B; and 10^5 years for Cr (Allaway, 1968). Several
investigations have confirmed that plant removal of fertilizer or
waste applied trace elements is also small (Page, 1974; Andersson and
Nilsson, 1972; Brown et al., 1962; Parker et al., 1978).

For sludge applied trace metals, Page (1974) concluded that in
most soils only small percentages of Ag, Ba, Cu, Cr, Hg, Mn, Ni, Pb,
Cd, Sn, and Zn would be leached beyond the tillage depth (sandy or
very acid soils being exceptions). Movement of Cu, Zn, Cd, Cr, Ni, Hg,
and Pb in sandy and silt loam soil profiles following the application
of a metal-spiked sewage effluent below the 15 cm depth (15-30 cm)
occurred only with very high effluent loading rates and low soil pH
(Iskandor, 1978). The low mobility of inorganic Zn was illustrated in
the column elution studies of Brown et al. (1962). Brown applied 28
kg/ha of Zn as ZnO or $ZnSO_4$ to columns containing sandy loam or silt
loam soil and detected practically no downward movement of Zn after
leaching with 91.4 cm of water.

Eluting soil columns with acidified water or acidified $FeCl_3$-$AlCl_3$
solutions increased the concentration of various trace metals in the
leachate, compared to the leachate from pure water. From these

experiments, Fuller et al. (1976) concluded that acidified wastes or acidified $FeCl_3-AlCl_3$ wastes may induce the soil itself to release metals, hence contributing to surface or ground water pollution, even though compositionally the waste is free of trace metals.

The mobility of neutral B, and anionic Mo and Cr(VI), exceeds that of the cationic trace metals. A majority of fertilizer B may be leached from the surface soil in well drained soils (Hodgson, 1963). Page (1974) indicated that Mo may be leached under neutral or alkaline soil conditions, but concluded that generally only B will be significantly mobile in sewage sludge amended soils. Hexavalent Cr may remain mobile and comprise a pollution problem in landfill disposal of wastes containing Cr(VI) (Griffin et al., 1977).

In soils the proportion of cationic trace metals extractable by water, and thus the concentration in the soil solution, is small. For example, the concentration of Zn, Cu, and Pb removed by a saturation paste extraction from 68 California soils was, on the average, 0.07, 0.04, and 0.05 µg/ml, respectively (Bradford, 1971); while the average total contents of Zn, Cu, and Pb in soils has been reported as 50, 20, and 10 µg/g, respectively (Alloway, 1968). Similarly, trace metals added to soils are found predominantly in other than water extractable forms. Zinc, as an illustration, from inorganic sources (Nelson and Melsted, 1955) and from sewage sludge (Silviera and Sommers, 1977), when incubated with soil was found predominantly in insoluble forms extracted with acid, rather than in water extractable or exchangeable forms. Even when soil Zn, Cu, Mn, and Fe were solubilized by lowering soil Eh and pH, these metals soon associated with exchangeable and

organic matter fractions (Sims and Patrick, 1978).

The concentrations of dissolved trace elements in sewage sludge, except possibly B, are reduced once the sludge comes in contact with the soil (Page, 1974). Also, trace metal extractability in incubated sludge-soil mixtures often decreases with time (Chaney and Giordano, 1976), suggesting that trace metals may revert to chemically less soluble forms in the soil after application.

The nature of sparingly soluble trace metal species and their mechanisms of sorption and precipitation in soils has been of considerable interest. Such information has been deemed necessary to predict long term plant availability and mobility of potentially toxic trace metals (Lindsay, 1973). The clay and organic matter fractions of soil contain negatively charged colloids which may adsorb and exchange cations. Since the cation exchange capacity (CEC) of a soil increases with clay and organic matter content, CEC has been considered an important measure of the soil's ability to sorb trace metals (Chaney, 1973; Leeper, 1972), although some investigators feel that cation exchange does not play a major role in trace metal sorption (Jenne, 1968; Korte et al., 1976).

Exchange reactions of the alkaline and rare earth metals (Ca, Mg, K, Na) with negatively charged collodial clay and organic matter are relatively well characterized (Buckman and Brady, 1974; Wiklander, 1965). Trace metals are also capable of ion exchange (nonspecific sorption), but often are subject to more specific sorption and precipitation reactions which limit their activity in solution. An important factor controlling the quantity of a cation on the exchange complex is

the ion activity in solution (Lindsay, 1973). Hence, mass action may displace exchangeable trace metals as their activity in solution is reduced through more specific sorption or precipitation reactions.

Cavalloro and McBride (1978) suggest ion exchange is responsible for Cd adsorption on acid soils since the adsorption equilibria for Cd was drastically shifted by competing Ca ions. In contrast, John et al. (1972) did not find soil CEC for 30 diverse soils significantly related to Cd sorption. Poor correlation with CEC does not necessarily detract from the importance of clay itself. For example, Korte et al. (1977) found that the percent of clay related most closely to sorption of a particular metal.

Precipitation of added trace metals has been suggested as controlling their activity in solution, particularly at high concentrations, in alkaline soils, or in coarse textured soils low in organic matter. Lindsay (1972) maintains that inorganic solid phases ultimately establish solubility limits for Zn, Cu, Fe, and Mn. Iron and Mn precipitation as insoluble hydrous oxides or oxides [$Fe(OH)_3$ and MnO_2] control their solubility in mineral soils.

Based on solubility product constants for carbonates, hydroxides, and sulfides, Pb also appears to be controlled by precipitation (Ellis, 1973). Solid phases of Pb [$PbCO_3$, $Pb_3(PO_4)_2$, and $PbSO_4$] in soils have been reported (Singer and Hanson, 1968).

Precipitation of Cr(III) by formation of insoluble hydroxy groups, analagous to the formation of Al polymers, has been reported (Bartlett and Kimble, 1976a). Copper, Zn, and Cd added to clay suspensions were also reported to precipitate as sparingly soluble hydroxy complexes

with increasing pH (Farrah and Pickernia, 1977). Street et al. (1977) felt the solid phase $CdCO_3$ may limit Cd activity in soils, since at high Cd concentrations deviation from a linear Freundlich isotherm occurred near the expected equilibrium concentration with $CdCO_3$. Silica is a common constituent of soils, and Legget (1978) provided evidence that $Si(OH)_4$ (monomeric silicic acid) in soils may form sparingly soluble precipitates with Zn.

Soil solutions undersaturated with respect to the least soluble mineral phase suggest precipitation reactions, or at least those solid phases considered, do not control metal concentration in the soil solution. Instead, specific sorption by clay minerals or by Fe and Mn hydrous oxides, and organic matter complexation have been identified as reactions maintaining low levels of trace elements in solution.

The principal soil constituent responsible for sorption of Mn, Fe, Co, Ni, Cu, and Zn was proposed by Jenne (1968) to be hydrous oxides of Mn and Fe. The oxides of Fe and Mn are common in soils. Manganese minerals are finely divided, have high surface areas, high negative charge (except in extremely acid conditions), and have high sorptive capacity for trace metals (McKensie, 1977). Evidence that trace metals may associate with Mn oxides in soils was provided by McKensie (1977), who reported the Mn, Co, Ni, V, Pb, Ba, and Zn concentration in manganese nodules of Australian soils was greater than the concentration of these elements in the whole soils. Another role of Mn oxides in soils has recently been reported by Bartlett and James (1979). They suggest that insoluble Cr(III) may be oxidized to relatively toxic and mobile Cr(VI) by oxidized soil Mn.

In a survey of Fe oxide mineralogy and chemistry, Schwertman and Taylor (1977) indicated that metal cations, and anions of Mo and As can be specifically adsorbed by the oxide surfaces. The surface charge, and hence the amount of a particular ion which may be adsorbed, is pH dependent. Korte et al. (1977), in elution studies, found the percent of free iron oxides correlated better than cation exchange capacity with retention of applied As, Be, Cd, Cr, Cu, Hg, Ni, Pb, Se, V, and Zn in 11 soils.

Three observations implicate soil organic matter as a major factor in sorption of applied trace metals (Keeney and Wildung, 1977): (1) humic and fulvic acid fractions of soil organic matter have relatively high stability constants for metals (Stevenson and Ardakani, 1972), (2) metal sorption or micronutrient deficiences have been highly correlated with organic matter content of soils (e.g., Cu deficiences on peat soil), and (3) after H_2O_2 destruction of organic matter in soil an increase in extractability has been measured. Immobilization of trace metals by organic matter has been attributed to the humic and fulvic acid fractions of high molecular weight and low solubility, while chelation of trace metals by soil biochemicals (mainly organic acids and amino acids) and by highly water soluble fulvic acids may solubilize trace metals and actually increase their availability to plants (Stevenson and Ardakani, 1972).

Soil organic matter effects on applied trace elements other than complexation, chelation, or cation exchange have been reported. For instance, Jenne (1968) suggests organic matter exerts a secondary influence on metal sorption through the oxidation-reduction chemistry

of hydrous oxides of Mn and Fe. Also, Bartlett and Kimble (1976b)
report that Cr(VI) is reduced by organic matter to insoluble Cr(III).

Leeper (1978) states that pH is the "most important single aspect
of the reaction between heavy metals and soils," and that the increas-
ing sorption or precipitation with a rise in pH is related to the
hydrolysis of the divalent metal (M^{2+}) to MOH^+. Leeper indicates that
though the coulombic attraction of negative surfaces is greater for M^{2+}
than for MOH^+, this is offset by the contrary attraction of water mole-
cules, which is greater for M^{2+} than for MOH^+ ions. Also, a greater
number of divalent cations as M^{2+} rather than MOH^+ can be sorbed by a
given number of specific negative sorption sites.

The behavior of Mo, B, and Cr(VI) in soils differs from the
cationic trace metals. Soluble anionic Mo concentration theoretically
increases 100-fold for each unit rise in pH, opposite to that of Zn,
Cu, Fe, and Mn (Lindsay, 1972). Molybdate (MoO_4^{2-}) is sorbed strongly
by Fe oxides and hydrous oxides, and may also be complexed by Al oxides
(Reisenaur et al., 1962). Boron exists predominantly as the neutral
species H_3BO_4 below pH 9.2, and as such is not affected by pH per se
(Lindsay, 1972). Though sorption of B is relatively weak, probable
adsorption sites are: (1) Fe and Al hydroxy or oxide compounds, (2)
micaceous-type clay minerals, and (3) magnesium-hydroxy clusters or
coatings that exist on the weathering surfaces of ferromagnesian miner-
als (Ellis, 1973). Similar to Mo, Cr(VI) solubility increases with pH,
sorption by kaolinite and montmorillonite clay minerals being greatest
at low pH (1.5 to 4.0) (Griffin et al., 1977). Even in the pH range
where Cr(VI) sorption was greatest, however, 30 to 300 times more

Cr(III) than Cr(VI) was adsorbed by the clay minerals, indicating the hexavalent $Cr_2O_7^{2-}$ ion remained relatively soluble.

In summary, the proportion of applied trace metal cations present in the soil solution or removed by plant uptake and leaching is small in comparison to the proportion precipitated or sorbed in the soil matrix. Importantly, a rise in soil pH increases trace metal precipitation and/or sorption, decreasing their concentration in the soil solution and mobility in the soil. Precipitation reactions establish solubility limits for trace elements, while sorption reactions provide additional sites for their retention in the soil matrix. Three soil components are responsible for sorption of trace elements: the clay minerals, organic matter, and oxides or hydrous oxides of Fe, Mn, and Al. Applied Mo is relatively mobile in neutral and alkaline soils, Cr(VI) may remain mobile in soils low in organic matter, while significant amounts of B applied in a soluble form may be leached from the surface in well drained soils.

Availability to Plants

Plant uptake and phytotoxicity from trace element addition to soils depends on the amount and type of metal applied; soil properties such as pH, organic matter, P content, and cation exchange capacity; reversion to chemically less available forms; and on the plant species and variety (Chaney, 1973).

Certain elements (Mn, Zn, Cd, B, Mo, Se) can readily move to plant tops when applied to soil, others (Ni, Co, Cu) move with intermediate ease, while some (Cr, Pb, Hg) are immobile (Chaney and Giordano, 1977).

Plant accumulation of some trace elements correlates well with amounts applied, while the concentration of other elements in plants is often unaffected by soil addition. The Cd concentration in wheat increased in proportion to the amount of sewage sludge applied to loamy sand (pH 4.8); at sludge rates of 0, 6.5, and 58 mt/ha, the Cd concentration in the wheat was 0.067, 0.119, and 2.357 µg/g, respectively (Linman et al., 1973). Similarly, cabbage grown on potted soil with 0, 5, and 10% fly ash contained 0.01, 0.24, and 0.95 µg/g Se, respectively (Furr et al., 1976b). In contrast, Cr and Pb additions often have little effect on plant contents. The Cr concentration in corn forage was not affected by application of a sewage sludge and garbage compost containing Cr, though over 1000 µg/g of Cr was added (Mortvedt and Giordano, 1975). Lead applied with organic wastes high in P has little effect on the Pb content of plants (Chaney and Giordano, 1977).

Different metals vary significantly in their phytotoxic levels in soils and plant tissues (Hunter and Vergnano, 1953; Weber, 1972). Sludge enriched with either Zn, Cu, Ni, or Cd was added to Redding fine sandy loam (pH 5.7) in a greenhouse experiment to determine relative metal toxicity (Mitchell et al., 1978). A 25% yield reduction in wheat grain occurred at the following soil metal additions: Zn (580 µg/g), Cu (145 µg/g), Ni (102 µg/g), and Cd (60 µg/g). However, these phytotoxic levels were not reproducible for lettuce grown on similarly treated Redding soil, or for wheat or lettuce grown on calcareous Domino silt loam (pH 7.5). Similar soil and plant species effects were evident in the tissue concentrations of Cd, Cu, Ni, and Zn associated with the 25% yield reductions.

The importance of soil pH on trace metal availability to plants
is well documented (Hodgson, 1963; Page, 1974). The influence of pH
on Ni toxicity was illustrated by the growth of oats and mustard on
limed and unlimed silt loam treated with $NiSO_4$. At 100 μg/g Ni in the
unlimed potted soils (pH 5.7), the oat and mustard yields were 5.9 and
0.8 g/pot, respectively. With the same Ni additions on the limed pots
(pH 6.4) the oat and mustard yields were 14.6 and 25.8 g/pot, respec-
tively, and were comparable to plant yields on control pots (Webber,
1972).

The Cd concentration of fodder rape grown on a loamy sand amended
with sewage sludge decreased from 1.021 μg/g at pH 4.8 to 0.412 and
0.236 μg/g at pH 6.0 and 7.2, respectively (Andersson and Nilsson,
1972). Numerous investigators have reported that plants grown on acid
soil accumulated more Cd than those grown on neutral or alkaline soils
(John et al., 1972; Miller et al., 1976; Mahler et al., 1978). The
availability of Zn also has been found to decrease with increasing soil
pH (Miller et al., 1964), as has Pb (Cox and Ramis, 1972), Cr (Dowdy
and Larson, 1975), Cu (Furr et al., 1976c), Mn (Christensen et al.,
1951), and other trace metals.

In contrast to the cationic trace metals, Mo becomes more avail-
able to plants with increasing soil pH (Hodgson, 1963). An important
effect of liming acid soils may be increased Mo availability, since
application of Mo to clovers has in some cases produced yields equiva-
lent to those obtained from the use of lime (Tisdale and Nelson, 1975).

The available P level in the soil has been implicated as affecting
trace metal accumulation by plants. Olsen (1972) reviewed micronutrient

interactions with P and reported that Zn, Cu, and Fe deficiencies may be induced by high available P levels in soils. Also, high levels of available P in the soil have been reported to reduce Pb uptake by corn plants (Miller et al., 1975). In contrast, increasing soil available P concentration has been reported to enhance Mo uptake in a variety of crops (Olsen, 1972). Increased accumulation of Cd by soybeans was related to increasing soil available P (Miller et al., 1976); however, P additions have been shown to reduce Cd uptake by corn (Street et al., 1978).

Chaney (1973) reports that increasing soil organic matter content generally reduces trace metal availability on acid soils, particularly for Cu and Ni. To determine the effect of organic matter on Cd availability, Haghiri (1974) treated Toledo clay with H_2O_2 to remove organic matter and grew oats on the treated soil, with and without the addition of 6% organic matter (muck). The Cd concentration of oat shoots grown on the treated soil was reduced from 13.7 to 7.9 µg/g with the addition of the organic matter. Haghiri attributed this reduction to the increase in cation exchange capacity when the organic matter was added.

The form of added metal influences its availability in soils to plants. Cunningham et al. (1975a) applied Cr, Cu, Zn, and Ni as inorganic salts or with sewage sludge at equivalent rates to Warsaw sandy loam (pH 6.8). The concentration of Cr, Cu, and Zn was generally greater in the tissue of corn and rye grown on the soil treated with inorganic metals. The organic source of Ni was apparently more available than the inorganic source, since plant contents of Ni were greater

on the sludge amended soil. In another experiment, Mortvedt and

Giordano (1975) grew corn on Hartsell fine sandy loam (pH 5.5) amended

with different sources of Cr. Growth and Cr content of the corn was

not affected by 1360 µg/g of sewage sludge applied Cr, while 80 µg/g

of inorganic Cr(VI) applied as $Na_2Cr_2O_7$, and 320 µg/g of inorganic

Cr(III) as $Cr_2(SO_4)_3$, resulted in severe toxicity. Increased Pb uptake

by corn following the addition of soluble Pb acetate to a silt loam

soil has been reported (Baumhardt and Welch, 1972), but as previously

discussed, Pb is usually unavailable to plants in soil amended with

organic wastes containing P.

Plant availability of applied trace elements may decrease with

time. To investigate this concept, Hinesly et al. (1978a) studied the

residual effect on Blount silt loam (pH 6.8) of cumulative sewage

additions of 1290 kg/ha of Zn and 58.3 kg/ha of Cd, on corn leaf and

grain concentration of these metals. In the last year of sludge irri-

gation the Zn and Cd contents in the corn leaves was 112 and 7.1 µg/g,

respectively. Four years later the leaf contents of Zn and Cd had

declined to 45 and 2.1 µg/g, respectively. An incremental decrease

with time was also measured in the corn grain, and in the third and

fourth year after sludge irrigation, sludge and control plots could not

be distinguished by differences in grain Zn and Cd concentration.

Plant species vary widely in their tolerance to trace metals,

plants in the beet family being very sensitive while grasses are rela-

tively tolerant (Chaney, 1973). Hinesly et al. (1978b) concluded from

studies with corn inbreds grown on sludge amended Blount silt loam, that

Zn and Cd in corn leaves and grain are determined as much by genetic

differences as by differences in the Zn and Cd content of the soil.
In 20 inbred lines of corn grown on the Blount soil containing 21 µg/g
total Cd, the concentration of Cd in the leaves varied from 2.47 to
62.93 µg/g, while kernel concentration varied from 0.08 to 3.87 µg/g.
That trace metal uptake is dependent on variety is similarly illustrated
in the work of John (1977) with Pb uptake by lettuce and by Boggess
et al. (1978) with Cd uptake by soybeans.

In summary, waste-applied trace metals may accumulate in the soil
to levels toxic to plants; however, phytotoxic concentrations may not
persist since some metals apparently revert with time to less available
forms. Addition of a few trace metals to the soil, e.g., Cr and Pb,
often has little effect on plant contents, while other elements such
as Cd are readily taken up by plants. Application rates associated
with phytotoxicity are metal, soil, and plant specific. In addition,
the chemical form of an element and the matrix in which it is applied
influences its availability in the soil: metals in organic wastes are
generally less available than inorganic salts. The availability of
most trace metals (excluding Mo) decreases with a rise in soil pH and,
at least on acid soils, with an increase in soil organic matter con-
tent. Increasing the soil available P content apparently reduces Pb
availability but may increase Mo uptake. Crop selection could be a
practical method of reducing trace metal problems in soil, since plant
species and varieties vary in their tolerance to trace metals, and in
the quantities they remove from the soil.

MATERIALS AND METHODS

Ash Characterization

Elemental Analysis

Ash samples (five replicates) were digested with HNO_3-$HClO_4$.
Nitric acid (10 ml) was added to ash (1.0 g) in 250 ml Erlenmeyer
flasks, glass beads added, and the samples heated on a hot plate for
a few hours, removed, and cooled. Perchloric acid (8 ml) was then
added and the samples heated in a perchloric acid hood to almost dry-
ness to ensure dehydration of silica with minimal metal retention
(Holmes, 1945). After cooling, distilled water (20 ml) and HNO_3 (1 ml)
were added to the flasks. The solutions were briefly heated, allowed
to sit overnight, then filtered into 100 ml volumetric flasks and
diluted to volume. The residue collected in the filter paper was dried
at 70°C for 24 hours and weighed to determine the portion of the ash
not solubilized by the acid digest.

Total Zn, Cd, Cu, Ni, Pb, Mn, Cr, Ca, Mg, K, Fe, and Na were
assayed directly from the acid digest or from suitable diluted aliquots
by air-acetylene flame atomic absorption. To reduce interferences in
the Ca and Mg determination, standard and sample solutions were pre-
pared to contain 2500 µg/g of Sr. For analysis of Na and K, LiCl was
added so that the final diluted solutions contained 1500 µg/ml Li.
Chromium standard and sample solutions were prepared to contain 1%
NH_4Cl to reduce Fe interference.

Total Al was assayed in the digest by nitrous-oxide flame atomic
absorption.

The concentration of Mo in the digest was determined by flameless atomic absorption using the Perkin-Elmer HGA 2000 graphite furnace (Table 4).

Total P was determined colorimetrically by the ammonium-vanadate molybdate method using a Bausch and Lomb Spectronic 20 colorimeter. Dilution of digest aliquots into the proper concentration range for P reduced Cr concentration to less than 0.5 µg/ml, and probably eliminated the interference from the chromate ion (Tandon et al., 1968).

Total B was assayed by drying acid digest aliquots (10 ml) and then resolubilizing the residue in 1N HCl (20 ml). The B content was measured colorimetrically by the curcumin method (Dibble et al., 1954), modified to include a method of standard additions.

Total N and SO_4-S were determined on duplicate samples of one ash (Berg and Gardner, 1978).

$CaCO_3$ Equivalence and Fineness Factor

Duplicate ash samples (1.00 g) were placed in 500 ml Erlenmeyer flasks and 1.13N HCl (25 ml) added. The solution was heated on a hot-plate to almost boiling. After cooling, distilled water (100 ml) was added and the solution boiled for 1 minute. After cooling, 5 drops of 1% phenolpthalein indicator was added and the solution back titrated with 1.04N NaOH (Jackson, 1958). The percent $CaCO_3$ was calculated as follows:

$$\% \ CaCO_3 = (V-T) \times \frac{5}{s} \ ,$$

V = meq of HCl added,

T = meq of NaOH added,

s = sample weight.

Table 4. Parameters used in the HGA 2000 graphite furnace for analysis of Cd, Mo, and Pb.[1]

		Parameters						
		Dry		Char		Atomization		Background
Metal	Matrix	Temp.	Time	Temp.	Time	Temp.	Time	Correction
		°C	sec	°C	sec	°C	sec	
Cd	HNO_3-$HClO_4$ digest or water extract	110	30	350	30	2500	10	Deuterium lamp
Cd	DTPA	100	20	300	30	1500	7	Deuterium lamp
Mo	HNO_3-$HClO_4$ digest	110	20	1450	20	2800+	10	None
Pb	HNO_3-$HClO_4$ digest or water extract	110	25	450	20	2500	12	Deuterium lamp

[1]Standard absorbances determined by a method of standard additions and 20 µl sample and standard aliquots were used.

A sample of each ash (50 g) was screened to determine particle size (Jackson, 1955). Screen mesh sizes were: 40 (0.425 mm openings), 20 (0.841 mm openings), and 10 (2.00 mm openings). The fineness factor was calculated by multiplying 1 times the percent ash passing the 40-mesh screen, 0.6 times the percent ash passing the 20 but retained by the 40-mesh screen, and 0.3 times the percent ash passing the 10 but retained on the 20-mesh screen.

pH

The pH of duplicate ash samples (20 g) was determined on 1:2 ash to water suspensions using a Corning pH meter.

Moisture Content

The moisture content of each ash was determined by weighing samples (50 g) before and after drying at 70°C for 24 hours. (Water was sprayed on some of the ashes at the Durham facilities to eliminate dust and facilitate handling.)

Conductivity

The electrical conductibility (EC) of the ashes was determined from saturated paste extracts (100 g ash plus 120 g distilled water) incubated for 24 hours, then filtered by suction. The Ec of the extracts was measured using an Rd-26, Solu-Bridge (Richards, 1954).

Water Extractable Trace Elements

Water extractable trace elements were determined from the saturated paste extracts used to measure electrical conductivity. Zinc, Cu, Ni, Mn, Cr, and B were assayed by procedures previously described, while Cd and Pb were determined by flameless atomic absorption (Table 4).

To estimate the total water soluble Cr in one ash sample (ash 2), 50 g of ash was mixed with 500 ml water and filtered by suction. The leaching procedure was conducted three times and the Cr concentration determined in the leachates by flame atomic absorption.

Incubation and Extraction of Ash-Soil Mixtures

Ash (50 g of ash sample 2) was mixed with surface or subsoil samples (50 g) from the Willamette soil profile. Three different soil samples were used: (1) dried, ground, and sieved surface soil, (2) fresh, moist, surface soil collected from the field plot area; and (3) dried, ground and sieved argillic horizon subsoil samples (75-90 cm). A subsample of fresh surface soil was air dried at room temperature to determine moisture content. The remaining moist soil was then mixed with ash at the equivalent of 50 g dried soil.

The ash-soil mixtures, along with pure ash and unamended dried surface soil, were then moistened with distilled water to about 75% of saturation moisture contents. The water additions were: 90 ml to 100 g ash-soil mixture, 45 ml to 50 g pure ash, and 15 ml to 50 g dried surface soil. After incubating the samples at room temperature for 48 hours, additional water was added to form saturated pastes: 30 ml to

the ash-soil mixtures, 15 ml to the pure ash, and 5 ml to the soil.
The pastes were incubated for 24 hours and then filtered by suction
and the water extracts acidified with HNO_3 (0.5 ml).

The Zn, Cu, Ni, Mn, Pb, Cd, and Cr content of the water extracts
was determined by atomic absorption procedures previously described.

Field Plots

1977 Lime-Ash Treatments

Field experimental plots were established at the North Willamette
Experiment Station, Aurora, Oregon in May, 1977, on Willamette silt
loam soil (Appendix I).

Ash was applied and disced into the field at rates of 0, 11, 22,
and 45 mt/ha (0.5, 9.5, and 19 tons/acre); in factorial combination with
0 and 90 kg/ha (80 lb/acre) of P (0-45-0) (Table 5). The P fertilizer
was banded at planting 5 cm (2 inches) to the side and 5 cm below the
corn seeds. The eight treatments were arranged in a randomized com-
plete block design with four replications (Figure 1). Each plot was
5.5 by 10.9 m (15 by 30 feet). Ash (sample 1) was used directly from
the Durham facilities, but only enough was received to treat replica-
tions 1, 2, and 3. Ash (sample 2) produced the following day was
applied to replication 4.

All plots received 56 kg/ha (50 lb/acre) of N as NH_4SO_4 (21-0-0)
banded at planting. After corn emergence from the soil, NH_4NO_3 (33-0-0)
was broadcast by hand at the rate of 168 kg/ha (150 lb/acre) of N.

Sweet corn (_Zea_ _mays_ L., Jubilee variety) was mechanically planted
within two weeks after ash application at a 76 cm (30 inch) row spacing.

Table 5. Lime-ash, alum-ash, and P fertilizer application to Willamette silt loam soil.

1977		1978		Total	
Lime-ash	P	Alum-ash	P	Ash	P
mt/ha	kg/ha	mt/ha	kg/ha	mt/ha	kg/ha
0	0	0	0	0	0
0	90	0	90	0	180
11	0	0	0	11	0
11	90	0	90	11	180
		16	90	27	180
22	0	0	0	22	0
22	90	0	90	22	180
		31	90	55	180
43	0	0	0	43	0
43	90	0	90	43	180
		63	90	106	180

1977 Lime-ash plots

Rep 4

22	0	43	11
90	90	90	90
0	43	22	11
0	0	0	0

Rep 3

43	0	22	11
0	90	0	0
22	11	0	43
90	90	0	90

11	11	0	22
0	90	90	90
43	43	0	22
90	0	0	0

0	43	22	0
0	0	0	90
22	43	11	11
90	90	90	0

Rep 1   Rep 2

← Lime-ash, mt/ha

Plot dimensions, 5.5 x 10.9 m

← P, kg/ha

1978 Alum-ash and residual lime-ash plots

Rep 4

31	0	0	16
90		90	90
0		63	0
90	90	90	90
0	0	0	0
0	0	0	0

Rep 3

0	0	0	0
0	90	0	0
0	16	0	63
90	90		90
31	0		0
90	90	0	90

0	16	0	0
	90		90
	0		31
0	90	90	90
0	0	0	0
90			
63			
90	90	0	0

0	0	0	0
0	0	0	90
31	0	0	0
90	90	90	
0	63	16	
90	90	90	0

Rep 1   Rep 2

Alum-ash, mt/ha

Plot dimensions, 5.5 x 5.5 m

P, kg/ha

Figure 1.   Field plot design.

Six rows of corn were contained within each plot.

Irrigation water was applied as needed. Weed control was accomplished by pre-emergence application of atrazine and alachlor at active ingredient rates of 1.4 kg/ha (1.25 lb/acre) and 2.24 kg/ha (2.0 lb/acre), respectively.

Corn leaf samples were collected for chemical analysis in June when the corn plants were about knee height. The third mature leaf was removed from about 15 plants within each plot.

Corn ear yield was determined by hand harvesting ears from two 7.2 m (20 foot) sections of two of the inner four rows in each plot, on 8/31/77. The ears were sorted into mature (#1) and immature (#2) ears and weighed. Culls (undeveloped ears) were discarded. Total ear yield was taken as the sum of the separately weighed #1 and #2 ears. Five #1 and five #2 ears were weighed without husks, dried at 70°C, and weighed to obtain moisture content. The dried ears were shelled to provide kernels for chemical analysis.

Whole corn plants were removed from two 2.2 m (6 foot) sections in each plot and weighed to determine silage yield on 9/2/77. From the whole plants five tops and five bottoms were retained to determine moisture content. After drying at 70°C, the moisture samples was shredded and a subsample taken for chemical analysis.

1978 Alum-Ash and Residual Lime-Ash Treatments

Plots which were amended with 0, 11, 22, and 45 mt/ha of lime-ash in 1977, but which received no banded P fertilizer, did not receive additional ash in 1978 (Figure 1). These plots were evaluated as residual lime-ash treatments.

Lime-ash amended plots which received banded P in 1977 were divided in 1978 into 5.5 by 5.5 m (15 by 15 foot) subplots (Figure 1). Additional ash containing alum (sample 6) was applied to one subplot at each lime-ash treatment level (Table 5). Where 11, 22, and 45 mt/ha of lime-ash had been applied in 1977; 16, 32, and 63 mt/ha of alum-ash, respectively, was applied in 1978. The subplots received banded P as in 1977.

Sweet corn was grown on all plots and was planted, fertilized, sampled, and managed according to procedures used in 1977, except for harvesting methods on the subplots. Corn ears on the subplots were hand picked from four 3.6 m (10 foot) sections of four inner rows of corn (as opposed to two 7.2 m sections of two rows on the plots which were not divided). Silage yield on the subplots was determined from the weight of whole corn plants taken from two 2.2 m (6 foot) sections, as for the undivided plots, except that these sections were removed from the two outside rows of corn.

Greenhouse Experiment

Sweet corn (Zea mays L., Jubilee variety) was grown in a greenhouse experiment in June, 1978 on Willamette soil. Ashes were applied at rates higher than the application rates used in the field study. The two ashes used, samples 2 and 3, differed in most chemical and physical properties (Tables 8, 10, 11), but perhaps most significantly, ash 2 had a greater content of lime (% $CaCO_3$) and water extractable Cr.

Application rates for each ash were based on the recommended allow- able Zn addition of 540 kg/ha to agricultural soil with a cation

exchange capacity of 5-15 meq/100 g (Knezek and Miller, 1976). Each

ash was mixed with dried soil (5 kg) to provide Zn at rates of 280,

540, 1120, 2240 kg/ha; thus at rates half, equal to, double, and four

times the recommended Zn addition. Since the ashes contained different

Zn concentrations, the application rates of the ashes (mt/ha) were con-

sequently different at each Zn level (Table 6). Pots were also pre-

pared containing each of the pure ashes, unamended soil, and soil with

a simulated banded P treatment [500 kg/ha P (0-45-0) 5 cm below the

soil surface in the center of the pots]. All treatments were replicated

four times and pots organized on greenhouse benches in a randomized

complete block design.

Six sweet corn seeds were planted per pot on May 27 and thinned to

four plants after germination. Nitrogen and S fertilizer was applied

weekly at a rate of 50 kg/ha of N (starting at planting) from an

aqueous solution of NH_4NO_3 and NH_4SO_4. The NH_4SO_4 provided one-third

of the N. All pots were watered regularly with distilled water at

rates which would not exceed field capacity moisture content.

Supplemental lighting from a 50/50 mixture of grow-lux (wide

spectrum) and day glow fluorescent tubes was provided 15 hours a day

from 15 to 20 cm above the growing corn.

Germination counts were made after ten days and foliar observations

taken regularly during plant growth. Whole plants were harvested on

June 30 and dried at 70°C, weighed to determine yield, and then ground

for elemental analysis.

Table 6. Ash applied to Willamette silt loam used in the greenhouse study.

Ash Application Rate	Ash Type	Ash Zn Applied	Ash in Pots (w/w)
mt/ha	sample number[1]	kg/ha	%
0	–	0	0
0 + P[2]	–	0	0
94	3	280	4.0
58	2	280	2.5
185	3	560	7.7
120	2	560	5.8
370	3	1120	14.2
240	2	1120	9.6
740	3	2240	24.9
475	2	2240	17.5
pure ash	3	–	100
pure ash	2	–	100

[1]Ash samples characterized in Tables 7, 9 and 10.

[2]500 kg/ha P (0-45-0).

Plant Analysis

Plant samples were dried at 70°C, ground to pass a 20 mesh screen using a Wiley Mill, and stored for analysis in paper envelopes.

Plant samples were "wet ashed" using a routine HNO_3-$HClO_4$ digestion (Jackson, 1958). Glass beads, plant material (1.0 g) and HNO_3 (14 ml) were added to 125 ml Erlenmeyer flasks. The flasks were heated on a hotplate in a digestion hood for about two hours, or until dense brown fumes subsided. After cooling, $HClO_4$ (8 ml) was added to each flask and the samples were further heated until the color disappeared. Distilled water (30 ml) was added after cooling and the solutions were filtered and diluted to 100 ml. Calcium, Mg, K, Na, P, Zn, Cd, Mn, and Pb were assayed from this solution or on appropriate dilutions.

In a second set of HNO_3-$HClO_4$ digests, plant material (2.0 g), was digested with HNO_3 (20 ml) followed with $HClO_4$ (15 ml). If a digest solution turned dark during the $HClO_4$ oxidation, it was cooled and additional HNO_3 and $HClO_4$ were added (3 ml each). The digests were heated to dryness and the residual salts dissolved in 1N HCl (20 ml), allowed to sit overnight, then filtered into plastic bottles. Copper, Ni, Cr, Mo, and B were determined on these digests.

Phosphorus was measured colorimetrically by the yellow ammonium molybdate-vanadate procedure (Jackson, 1958). Sample and standard solutions (1 ml) were diluted with color forming reagent solution (9 ml) containing 0.25% ammonium vanadata (200 ml), 5.0% ammonium molybdate (200 ml), and distilled water (1400 ml). A Bausch and Lomb spectronic 20 was used to compare absorbance in samples to standards.

Calcium, Mg, K, Na, Zn, Mn, Cu, Ni, and Cr were measured by air-acetylene flame atomic absorption using a Perkin-Elmer Model 306 spectrophotometer. Interferences in the Ca, Mg, K, Na, and Cr analyses were reduced by procedures used for the ash samples. Cadmium, Mo, and Pb were determined by flameless atomic absorption using the Perkin-Elmer HGA 2000 graphite furnace (Table 4).

The B concentration in the corn leaves and kernels harvested in 1978 was determined from aliquots of the acid digest solubilized in 1N HCl. The curcumin colorimetric method was used (Dibble et al., 1954), but the procedure was modified to include a method of standard additions.

Soil Sampling and Analysis

Surface soil samples were collected from all field plots in September, 1977 and 1978. Profile samples (0-15, 15-30, 30-45, 45-60, 60-75, and 75-90 cm) were collected in September, 1978, from plots which received the highest cumulative ash application (106 mt/ha) and from P fertilized control plots. Soil samples were air-dried at room temperature, crushed to pass a 2 mm sieve, and stored in plastic-lined soil sample bags.

Exchangeable Ca, Mg, K, and Na; pH; cation exchange capacity (1977 only); total and available P; and total and DTPA-extractable trace metals were assayed on the surface soil samples. Total P, total trace metals, and exchangeable Ca, Mg, and K were assayed on the profile samples. Water extractable trace metals and B were determined on the 1978 surface soil from the plots where profile samples were collected, and on 1978 surface soil which received 43 mt/ha of lime-ash in 1977 (a residual lime-ash plot).

A core was removed from the potted greenhouse soils following
plant harvest and bulk density and pH determined.

Bulk Density

The soil cores collected from the greenhouse pots were removed
using a metal cylinder of known volume. The oven dry weight (105°C)
of the soil core was divided by the cylinder volume (68.72 cm^3), to
obtain bulk density.

pH

Soil pH measurements were made on a solution suspension (1:2 soil
to distilled water) using a Corning pH meter (Jackson, 1958).

Phosphorus

Available P was extracted by the Bray-1 dilute acid-F method (1:7
soil to solution) and measured using the ammonium vanadate-molybdate
reagent (Bray and Kurtz, 1945). Initial problems of variability in
this procedure were apparently eliminated by weighing out 0.10 g of
charcoal (rather than using the larger volumetric measurement) and
randomizing the 1977 and 1978 samples together for extraction and
analysis.

Total P was determined on a HNO_3-$HClO_4$ digest (Holmes, 1945). Air
dried soil (1.0 g) was weighed into 125 ml Erlenmeyer flasks and HNO_3
(6 ml) and $HClO_4$ (15 ml) added. The flasks were heated on a hotplate
for 6 to 8 hours in an $HClO_4$ digestion hood. If these solutions did
not clear, additional $HClO_4$ (5 ml) was added and the flasks further

heated to near dryness. After cooling, HNO_3 (1 ml) and distilled water (30 ml) were added, each flask gently heated, and then allowed to sit overnight. The solutions were filtered and diluted to 100 ml in volumetric flasks. The P content was determined by the vanadate-molybdate method (modified from Tandon et al., 1968), using the same procedure described for plant tissues. The acidity of the color forming solution and the acidity of the sample aliquot were calculated to give the optimum acidity range for this analysis (Tandon et al., 1968).

Exchangeable Ca, Mg, K, Na and Cation Exchange Capacity

Exchangeable Ca, Mg, K, and Na were determined by air-acetylene flame atomic absorption following extraction from the soil by $1\underline{N}$ ammonium acetate, pH 7.0 (Pratt, 1965). Strontium and Li solutions were used to eliminate interference and ionization problems.

Cation exchange capacity (CEC) was determined by the $1\underline{N}$ ammonium acetate (pH 7.0) single extraction method (Berg and Gardner, 1978). The exchangeable NH_4 was extracted with $0.1\underline{N}$ HCl and determined in the supernatant solution by a semi-micro Kjeldahl technique.

Total Trace Metals

Total Zn, Cd, Cu, Ni, Pb, Mn, and Cr were assayed in the HNO_3-$HClO_4$ soil digest used for total P. Each metal except Cd was assayed by air-acetylene flame atomic absorbtion. Cadmium was measured by flameless atomic absorption (Table 4).

DTPA-Extractable Trace Metals

Zinc, Cd, Cu, Ni, Pb, Mn, and Cr were extracted from the soil using the DTPA (diethylene-triaminepentacetic acid) extraction procedure (Lindsay and Norvell, 1978). Surface soil samples from 1977 and 1978 were randomized and extracted using the same DTPA solution at 25°C. Analysis was by air-acetylene flame atomic absorption except for Cd, which was determined by flameless atomic absorption on the DTPA extracts (1 ml) diluted with distilled water (9 ml) (Table 4).

Water Extractable Trace Metals

Water extractable Zn, Cd, Cu, Ni, Pb, Mn, Cr, and B were determined by a saturation paste method (Richards, 1954). Dried soil (40 g) was brought up to 40% gravimetric water content with distilled water (16 ml), sufficient to form the "glistening" saturated paste. The solution was extracted by filtering under suction, and the elements assayed by methods previously described (Table 7).

Statistics

Statistical analysis of variance (F test) was accomplished on yield, plant elemental content, and soil analysis data according to field plot or greenhouse experimental designs. A least significant difference (LSD) at the 0.10 level was determined if the preliminary F test at the 0.10 level was significant (Carmer and Swanson, 1971).

Simple correlation coefficients (r) were determined by linear regression analysis of leaf trace metal contents with soil DTPA-extractable trace metal contents, if analysis of variance gave significant F values for both variables.

Table 7. Methods used in soil analysis.

Determination	Method	Reference
pH	1:2 soil:water suspension	Jackson, 1958
Available P	Dilute acid - F vanadate molybdate color method	Bray and Kurtz, 1945
Exchangeable bases (Ca, Mg, K, Na)	Ammonium acetate, pH 7.0, atomic absorbtion	Pratt, 1965
Cation exchange capacity	Ammonium acetate saturation at pH 7.0, HCl displacement, Kjeldhal analysis	Berg and Gardner, 1978
Total trace metals (Zn, Cd, Cu, Ni, Pb, Mn, Cr)	HNO_3-$HClO_4$ digestion, atomic absorption	Holmes, 1945
Total P	HNO_3-$HClO_4$ digestion, vanadate molybdate color method	Tandon et al., 1968
DTPA-extractable trace metals	DTPA-TEA, pH 7.3, 25°C, 1:2 soil:solution	Lindsay and Norvell, 1978
Water-extractable metals	Saturation paste extract	Richards, 1954
Bulk density	Dry weight of soil core divided by core volume	

RESULTS AND DISCUSSION: ASH CHARACTERIZATION

Elemental Analysis

Calcium, P, Al, and Fe were the most abundant constituents in the ashes solubilized by the acid digest (Table 8).   From 40 to 75% of the ashes did not dissolve in the digest (Table 10), but this inert residue should be of little importance as a source of elements available for plant uptake or susceptible to leaching.

Ash (sample 1) was assayed for total N and SO_4-S and both elements were detected in trace amounts (less than 0.1%) (Table 8).   Since N and S in sewage sludge are volatilized by incineration (USEPA, 1972), the other ashes probably contained similarly low concentrations.   Also a relatively minor constituent was K, the mean content in the ashes equaled 0.29% (0.35% K_2O).   In comparison to commercial fertilizers sources of N, K, and S, the ashes contain negligible amounts of these plant nutrients.   In contrast, the ashes were relatively rich in P, containing on the average 5.5% P (12.6% P_2O_5) (Table 8).   Ash 4 (18% P_2O_5) contained almost as much P as ordinary superphosphate (20% P_2O_5) and 41% of the P in triple superphosphate (45% P_2O_5).

The average concentration of Zn, Cd, Cu, Ni, Pb, and B in the ashes was 4200, 14, 1600, 190, 2600, and 45 µg/g, respectively (Table 8).   These levels were greater than the median content of metals found in sewage sludges and, except for Cd and B, exceeded the metal concentrations in sludge proposed by Chaney (1973) as suitable for land application (Table 9).   The average Mn, Cr, and Na concentration in the ashes was between 1000 and 2000 µg/g.   In comparison to the other

Table 8. Elemental content of sewage sludge ashes.[1]

Ash Sample	Zn	Cd	Cu	Ni	Pb	Cr	Mn	Mo	B	Na	Fe	Ca	Mg	K	Al	P	TN	SO$_4$-S
	µg/g										%							
1	3600	15	1330	130	2000	1610	1200	3.3	51	1100	2.8	16.4	0.31	0.25	2.3	4.1	0.035	0.086
2	4700	18	1500	130	2600	1900	1400	3.0	61	1150	3.1	13.6	0.35	0.27	2.4	5.2	NA	NA
3	3000	9	1160	140	1900	480	1800	5.5	33	900	2.6	6.0	0.38	0.16	1.1	5.8	NA	NA
4	4900	21	1710	190	3800	1040	1100	NA[2]	56	1200	2.2	11.0	0.27	0.27	4.0	8.1	NA	NA
5	6000	11	1900	240	2500	1200	3300	NA	NA	4200	NA	5.2	1.3	0.43	NA	4.1	NA	NA
6	2700	10	2260	300	3000	590	1840	4.5	22	1000	3.2	6.6	1.0	0.38	NA	5.8	NA	NA
Mean	4200	14	1600	190	2600	1140	1800	4.1	45	1600	2.8	9.8	0.60	0.29	2.5	5.5		

[1]Average of five replications except for TN and SO$_4$-S, which were duplicates.

[2]Not analyzed.

Table 9. Metal content of sewage sludge.[1]

Element	Concentration[1]			Content Appropriate for Land Application[2]
	Minimum	Maximum	Median	
		µg/g		µg/g
Zn	100	28,500	2,200	<2,000
Cd	1	1,100	10	<0.5% of Zn
Cu	100	11,700	700	<800
Ni	10	4,500	50	<100
Pb	10	26,000	500	<1,100
Cr	20	33,000	400	
Mo	2	1,000	5	
B	4	680	20	<100

[1]Page and Chang (1975).

[2]Chaney (1973).

trace elements, the concentration of Mo in the ashes was relatively low, 3.0 to 5.5 μg/g.

Variability between the ashes in elemental content was evident (Table 8). For example, the maximum concentration of Zn, Cd, Cu, Ni, and Pb was generally two to three times greater than the lowest level measured. However, Zn and Pb were consistently the most abundant and Cd and Mo the least concentrated of the trace metals.

The U.S. Environmental Protection Agency has suggested that sewage sludge application to agricultural land should be limited by cumulative added amounts of Pb, Zn, Cu, Ni, and Cd (USEPA, 1977) (Table 3). According to these guidelines the amount of five of the six ash samples that could be applied to the Willamette soil (cation exchange capacity less than 15 meq/100 g) would be limited by the addition of 500 kg/ha of ash-applied Zn. Ash sample 6 would be limited by the addition of Cu. Assuming a "typical" ash to be "Zn limited" and to contain the average concentration of Zn in the six ashes (4200 μg/g), then 119 mt/ha (53 tons/acre) of the "typical" ash would be the maximum allowable application. This rate was calculated as follows:

$$\text{maximum ash application rate} = \frac{\text{Zn application limit}}{\text{Zn concentration in the ash}}$$

$$= \frac{500 \text{ kg Zn/ha}}{0.0042 \text{ kg Zn/kg ash}}$$

$$= 119000 \text{ kg ash/ha or } 119 \text{ mt/ha.}$$

Lime Value

The pH of the ashes varied from 7.7 to 10.8 (Table 10), indicating they are alkaline and thus have the potential to neutralize soil acidity.

Their capacity to do so and the rate at which it is accomplished, how-ever, is dependent upon their $CaCO_3$ equivalence and particle size.

Ash samples 1 and 2 had the greatest $CaCO_3$ equivalences of the six ashes, 34 and 23%, respectively (Table 10). These ashes were col-lected from the Durham facilities during May of 1977 when lime (CaO) was used to precipitate P from the sewage effluent. Some of this lime was incinerated with the sewage sludge and contributed significantly to the $CaCO_3$ equivalence of the ashes. Ash collected in October of 1976 (sample 5), when P was not being removed from the effluent, had a much lower $CaCO_3$ equivalence, about 2%. This suggested the liming value of an incinerated organic sludge, containing no added lime, was relatively low.

Operational problems with the use of lime prompted the change to alum (Al_2O_3) to precipitate effluent P later in the summer of 1977. Alum containing ashes 4 and 6 had $CaCO_3$ equivalents of 4 and 13%, respectively.

The fineness factor of the ashes varied from 57 to 79 (Table 10). This measure of the different sized particles in a liming material predicts reaction rates of the lime in an acid soil (Jackson, 1955). The "lime score," which takes into account both purity and particle size of liming materials, is obtained by multiplying the % $CaCO_3$ by the fineness factor. Pure $CaCO_3$, very finely divided, would have a lime score near 100. The highest lime score of the ashes was 27 (sam-ple 1), which is relatively low compared to the lime scores (>80) of lime from the Oregon Portland Cement Company and sugar lime, the two common limes used in the Willamette Valley. The ashes would therefore

Table 10. Physical and chemical properties of sewage sludge ash.[1]

Ash Sample	Electrical Conductivity	pH	Lime Value		Moisture Content	Content Not Acid Digestible
			CaCO$_3$ Equiv.	Fineness Factor		
	mmhos/cm		%		%	%
1	3.5	10.8	34	79	4.2	55
2	3.4	8.4	23	72	5.4	60
3	2.2	8.1	15	74	1.0	75
4	NA[2]	8.1	4	NA	NA	40
5	NA	7.7	2	NA	NA	NA
6	2.9	7.8	13	57	30.0	58

[1]Average of two replications.

[2]Not analyzed.

probably not be commercially competitive liming materials.

With regard to disposal in landfills or on acid agricultural soil, the lime content of the ashes, through its effect on soil pH, should reduce the solubility of ash trace metals [Zn, Cd, Cu, Ni, Pb, Mn, Cr(III)] and is a valuable constituent in this respect.

Extract Conductivity

The electrical conductivity (EC) of the saturation paste extracts, a measure of the ashes soluble salt content, varied from 2.2 in ash 3 to 3.5 mmhos/cm in ash 1 (Table 10).

A yield reduction in corn does not generally occur until the EC of a soil is 5 mmhos/cm or more (Berstein, 1964). Therefore, the soluble salt content of the ashes would probably not be a limitation to their use on agricultural land.

Water Extractable Trace Elements

Water extractable Zn, Cd, Cu, Ni, Pb, Mn, and Cr (Table 11) comprised, in general, considerably less than 1% of the total content of these trace metals in the ashes (Table 8). For example, ash 1 contained 2000 μg/g of Pb, of which only 0.018 μg/g was extracted by water.

A larger fraction of the total B content (Table 8) of the ashes was water soluble (Table 11). In ash 2 and 6 water extracted 1.4 and 1.6 μg/g, or 2.3 and 7.3%, respectively, of the total B content of these ashes. The B concentrations in the extracts were below the average reported for California soils (Table 13), which suggests that

Table 11. Water extractable trace elements in sewage sludge ash.[1]

Ash Sample	Zn	Cd	Cu	Ni	Pb	Cr	Mn	B
				µg/g				
1	0.24	0.0046	3.3	<0.5	0.018	1.8	0.11	1.6
2	0.10	0.0013	1.1	<0.5	0.018	12.5	0.08	1.4
3	0.14	0.0023	0.31	<0.5	0.11	0.054	0.29	1.4
4	0.17	0.0046	0.58	<0.5	0.066	0.11	0.60	1.6

[1]Average of two replications.

Table 12. Chromium leached from sewage sludge ash.[1]

500 ml Leachings			
1	2	3	Total
	µg/g		
11.4	2.9	0.9	15.2

[1]Ash sample 2.

Table 13. Saturated paste extract composition of California sludges and soils[1] and sewage sludge ash.

Element	Range			Mean			Median		
	Sludge	Soil	Ash	Sludge	Soil	Ash	Sludge	Soil	Ash
				μg/ml					
Zn	0.5–2.5	0.01–0.40	0.08–0.20	0.8	0.07	0.13	0.6	0.04	0.14
Cd	0.05–1.2	<0.01	0.0011–0.0038	0.29	<0.01	0.003	0.09	<0.02	0.0029
Cu	0.14–24.0	<0.01–0.20	0.26–2.8	4.8	0.04	1.10	1.1	0.03	0.70
Ni	0.6–18.0	<0.01–0.04	<0.5	6.0	0.02	<0.5	1.7	<0.01	<0.5
Pb	0.13–2.0	0.01–0.30	0.015–0.092	0.67	0.05	0.057	0.3	<0.01	0.035
Cr	<1.0	<0.01–0.017	0.045–10.4	<1.0	0.01	3.6	<1.0	<0.01	0.80
B	2.7–17.0	<0.10–26.0	1.2–1.3	6.3	3.06	1.25	4.4	<0.1	1.25

[1]Bradford et al. (1975).

ash application would not increase the content of available B in the soil to levels hazardous to crops.

The concentrations of Zn, Cd, Cu, Ni, Pb, and B in the water extracts of the ashes were less than the concentrations of these elements in the extracts of California sewage sludges (Table 13). The sludge trace elements were apparently converted to less soluble forms by incineration. Trace metals in sewage sludge ash are probably in oxide forms (USEPA, 1972). Since the oxides of most trace metals are sparingly, if at all, soluble in water (Handbook of Physics and Chemistry, 1973) only a small portion should be water extractable.

A relatively large concentration of water extractable Cr was present in one of the ashes (sample 2) collected in May of 1977 (Table 11). The 12.5 $\mu g/g$ of Cr extracted from ash 2 was over 100 times that extracted from ash 3 or 6, and was also considerably in excess of that extracted from California sludges or soils (Table 13). Successive leaching with water removed 15.2 $\mu g/g$ of Cr from ash 2 (Table 12); still a small fraction of the 1900 $\mu g/g$ of total Cr in the ash. However, this water soluble Cr could be Cr(VI), which is more toxic to plants than Cr(III) and is also more mobile in soils since it exists as the chromate anion (Bartlett and Kimble, 1976a).

In sand culture, 10 $\mu g/g$ of Cr(VI) applied as $K_2Cr_2O_7$ was found to be toxic to corn (Soane and Saunders, 1959). A very high application rate of ash 2, 1480 mt/ha (660 tons/acre), would be required to add 10 μg of water soluble Cr per gram of soil.[2] Using the USEPA (1977)

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[2]Ash 2 contained 15.2 x 10^{-4}% water soluble Cr, thus: 660 tons/acre x 2000 lb/ton x 15.2 x 10^{-6} lb Cr/lb ash = 20 lb water soluble Cr/acre. Assuming the acre-furrow-slice (acre x 6 inches) = 2 x 10^6 lb dry soil, then: (20 lb water soluble Cr)/(2 x 10^6 lb dry soil) = 10 ppm $\simeq$ 10 $\mu g/g$.

guidelines previously discussed, application of ash 2 to the Willamette

soil would be limited to 106 mt/ha by the addition of ash Zn. At this

rate, less than 1 µg of water soluble Cr per gram of soil would be

applied with the ash. Hence, the water soluble Cr, even if Cr(VI),

probably would not present a threat to corn production when ash is

applied at rates limited by the addition of Zn. This may not apply,

of course, to ashes containing higher levels of water soluble Cr.

Water Extractable Trace Metals in Ash-Soil Mixtures

When ash (sample 2) was mixed with an equal weight of Willamette

soil the concentration of Cr in the water extracts varied from 1.3 to

4.0 µg/ml, considerably in excess of the <0.1 µg/ml extracted from the

surface soil alone (Table 14). The water soluble Cr in ash 2 was

therefore not attenuated by the Willamette soil samples to levels of

water extractable Cr probably normal for the soil. Also, the concen-

tration of Cr in the extracts from the ash-soil mixtures exceeded the

maximum allowable concentration of Cr in domestic or irrigation water

supplies (Table 15). If, under field conditions, the water soluble Cr

was to move with infiltrating water without being sorbed or diluted in

the soil, it could comprise a source of local ground or surface water

contamination.

Each of the incubated systems, except the pure soil, contained 50 g

of ash 2, and therefore initially contained equal amounts of water

soluble Cr from the ash. Since ash 2 contained 12.5 µg/g of water

extractable Cr, the pure ash and the ash-soil mixtures initially con-

tained a total of 625 µg of water extractable Cr (12.5 µg/g Cr x 50 g

Table 14. Water extractable metals in ash-soil mixtures after two days incubation.[1]

Ash Sample	Soil		Concentration in Extract							Total Extracted Cr
	Depth	Condition	Cd	Zn	Cu	Ni	Pb	Mn	Cr	Cr
	cm					μg/ml				μg
2	0-15	Dried, ground, sieved	0.0053	0.18	0.32	<0.5	0.028	0.50	1.3	156
2	0-15	Fresh, moist, unsieved	0.0033	0.03	0.16	<0.5	0.018	0.17	2.3	280
2	75-90	Dried, ground, sieved	0.0040	0.09	0.19	<0.5	0.023	0.18	4.0	480
2	-	-	0.0031	0.15	0.85	<0.5	0.025	0.10	6.9	420
-	0-15	Dried, ground, sieved	0.0025	0.31	0.15	<0.5	0.032	0.20	<0.1	<2
LSD(0.10)			NS[2]	NS	NS		NS	0.18	1.03	

[1]Average of three replications.

[2]Not significant.

ash). After incubation, similar amounts (>400 μg) of Cr were extracted from the incubated ash and from the ash-subsoil mixture (Table 14), indicating little sorption of the water soluble Cr by the finer textured subsoil. From the surface soils mixed with ash 2, less than 300 μg of Cr (or less than 50% of the initial water extractable Cr), was removed by the water extract. The surface soils therefore sorbed over half of the water soluble Cr in ash 2.

The reduction in the amount of water extractable Cr when ash 2 was mixed with surface soil suggests that when ash is applied to surface soil in the field at least a portion of the water soluble Cr would be sorbed. However, it is difficult to extrapolate laboratory results to field conditions where varying soil moisture content, temperature, microbial activity, and the influence of plant growth and soil structure may modify the sorption process.

Organic matter has been shown to reduce mobile Cr(VI) to relatively insoluble Cr(III) (Bartlett and Kimble, 1976b). If the water soluble Cr in ash 2 is Cr(VI), greater sorption in the surface soil containing more organic matter, as occurred in the incubation experiment, would be expected.

As previously discussed, less than 1 μg/g of water soluble Cr per gram of soil would be added if ash 2 was applied at the Zn limiting rate. From a practical perspective, even assuming no sorption occurred, the threat to ground or surface waters from this trace amount of water soluble Cr would probably be minimized by simple dilution as it moved through the soil profile.

Water extracted less than 0.5 μg/ml of Zn, Cd, Cu, Ni, and Pb from

the ash-soil mixtures (Table 14). As for the pure ashes, these water extractable metals comprised a small percentage of the total metal concentration present. Similar findings by Silviera and Sommers (1977) of relatively low amounts of water soluble metals in sewage sludge-soil mixtures led them to conclude that leaching of metals would not be an environmental threat if soil pH is maintained near neutrality. The concentration of Zn, Cu, Cd, and Pb in the saturation extracts from the ash-soil mixtures were below the maximum concentrations allowed in domestic or irrigation water (Table 15), which further suggests that these metals should not be a source of ground or surface water contamination when sludge ash is applied to the Willamette soil.

Summary

Based upon composition, the fertilizer value of the incinerated sewage sludge ashes from the Durham facilities would probably be due to their content of P (9.2 to 18.5% P_2O_5), lime, and perhaps micronutrients. The ashes contained negligible N, K, and S compared to commercial fertilizers. The ashes had a variable lime content (2 to 34% $CaCO_3$); those with greater $CaCO_3$ equivalence were produced during the summer when lime was used to precipitate P from the sewage effluent.

The extract electrical conductivity and B content of the ashes suggest that ash application to soils would not add levels of soluble salts or B hazardous to crop production.

The most abundant trace elements in the ashes were Zn and Pb, while the least concentrated were Cd and Mo. According to the USEPA

Table 15. Water quality criteria for trace metals.

	Maximum Concentration					
	Zn	Cd	Cu	Ni	Pb	Cr(VI)
	μg/ml					
Domestic supplies[1]	5.00	0.01	1.00		0.05	0.05
Irrigation water[2]	5.00	0.01	0.20	0.20	5.00	0.10

[1]USEPA (1976).

[2]National Academy of Science (1973).

(1977) recommended limits for added Pb, Zn, Cu, Ni, and Cd to agricul-
tural soil, the maximum application rate of the ashes would be limited
by the addition of ash Zn or Cu.

Water extractable Zn, Cd, Cu, Ni, Pb, Cr, and Mn comprised a
small portion of the total concentration of these trace metals in the
ashes. Also, the concentration of Zn, Cd, Cu, Ni, Pb, and B in the
saturation extracts of the ashes were less than that reported for
sewage sludges, suggesting that these trace elements are converted
to less soluble forms by incineration.

A relatively large amount of water extractable Cr was present in
one ash, considerably in excess of levels present in sewage sludge or
soils. The water soluble Cr was only partially sorbed when the ash
was mixed with an equal weight of surface soil and therefore could
remain leachable or, if applied in copious amounts to the soil, cause
toxicity problems in plants. However, if the ash was applied at rates
in accordance with USEPA (1977) guidelines for Zn, the amount of added
water soluble Cr would probably be insufficient to adversely affect
the growth of corn and also dilute enough to minimize the threat to
groundwater.

RESULTS AND DISUCSSION: FIELD STUDY

Soil Analysis

Soil pH

The surface soil pH increased from 5.2 to 5.4 on control plots to

a maximum of 6.0 on plots which received 106 mt/ha of the incinerated

sewage sludge ash (Tables 17 and 18). The lime-ash applied in 1977

neutralized soil acidity more effectively than the 1978 applied alum-

ash. The pH increased about 0.5 pH units with the application of 43

mt/ha of the lime-ash while 63 mt/ha of the alum-ash applied to the

Willamette soil increased the pH only 0.2 units (Table 18). When alum-

ash was applied at rates of 16 and 31 mt/ha, equivalent to 2.2 and 4.0

mt/ha of lime was added to the soil, but no increase in the soil pH

was detected (Table 18). The relative effectiveness of these two

ashes as liming materials was a function of their $CaCO_3$ equivalence,

which was 34% for the lime-ash and only 13% for the alum-ash.

Exchangeable Ca, Mg, K, Na and Cation Exchange Capacity

Exchangeable Ca levels in the surface soil increased with ash

applications from 4.4 meq/100 g in untreated soils, to 6.4 meq/100 g

in soils treated with 106 mt/ha of the ash (Tables 17 and 18). Com-

pared to Ca, considerably less Mg, K, and Na were applied with the

sewage sludge ashes (Table 16), and the exchangeable Mg, K, and Na

levels in the soil were not significantly altered by the ash addi-

tions.

Table 16. Elemental additions to field plots treated with sewage sludge ash.

Treatment																	
Ash			P														
1977	1978	Total		Zn	Cd	Cu	Ni	Pb	Mn	Cr	Mo	B	Na	Ca	Mg	K	P
—mt/ha—			kg/ha	————————————————————— kg/ha —————————————————————													
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	90	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	11	0	38	0.16	15	1.3	21	12	17	0.03	0.50	11	1700	32	27	440
11	0	11	0	38	0.16	15	1.3	21	12	17	0.03	0.50	11	1700	32	27	440
11	16	27	90	81	0.31	49	4.6	68	41	26	0.10	0.76	27	2300	190	86	1300
22	0	22	0	76	0.31	29	2.7	42	24	34	0.07	1.0	22	3500	65	54	870
22	0	22	90	76	0.31	29	2.7	42	24	34	0.07	1.0	22	3500	65	54	870
22	31	53	90	161	0.63	99	9.2	136	83	52	0.20	1.5	55	4500	380	170	2700
43	0	43	0	153	0.63	58	5.4	85	49	67	0.13	2.1	45	7000	130	108	1700
43	0	43	90	153	0.63	58	5.4	85	49	67	0.13	2.1	45	7000	130	108	1700
43	63	106	90	323	1.25	197	18	272	166	103	0.40	3.0	110	9000	760	340	5400

Table 17. Cation exchange capacity, exchangeable bases, P, and pH of Willamette silt loam collected in September, 1977.[1]

Treatment			Exchangeable				P		
Ash	P	CEC	Ca	Mg	K	Na	Total	Avail.	pH
mt/ha	kg/ha	— meq/100 g —					— μg/g —		
0	0	14.9	4.8	0.98	0.42	0.21	1500	82	5.3
0	90	15.5	4.7	0.94	0.41	0.28	1600	92	5.2
11	0	15.8	4.5	0.86	0.36	0.30	1700	97	5.2
11	90	14.8	4.3	0.80	0.35	0.28	1700	100	5.3
22	0	15.6	5.5	0.92	0.39	0.26	1900	120	5.4
22	90	14.8	5.2	0.90	0.39	0.28	2000	97	5.4
43	0	15.5	6.4	0.98	0.40	0.28	1800	94	5.6
43	90	15.1	5.9	0.85	0.40	0.28	1800	88	5.5
LSD(0.10)[2]		NS[3]	0.31	NS	NS	NS	200	NS	0.13

[1]Average of four replications.

[2]Analysis of variance F values, Appendix VII.

[3]Not significant.

Table 18. Exchangeable bases, P, and pH of Willamette silt loam collected in September, 1978.

Treatment				Exchangeable				P		
Ash			P							
1977	1978	Total		Ca	Mg	K	Na	Total	Avail.	pH
— mt/ha —			kg/ha	———— meq/100 g ————				——— µg/g ———		
0	0	0	0	4.4	1.0	0.36	0.027	1500	76	5.3
0	0	0	90	4.6	0.98	0.37	0.026	1700	102	5.4
11	0	11	0	4.8	0.90	0.34	0.023	1600	93	5.4
11	0	11	90	5.0	1.1	0.34	0.026	1700	104	5.5
11	16	27	90	5.6	0.98	0.34	0.031	2100	123	5.5
22	0	22	0	5.5	0.98	0.35	0.031	1700	108	5.6
22	0	22	90	5.6	1.0	0.35	0.026	1900	112	5.6
22	31	53	90	5.6	1.1	0.34	0.027	2300	130	5.6
43	0	45	0	5.7	0.98	0.35	0.030	2000	103	5.8
43	0	45	90	6.0	1.0	0.34	0.031	2000	125	5.8
43	63	106	90	6.4	1.1	0.34	0.033	3000	165	6.0
LSD(0.10)[2]				0.78	NS[3]	NS	NS	164	24	0.1

[1]Average of four replications.

[2]Analysis of variance F values, Appendix VII.

[3]Not significant.

At the highest application rate of the ash material, Ca was added equivalent to about 20 meq/100 g soil in the surface 15 cm (assuming the mass of a hectare of Willamette soil to a depth of 15 cm equals 2.24×10^6 kg). Since the exchangeable Ca content in the surface soil increased only 2 meq/100 g (Table 18), a majority of the waste applied Ca probably remained in the soil as a phosphate or some other salt, or as unreacted lime.

Exchangeable Ca, Mg, and K contents in the subsoil (30-90 cm) were not affected by application of 106 mt/ha of sewage sludge ash (Table 22). A slight increase in exchangeable Ca, but not exchangeable K and Mg, was detected at the 15-30 cm soil depth; however, most of the added Ca was retained in the surface 15 cm of the soil.

The cation exchange capacity of the surface soil in September, 1977 varied from 14.8 to 15.8 meq/100 g (Table 17), and was unaffected by the lime-ash applications.

Soil P

Up to 5,400 kg/ha of P was added to the soil with the sewage sludge ash (Table 16). Consequently, the total P content of the surface soil increased significantly, and in proportion to the waste applications (Tables 17 and 18). Soils in the control plots which were treated both years with 90 kg/ha of P fertilizer contained 1700 µg/g total P, while soils treated with the same amount of P and 106 mt/ha of sewage sludge ash contained 3000 µg/g total P. No difference in total P concentration in the control soil and the soil treated with 106 mt/ha of sludge ash was detected at soil depths between 30 and 90 cm (Table 22). Hence, the

ash applied P was retained in the surface soil.

The major source of P to surface waters has been attributed to surface runoff from agricultural land (Task Group 2710 P, 1967). Since the field plots were located on a well-drained and topographically level soil, it seems unlikely the surface retained P on this site would be eroded.

Phosphorus movement into groundwater is limited by the formation of relatively insoluble precipitates. In acid soils, Fe and Al provide a theoretically large capacity to retain P, while with a soil pH greater than 6.5 Ca and Mg phosphates will precipitate and immobilize P (Lindsay, 1973). In addition, the sewage sludge ash contained Al, Fe, and Ca oxide compounds which may sorb the applied P.

Despite the increase in total P content, the available P levels in the soil were not significantly affected by the lime-ash treatments in 1977 (Table 17). The following year, the available P content on the residual lime-ash plots (plots which did not receive additional ash in 1978) exceeded that of the control soil (Table 18). For example, the available P content of the control soil was 76 μg/g in 1978, while on the residual lime-ash plot which received 22 mt/ha of ash the previous year, but no banded P, the available P content had increased to 108 μg/g.

The alum-ash applied in 1978 increased the available P concentration in the soil (Table 18). Soils which received 43 mt/ha of lime-ash in 1977 contained 125 μg/g available P in 1978, but when an additional 63 mt/ha of alum-ash was applied the available P level increased to 165 μg/g, the highest concentration measured in either year.

Differences may exist in the availability of P between the lime-ash and the alum-ash, but are difficult to evaluate in this field study because the alum-ash was applied to plots already amended with the lime-ash. Both ash containing lime and ash containing alum, however, increased the pool of available P in the soil.

Total Trace Metal Content and Distribution in the Soil Profile

The total Zn, Cu, Pb, and Cr content of the surface soil increased with lime-ash application in 1977 (Table 19) and with alum-ash additions in 1978 (Table 20). Relatively small amounts of Cd and Ni were applied by both ashes (Table 16) and the concentration of these metals in the surface soil increased significantly only where additional alum-ash was applied the second year (Table 20). Though up to 166 kg/ha of Mn was applied with the ash, the total Mn content of the surface soil was not measurably affected, probably because the ash applied Mn comprised a small fraction of the native soil Mn present.

Trace metal enrichment in the surface soil was greatest for Pb and Cu, followed by Zn, Cr, and Cd, and was lowest for Ni. The total Pb and Cu concentration in the surface soil amended with 106 mt/ha of the sewage sludge ash (the maximum applied) was, respectively, 780 and 580% greater than the content in the P fertilized control soil (Table 20). For the same treatments, the other trace metal increases were (in %): Zn (330), Cr (260), Cd (230), and Ni (160). Despite these significant soil enrichments, the trace metal concentrations were within the ranges reported for soils (Table 21). Also, added amounts of sludge ash Zn, Cd, Cu, Ni, and Pb (Table 16) were within the limits proposed by the

Table 19. Trace metal concentration in Willamette silt loam collected in September, 1977.[1]

Treatment		Total							DTPA-Extractable						
Ash	P	Zn	Cd	Cu	Ni	Pb	Mn	Cr	Zn	Cd	Cu	Ni	Pb	Mn	Cr
									μg/g						
0	0	70	0.11	17	24	17	1100	24	0.92	0.080	0.52	0.42	0.48	28	<0.2
0	90	73	0.11	17	21	20	1100	22	0.82	0.076	0.44	0.36	0.36	26	<0.2
11	0	132	0.16	18	22	22	1200	28	1.1	0.074	0.58	0.44	0.62	24	<0.2
11	90	77	0.15	19	21	22	1100	23	1.0	0.058	0.64	0.46	0.64	26	<0.2
22	0	114	0.14	22	23	28	1100	28	1.5	0.066	0.80	0.48	1.1	22	<0.2
22	90	198	0.15	24	24	27	1100	30	1.1	0.078	0.82	0.44	0.96	20	<0.2
43	0	162	0.16	29	25	38	1100	32	1.7	0.084	1.3	0.35	1.6	22	<0.2
43	90	177	0.17	26	24	36	1100	29	1.7	0.102	1.2	0.46	1.6	22	<0.2
LSD(0.10)[2]		62	NS[3]	1.7	NS	4.4	NS	5.3	0.34	NS	0.22	NS	0.40	5.7	

[1]Average of four replications.

[2]Analysis of variance F values, Appendix VII.

[3]Not significant.

Table 20. Trace metal concentration of Willamette silt loam collected in September, 1978.[1]

Treatment Ash 1977	Ash 1978	Total	P Total	Total Zn	Cd	Cu	Ni	Pb	Mn	Cr	DTPA-Extractable Zn	Cd	Cu	Ni	Pb	Mn	Cr
— mt/ha —			kg/ha							µg/g							
0	0	0	0	90	0.11	18	21	19	1015	26	1.0	0.068	0.58	0.38	0.66	21	<0.2
0	0	0	90	72	0.15	17	20	19	1015	22	1.0	0.088	0.60	0.48	0.60	23	<0.2
11	0	11	0	90	0.13	20	23	27	1050	24	1.2	0.078	0.82	0.41	0.98	19	<0.2
11	0	11	90	170	0.15	21	27	24	1050	26	1.9	0.090	0.94	0.38	1.1	21	<0.2
11	16	27	90	170	0.17	32	24	45	1090	26	3.2	0.074	1.80	0.50	1.9	17	<0.2
22	0	22	0	100	0.14	24	22	90	1070	36	2.0	0.132	1.2	0.45	1.5	19	<0.2
22	0	22	90	124	0.18	31	25	44	1060	32	2.9	0.080	1.6	0.44	1.9	12	<0.2
22	31	53	90	175	0.24	49	29	74	1110	43	5.3	0.118	1.7	0.64	3.0	16	<0.2
43	0	45	0	114	0.14	29	24	43	1040	35	2.0	0.068	1.3	0.49	2.0	14	<0.2
43	0	45	90	145	0.21	43	26	65	1000	39	4.4	0.114	2.7	0.60	3.1	14	<0.2
43	63	106	90	240	0.34	98	32	148	1070	58	6.6	0.128	5.1	0.59	5.0	13	<0.2
LSD(0.10)[2]				75	0.05	1.7	2.3	25	NS[3]	8	1.4	0.04	0.93	NS	0.78	6.1	

[1]Average of four replications.

[2]Analysis of variance F values, Appendix VII.

[3]Not significant.

Table 21. Trace element concentration in soils.[1]

	Total Concentration	
Element	Range	Mean
	µg/g	
B	2-200	10
Cd	0.01-7.0	0.06
Cr	5-3000	100
Cu	2-100	20
Pb	2-200	10
Mn	100-4000	850
Mo	0.2-5	2
Ni	10-1000	40
Zn	10-300	50

[1]Allaway (1968).

USEPA (1977) (Table 3). Ash applied Zn and Cu came the closest to the recommended allowable additions. At the maximum rate of ash application Zn and Cu additions were 65 and 79%, respectively, of the recommended limits.

The Zn, Cd, Cu, Ni, Pb, and Cr concentration in the soil profile on plots treated with 106 mt/ha of ash, at depths between 30 and 90 cm, were similar to that measured in the control soil profile (Table 22). Trace metal concentrations in the 0-15 and 15-30 cm soil depth were greater in the ash amended soil than in the control, although the metal enrichment occurred primarily in the 0-15 cm soil depth where the ash was incorporated. Little downward movement of the Zn, Cd, Cu, Ni, Pb, and Cr occurred. These metals appeared immobile in the Willamette soil, at least for the duration of the study, in which the soil received 52 cm of irrigation water and 90 cm of rainfall between the first ash application and the soil sample collection dates.

DTPA-Extractable Zn, Cu, and Mn

Zinc and Cu extracted from the surface soil by DTPA increased in proportion to sewage sludge ash applied while the extractable Mn content decreased (Tables 19 and 20). Similar levels of Zn and Cu were extracted from the soil on the undivided residual lime-ash plots 5 and 17 months after the application of the lime-ash in 1977 (Figure 2). The Zn and Cu applied did not appear to revert to chemically less extractable forms after more than a year in the soil, and thus may have residual availability to plants.

The DTPA-extractable Zn content of the control soils (which

Table 22. Trace metal, P, and exchangeable base concentration of Willamette silt loam profile samples collected in September, 1978.[1]

Ash Total	Depth	Total								Exchangeable		
		Zn	Cd	Cu	Ni	Pb	Mn	Cr	P	Ca	Mg	K
mt/ha	cm	——————————— µg/g ———————————								—— meq/100 g ——		
0	0-15	90	0.15	17	20	19	1015	22	1700	4.8	0.9	0.34
106		240	0.34	99	32	150	1069	58	3000	6.4	1.1	0.34
0	15-30	129	0.067	18	11	19	1000	26	1400	5.6	1.6	0.54
106		139	0.11	26	13	33	980	33	1700	6.1	1.4	0.47
0	30-45	78	0.051	19	16	18	890	27	1100	5.6	2.0	0.53
106		96	0.049	20	11	23	770	28	1200	5.6	1.9	0.54
0	45-60	100	0.041	21	15	21	589	29	1000	6.8	2.5	0.61
106		93	0.045	23	14	20	790	31	1100	6.7	2.6	0.55
0	60-75	85	0.025	24	14	17	740	31	940	8.3	3.1	0.59
106		83	0.022	25	14	20	740	28	990	7.6	2.9	0.61
0	75-90	85	0.019	25	16	19	726	30	880	9.3	3.4	0.55
106		90	0.021	27	15	21	770	31	840	8.4	3.5	0.52

[1]Average of four replications.
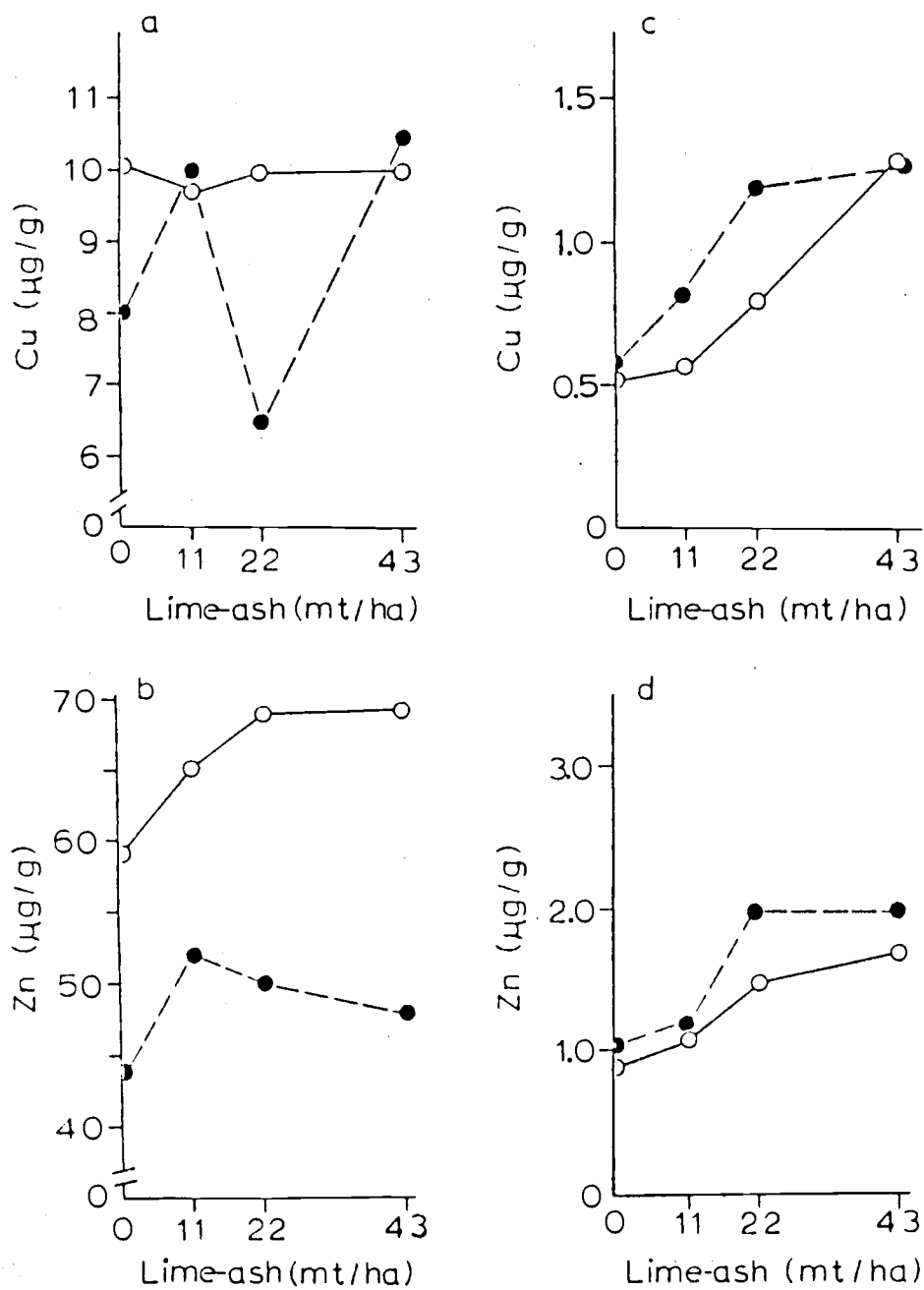
Fig. 2. Zinc and Cu concentration in corn leaves (a and b) and DTPA soil extracts (c and d) (o———o, 1977; •- - -•, 1978).

received P fertilizer) was 0.82 µg/g in 1977 and 1.0 µg/g in 1978.

These levels were greater than the 0.8 µg/g of extractable Zn found

to be the critical level for corn in Colorado soils (Lindsay and

Norvell, 1978), hence a yield response to applied Zn would probably

not occur. At the maximum application rate of ash (106 mt/ha) the

DTPA-extractable Zn content increased to 6.6 µg/g. This was the

highest level measured and is below concentrations of DTPA-extractable

Zn that have been associated with yield reductions. For instance,

when sweet corn was grown on Zn treated alkaline soil a 20% yield

reduction did not occur until DTPA-extractable Zn exceeded 88 µg/g

(Boawn and Rasmussen, 1971); while on acid soil (pH 5.5) 25% yield

reductions did not occur until the soil extractable Zn content was

between 86 and 142 µg/g for lettuce, and between 276 and 540 µg/g for

wheat (Mitchell et al., 1978).

The DPTA-extractable Cu content of the surface soil treated with

ash, and the control soils, exceeded the critical level for corn of

0.3 µg/g of extractable Cu (Lindsay and Norvell, 1978). The maximum

extractable Cu concentration was 5.1 µg/g and occurred with the highest

application rate of the ash (Table 20). Higher levels of DTPA-

extractable Cu are probably associated with Cu toxicities, since wheat

yield on a sandy loam soil (pH 5.5) was not decreased until sludge

treatments increased DTPA-extractable Cu content to over 50 µg/g

(Mitchell et al., 1978).

DTPA extracted 1.4 and 3.5% of the total Zn and Cu, respectively,

from the control soil (with banded P) in 1978. Since 2.8% of the

total Zn and 5.2% of the total Cu was extracted from the plots treated

with 106 mt/ha of ash, the ash applied Zn and Cu were more readily
extracted than native soil Zn and Cu. This relationship was not
observed for the other trace metals (Mn, Cd, Pb, Cr, Ni).

The decrease in DTPA-extractable Mn content with ash applications
(Table 19 and 20) was probably a result of the concurrent increase in
soil pH (Tables 17 and 18). The solubility of Mn decreases with
increasing soil pH (Willis, 1932; Lindsay, 1972). The lowest DTPA-
extractable Mn level, 13 µg/g, was still substantially above the
critical level for corn of 1.0 µg/g (Lindsay and Norvell, 1978).

DTPA-Extractable Cd, Ni, Pb, and Cr

Lead extracted from the surface soil by DTPA increased in propor-
tion to the incinerated sewage sludge ash applied. Extractable Cd
increased only with ash applications in 1978, while extractable Ni and
Cr levels were not measurably affected by the ash additions (Tables
19 and 20).

DTPA extracted between 2 and 5% of the total soil Pb content
(Tables 19 and 20). With the maximum addition of ash (106 mt/ha),
the soil DTPA-extractable Pb content increased to 5.0 µg/g, more than
seven-fold over control soil levels. On the undivided residual lime-
ash plots, slightly more Pb was extracted in 1978 (17 months after ash
application) than in 1977 (5 months after ash application) (Figure 3).
Thus, similar to Zn and Cu, the lime-ash applied Pb extractable from
the soil with DTPA had not reverted to less extractable forms between
the September 1977 and September 1978 soil sampling dates.

DTPA-extractable Cd levels in the surface soil were unaffected by

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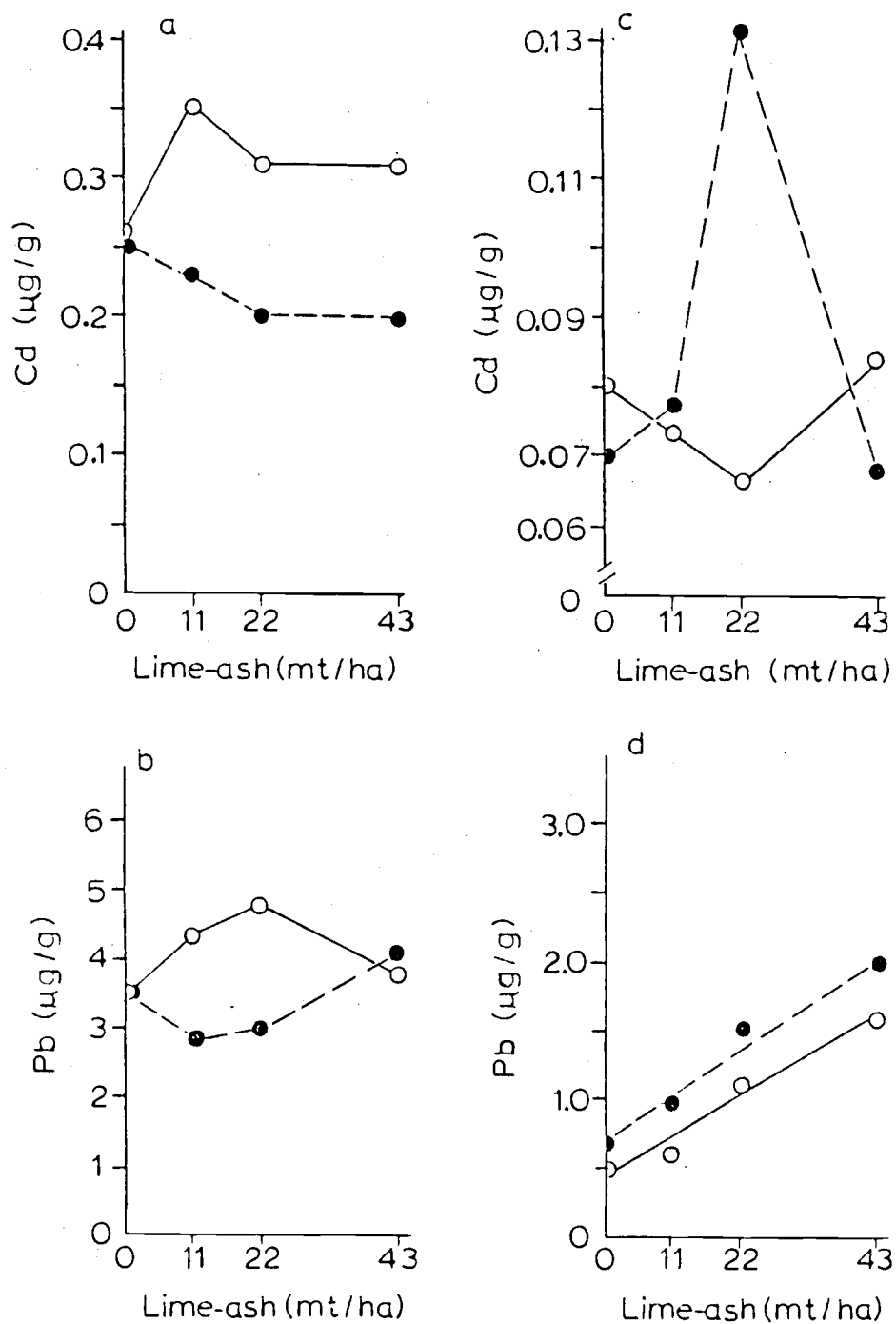
Fig. 3. Cadmium and Pb concentration in corn leaves (a and b) and DTPA soil extracts (c and d) (o———o, 1977; ●- - -●, 1978).

lime-ash additions in 1977 (Table 20). Four out of 9 ash amended plots in 1978 contained soil DTPA-extractable Cd levels in excess of the control soil (Table 20). The increases occurred mainly with the higher application rates of the sludge ashes; however, the extractable Cd concentrations were still quite low (<0.15 μg/g).

A larger fraction of the total soil Cd was extractable with DTPA compared to the proportion of total soil Zn, Cu, Ni, Pb, Cr, and Mn. DTPA extracted over 50% of the total Cd in the control soil and in most ash amended soils, while the DTPA-extractable fractions of the other trace metals were generally less than 5%.

Though diagnostic DTPA-extractable Cd levels associated with yield reductions are plant and soil specific (Mahler et al., 1978), the DTPA-extractable Cd levels on the ash amended soils are well below probable phytotoxic levels. For example, wheat yields were reduced 25% when the DTPA-extractable Cd content was between 30 and 60 μg/g on sludge amended soil (Mitchell et al., 1978) and Street et al. (1978) found no phytotoxic symptoms on corn seedlings grown on soil containing over 3 μg/g DTPA-extractable Cd.

The DPTA-extractable Ni and Cr content of the surface soil was not measurably affected by lime-ash applications in 1977 (Table 19) or by alum-ash treatment in 1978 (Table 20). DTPA extracted less Cr from the soil (<0.2 μg/g) than could be detected by flame atomic absorption. Nickel extracted from the soil by DTPA varied from 0.33 to 0.64 μg/g: levels considerably less than DTPA-extractable Ni concentrations associated with yield reductions. A 25% yield reduction in wheat and lettuce occurred when soil DTPA-extractable Ni levels exceeded 66 and 30 μg/g, respectively (Mitchell et al., 1978).

Water Extractable Trace Elements

Water extracted a variable Zn, Cd, Cu, Pb, and Mn content from the selected 1978 soil samples (Appendix V, Table 6), and significant differences in the water extractable metal concentrations were not detected between control surface soil and surface soils treated with ash applied at rates of 43 or 106 mt/ha (Table 23). The Ni and Cr levels were below detection limits in the saturation paste extracts (Table 23).

The water extractable trace metal concentrations were low, less than 0.5 µg/g, and comprised a small portion of the total Zn, Cd, Cu, Ni, Pb, Mn, and Cr content in the surface soils (Table 20). Generally between 0.2 and 0.5% of the total Zn, Cd, Cu, and Ni were water extractable, while an even smaller percent (<0.2) of the total Pb, Mn, and Cr were removed from the soil by the saturation paste extraction. The low water solubility of the sewage sludge ash applied Zn, Cd, Cu, Ni, Pb, Mn, and Cr in the surface soil (and their retention in the 0-30 cm soil depth) suggested that accumulation of these ash trace metals in the Willamette soil did not represent a pollution hazard to groundwater with ash application up to 106 mt/ha.

The water extractable B content of the control and ash amended soil was less than 0.1 µg/g (Table 23). Though not measurably affected by even the highest application rate of ash (106 mt/ha), any water soluble B applied with the ashes could have been leached from the surface soil in the months that elapsed between the May 1977 lime-ash addition, the May 1978 alum-ash addition, and the September 1978 soil sampling date. However, any initial increase in water extractable B

Table 23. Water extractable trace elements of Willamette silt loam collected in September, 1978.[1]

1977	Ash 1978	Total	Cd	Zn	Cu	Ni	Pb	Mn	Cr	B
	mt/ha		ng/g				µg/g			
0	0	0	0.34	0.27	0.024	<0.2	0.010	0.080	<0.05	<0.1
43	0	43	1.12	0.30	0.084	<0.2	0.008	0.056	<0.05	<0.1
43	63	106	0.80	0.24	0.072	<0.2	0.020	0.068	<0.05	<0.1
LSD(0.10)[2]			NS[3]	NS	NS		NS	NS		

[1]Average of four replications.

[2]Analysis of variance F values, Appendix VII.

[3]Not significant.

would have been small since only 3.0 kg/ha (2.7 lb/acre) of ash B was added with the highest application of ash, and less than 10% of the total B in the ashes was water extractable (Tables 8 and 11).

Soils in the Pacific Northwest are often low in B, and commercial fertilizers apply this micronutrient at rates (up to 6.2 kg/ha) exceeding that applied by the ash materials (Tisdale and Nelson, 1975). Therefore, the amount of B applied with the sludge ashes would not be expected to increase soil available B to phytotoxic levels.

Corn Yield

Sweet corn germinated satisfactorily on all field plots. During and at the end of the growing seasons, corn grown on soil treated with sewage sludge ash could not be distinguished from corn grown on control plots by visual inspection; however, measurable increases in ear and silage yield with ash applications occurred.

Total ear and silage yield increased with ash application in 1978 (Table 25), though was unaffected by application of the waste material in 1977 (Table 24). The total ear and silage yield in 1978 on plots treated with the highest application rate of ash (106 mt/ha) were 20 and 16% greater, respectively, than total ear and silage yield on the P fertilized control soil. The sewage sludge ashes thus had some fertilizer value, while the ash trace element additions were insufficient to restrict corn growth.

The primary effect of the ash treatments on corn growth was to enhance corn ear maturity. Mature ear yield increased with rate of ash applied in 1978 on both residual lime-ash plots, and on plots treated

Table 24. Yield of sweet corn grown in 1977.[1]

Treatment		Ears			Silage	Moisture Content	
Ash	P	Mature	Immature	Total		Ears	Silage
mt/ha	kg/ha			mt/ha			%
0	0	15.9	13.2	29.1	72	18	72
0	90	21.1	10.5	31.4	83	20	69
11	0	16.6	12.3	29.1	72	19	70
11	90	20.8	9.6	31.4	78	20	69
22	0	15.9	15.5	31.4	90	19	70
22	90	22.0	9.9	31.4	81	20	70
43	0	19.9	11.9	31.4	83	20	70
43	90	21.5	10.3	31.4	72	20	65
LSD(0.10)[2]		3.9	3.4	NS[3]	NS		

[1]Average of four replications, fresh weight basis.

[2]Analysis of variance F values, Appendix VII.

[3]Not significant.

Table 25. Yield of sweet corn grown in 1978.[1]

Treatment				Ears			Silage	Moisture Content	
Ash			P						
1977	1978	Total		Mature	Immature	Total		Ears	Silage
— mt/ha —			kg/ha	——————— mt/ha ———————				—— % ——	
0	0	0	0	9.4	11.0	20.4	60	82	74
0	0	0	90	12.8	6.9	19.7	65	82	73
11	0	11	0	9.6	10.1	19.9	67	81	73
11	0	11	90	14.6	6.0	20.6	60	81	74
11	16	27	90	15.2	6.7	22.0	60	90	74
22	0	22	0	13.0	7.4	20.4	74	81	74
22	0	22	90	13.9	6.9	20.8	74	81	74
22	31	53	90	15.2	5.6	20.6	63	81	72
43	0	43	0	12.3	7.6	19.9	69	86	71
43	0	43	90	17.9	5.4	23.3	67	80	73
43	63	106	90	16.6	6.3	22.8	78	80	74
LSD(0.10)[2]				2.51	2.0	1.9	10.8		

[1]Average of four replications, fresh weight basis.

[2]Analysis of variance F values, Appendix VII.

with additional alum-ash (Table 25). Conversely, immature ear yield decreased with ash application. The mature ear yields on ash treated soil which received banded P were up to 40% greater than mature ear yield on the P fertilized control soil.

Differences in mature ear yield in 1977 were attributed to the banded P treatment (the F value from analysis of variance was significant for the P variable but not for the ash treatments, Appendix VII). At each rate of lime-ash application with banded P, compared to the same rates without banded P, the mature ear yield increased while the immature ear yield decreased (Table 24). Hence, the P fertilizer enhanced ear maturity despite a sufficient P content in leaves from corn grown on soil which did not receive the banded P treatment (Tables 26 and 27). The response with ash application in 1978 was similar. Increased mature ear yield suggested a response to P in the ash product. Additional evidence of a P response was the increase in leaf P content with ash application (Table 29), since corn yield tends to increase with the P content of the young tissues (Adriano and Murphy, 1970). Also, the available P content of the soil increased only in 1978 (Tables 17 and 18) when mature ear yield also increased with ash application. While a P response was suggested, other effects resulting from application of the waste material may also have contributed to the increase in corn yield. For instance, the corn leaf Ca, Mg, Zn, B, and possibly Mo concentrations increased with ash applications, as did the soil pH.

Table 26. Elemental concentration of corn leaves, 1977.[1]

Treatment														
Ash	P	Zn	Cd	Cu	Ni	Pb	Mn	Cr	Mo	Na	Ca	Mg	K	P
mt/ha	kg/ha					µg/g						%		
0	0	59	0.26	10	<5	3.5	81	1.3	<0.5	80	0.32	0.17	2.8	0.34
0	90	57	0.31	7.7	<5	3.7	91	1.7	1.0	80	0.33	0.17	2.6	0.36
11	0	65	0.35	9.8	<5	4.4	75	1.9	1.1	70	0.34	0.17	2.8	0.34
11	90	59	0.35	7.8	<5	3.2	88	1.3	0.7	40	0.36	0.18	2.5	0.35
22	0	69	0.31	10	<5	4.8	71	2.0	<0.5	110	0.33	0.18	2.7	0.37
22	90	60	0.29	9.1	<5	2.2	82	1.8	2.0	50	0.38	0.19	2.4	0.38
43	0	69	0.31	10	<5	3.8	73	1.5	1.9	70	0.35	0.18	2.6	0.38
43	90	60	0.35	8.7	<5	2.7	72	1.8	0.73	50	0.37	0.18	2.6	0.39
LSD(0.10)[2]		6.2	0.052	0.97		NS[3]	7.6	NS	NS	NS	0.022	0.007	0.14	0.033

[1]Average of four replications.

[2]Analysis of variance F values, Appendix VII.

[3]Not significant.

Table 27. Elemental concentration of corn leaves, 1978.[1]

1977	1978	Total	P	Zn	Cd	Cu	Ni	Pb	Mn	Cr	Mo	B	Na	Ca	Mg	K	P
Ash																	
— mt/ha —			kg/ha						µg/g							%		
0	0	0	0	44	0.25	8.0	<5	3.5	72	1.9	<0.10	5.3	120	0.48	0.15	2.8	0.36
0	0	0	90	47	0.23	9.0	<5	3.1	83	1.4	<0.10	5.0	80	0.50	0.15	2.8	0.36
11	0	11	0	52	0.23	10.0	<5	2.9	69	3.0	0.14	5.3	130	0.53	0.15	2.7	0.37
11	0	11	90	49	0.21	6.0	<5	3.9	78	3.2	<0.10	8.7	90	0.52	0.16	2.6	0.37
11	16	27	90	61	0.24	8.5	<5	2.8	77	1.2	0.30	5.8	100	0.51	0.17	2.7	0.40
22	0	22	0	50	0.20	6.5	<5	3.0	67	2.8	<0.10	5.4	80	0.53	0.16	2.7	0.38
22	0	22	90	47	0.20	7.5	<5	2.8	67	3.0	0.20	5.7	80	0.50	0.16	2.7	0.37
22	31	53	90	69	0.24	10.0	<5	2.6	69	0.73	0.60	5.0	160	0.53	0.18	2.6	0.43
43	0	43	0	48	0.20	10.5	<5	4.1	57	2.8	0.27	6.1	70	0.45	0.14	2.5	0.37
43	0	43	90	58	0.27	8.0	<5	2.5	63	3.3	0.70	6.3	100	0.51	0.17	2.7	0.41
43	63	106	90	71	0.28	7.0	<5	2.8	61	1.3	1.0	6.2	100	0.67	0.18	2.4	0.44
LSD(0.10)[2]				7.1	NS[3]	NS	NS	NS	7.6	NS	NS	1.4	NS	NS	0.015	NS	0.018

[1]Average of four replications.

[2]Analysis of variance F values, Appendix VII.

[3]Not significant.

Corn Tissue Analysis

Sweet corn grew normally on the untreated and waste-treated
Willamette soil and did not exhibit deficiency or toxicity symptoms.
This suggested the plants contained an adequate supply of nutrient
elements and that trace elements applied with the waste product did
not represent a problem for corn production.

Leaf P, Ca, Mg, K, and Na Content

Phosphorus. The P concentration in the corn leaves increased with
application of sewage sludge ash containing lime in 1977 (Table 26) and
with ash containing alum in 1978 (Table 27). Thus, both ashes added
some P in a form available to corn, though the soil available P levels
increased significantly only with ash applications in 1978 (Table 18).

The P content in the corn leaf samples collected from control
plots varied from 0.34 to 0.36%, which exceeded the critical level of
0.30% P for corn leaves (Tisdale and Nelson, 1975). Banding P at
planting increased the leaf P content on the control plots in 1977 from
0.34 to 0.36%, while corn leaves contained 0.38% P when lime-ash was
applied at a rate of 43 mt/ha without banded P. In 1978, the control
leaf P contents were 0.36% and were unaffected by the P fertilizer
treatment, but at the highest application rate of ash (106 mt/ha) corn
leaves contained 0.44% P. Hence, a greater increase in the corn leaf
P content occurred with the ash applied P than with the banded P fer-
tilizer, probably because considerably more ash P (up to 5400 kg/ha)
was applied than P fertilizer (90 kg/ha/year).

Though the leaf P levels were not below the deficient level, the ash applied P may have had some fertilizer value, since increasing P content in plant tissues is associated with enhanced seedling vigor, and has been related to earlier maturity of cereal crops (Tisdale and Nelson, 1975).

Calcium, Mg, K. The corn leaf Ca and Mg contents increased with application of sewage sludge ash in 1977, while K contents decreased (Table 26). Similar trends occurred in 1978 on residual plots and on plots which received additional ash, but were statistically significant only for Mg (Table 27). The depression in K uptake was probably due to antagonism with Ca and Mg, since relatively small amounts of K, compared to Ca and Mg, were added to the soil with the waste product (Table 16). The lowest leaf K content measured, 0.24%, was still greater than the 0.2% critical K level for corn leaves (Tisdale and Nelson, 1975); hence a K deficiency was not induced by the enhanced Ca and Mg uptake.

Leaf Ca contents in 1977 (0.32-0.38%) and Mg contents in 1978 (0.14-0.18%) were potentially low compared to critical levels for these elements of 0.40% for Ca (Melsted et al., 1969) and 0.15% for Mg (Peaslee and Moss, 1966). Since leaf Ca and Mg contents increased with ash application, some fertilizer value may have been derived from the ash additions of Ca and Mg.

At most application rates of ash in 1977, the banded P variable enhanced Ca and Mg uptake and depressed K assimilation (Table 26). Analysis of variance F values were greater for the banded P treatment than for the ash treatments (Appendix VII), suggesting variations in

leaf Ca, Mg, and K contents related more to the banded P than to the lime-ash applications. No interaction between banded P and ash treatments occurred; thus, the effect of ash applications on the corn leaf Ca, Mg, and K levels was similar whether or not P fertilizer was applied.

Sodium. No significant variation in leaf Na content as a function of ash application was observed (Tables 26 and 27). Sodium was a minor constituent of the ashes (<0.2%) and the amounts applied (Table 16) may have been insufficient to result in a detectable increase in uptake. Also, similar to K, the enhanced uptake of Ca and Mg with ash application may have inhibited Na uptake.

Leaf Zn, Cu, Mn, Mo, and B Content

Zinc, Cu, Mn. Leaf Zn and Mn contents increased and declined, respectively, with sewage sludge ash applications while Cu levels in the corn leaves were affected very little (Tables 26 and 27).

The Zn content of the corn leaves increased with ash application from between 44 and 59 µg/g on control plots to a maximum of 71 µg/g when 106 mt/ha of the waste product was applied. Phytotoxic Zn concentration in plant tissues exceeds 200 µg/g (Allaway, 1968) while the critical level for corn leaves has been reported as 15 µg/g (Melsted et al., 1969), thus ash applications did not adversely or beneficially affect Zn content in the corn leaves.

The Zn concentration in the corn leaves correlated with Zn extracted from the soil by DTPA (r = 0.50 in 1977, r = 0.68 in 1978); however, the leaf Zn content did not increase linearly with DTPA-

extractable Zn, or with ash applied, at the higher application rates
of the waste material. In 1978, for example, the Zn concentration in
the corn leaves from the P fertilized control plots was 47 µg/g and
increased to 69 µg/g when 53 mt/ha of ash (161 kg/ha of Zn) was applied;
but when the rate of ash applied was doubled to 106 mt/ha (323 kg/ha
of Zn), the Zn concentration in the leaves increased only an additional
2 µg/g (to 71 µg/g). The lack of proportionality between Zn uptake and
Zn applied was probably a result of the increase in soil pH that
occurred with ash application, which would have reduced Zn availability.

Corn leaves on the residual lime-ash plots (14 months after ash
application) still contained a greater Zn content than leaves from
plants grown on control plots (Figure 2). The lime-ash applied Zn
apparently remained available to corn and could be extracted from the
soil by DTPA.

Zinc deficiencies in agricultural crops occur commonly (Lindsay,
1972). Since sewage sludge ash applications increased both soil and
plant Zn contents, the waste products would probably be effective
sources of Zn when applied to soils deficient in this micronutrient.
Use of the ashes as Zn fertilizers, however, would not be as efficient
as use of commercial fertilizers in which Zn is more concentrated.
Greater transportation and handling costs would be incurred from use
of the ash materials, since Zn was only a minor constituent (<1%).

Although up to 197 kg/ha of Cu was applied as a constituent of
the sewage sludge ash (Table 16), corn leaf Cu concentrations were
largely unaffected by addition of the waste material to the soil
(Tables 26 and 27). The leaf Cu content varied from 6.5 to 10.5 µg/g,

concentrations in excess of the corn leaf critical Cu content of 5 µg/g (Melsted et al., 1969), but below the 20 µg/g that may be phytotoxic (Allaway, 1968).

Copper extracted from the soil by DTPA increased in proportion to the application rate of the ashes (Figure 2, Tables 19 and 20), but a corresponding increase in corn leaf Cu content was not observed. Similar to Zn, the availability of the ash applied Cu would be expected to decrease with the increase in soil pH. Also, Cu in the ash material was probably not in a form readily taken up by corn, since application of 16 and 31 mt/ha of alum-ash in 1978, treatments which had no effect on the soil pH, did not increase the Cu concentration of the leaf tissues (Table 27).

Corn leaf Mn content decreased with addition of the sewage sludge ash, primarily as a result of the lime-ash applications (Tables 26 and 27). The depression in Mn uptake was related to the increase in soil pH. The Mn concentrations in the leaves of corn grown on the ash amended soil, though depressed, were still considerably above the 15 µg/g Mn reported to be the critical level for corn leaves (Melsted et al., 1969). The lowest Mn level detected in the corn leaves was 57 µg/g while the highest was 91 µg/g. Since plant tissues normally contain up to 100 µg/g of Mn (Allaway, 1968), Mn uptake by corn from the field plots was not excessive. Soil DTPA-extractable Mn also decreased with ash applications (Tables 19 and 20) and was positively correlated with leaf Mn contents (r = 0.26 in 1977; r = 0.45 in 1978).

Leaf Zn, Cu, and Mn contents were significantly affected by the banded P fertilizer treatment in 1977 (Table 26). Analysis of variance

F values were, in fact, larger for the P variable than for the ash treatments (Appendix VII). At each rate of ash application, banding P reduced the Zn and Cu concentration in the leaves, while the opposite was true for Mn. The depressed Zn and Cu contents may have been a dilution effect resulting from the more vigorous early corn grown with banded P, while acidification in the fertilizer band may have solubilized soil Mn thus enhancing its uptake. No interaction between ash and P treatments was detected (interaction F value not significant); hence, the effect of the ash applications on leaf Zn, Cu, and Mn levels was qualitatively the same with and without the P treatment.

Boron and Mo. Boron concentration in the corn leaves increased slightly, but significantly, with ash applications in 1978 (Table 27). Though a majority of the ash B was not water extractable (Tables 8 and 11), a portion was apparently available to corn. All leaf B values were below the critical level of 10 µg/g for corn leaves (Melsted et al., 1969). The method of B determination probably underestimated the actual leaf B contents, however, since simultaneous determination of B in orchard leaves (1571) from the National Bureau of Standards indicated they contained only 12.5 µg/g, compared to their listed content of 33 µg/g B.

The Mo concentration of leaves from corn grown in 1978 on the control plots, and on residual lime-ash plots treated with 11 and 22 mt/ha of ash, were less than 0.1 µg/g (Table 27). These Mo levels were low compared to the Mo sufficiency range for corn leaves of 0.6-1.0 µg/g (Jones and Eck, 1973). When 53 and 106 mt/ha of ash was applied the corn leaf Mo content increased to 0.60 and 1.0 µg/g, respectively,

suggesting an increase in corn leaf Mo content to a more adequate

level with ash application. The Mo concentrations were variable

within treatments, however, and the apparent increase in Mo content

was not statistically significant. Molybdenum concentrations did not

vary significantly with ash application in 1977 and no trend was

apparent (Table 26).

Molybdenosis (a disturbance of Cu metabolism) may develop in

ruminant animals when their pasture or feed Mo concentration exceeds

5 µg/g (Tisdale and Nelson, 1975) or when the Mo:Cu ratios in the feed

exceeds 2 to 4 (Underwood, 1977). By both criteria, Mo concentration

and Mo:Cu ratio, the leaf Mo contents of the corn leaves were not

sufficiently high to be a nutritional hazard to animals.

Relatively small amounts of B and Mo were applied as constituents

of the sewage sludge ashes compared to the quantity of other trace

elements (except Cd) (Table 16). With the highest application rate of

ash (106 mt/ha), 3.0 kg/ha of B and 0.4 kg/ha of Mo were added to the

Willamette soil. These additions were within commercial fertilizer

application rates of 0.14 to 2.24 kg/ha of Mo, and 1.2 to 6.2 kg/ha

of B (Tisdale and Nelson, 1975).

Leaf Cd, Pb, Ni, and Cr Content

Cadmium and Pb. The Cd concentration in the corn leaves increased

slightly with lime-ash additions in 1977 (Table 26) but did not vary

significantly with waste application in 1978 (Table 27). The Cd con-

tent of leaves from corn grown in 1978 on the residual lime-ash plots

were less than the Cd contents of corn grown on the control plots

(Figure 3). This suggested the lime-ash applied Cd had become less available during the year. The apparent decrease in Cd uptake with time may have resulted from the increase in soil pH, or a reversion of the added Cd to a less soluble form.

The leaf Cd concentrations (0.20 to 0.35 µg/g) were not excessive. Allaway (1968) reports that plants normally contain from 0.2 to 0.8 µg/g Cd and that phytotoxic Cd concentrations probably exceed 3 µg/g. The minimum concentration of Cd in food that could lead to significant Cd accumulation in the tissues of animals or humans is not established, though 1.0 µg/g has been suggested (Williams et al., 1978). Since leaf Cd contents were less than 0.4 µg/g and varied little with sewage sludge ash applications, Cd uptake by corn from the ash amended soil did not represent a threat to the food chain.

Application of the ash material to the Willamette soil did not significantly alter the Pb content in the corn leaves (Tables 26 and 27). Although up to 272 kg/ha of ash Pb was applied (Table 16) and the soil Pb content increased over seven-fold, the increase in soil pH and P content with ash application probably reduced Pb availability in the soil. Both lime and P applications have been reported to reduce Pb uptake by corn (Zimbal and Foster, 1976). The leaf Pb concentrations were within the range reported to occur in plant tissues (0.1 to 10 µg/g; Allaway, 1968). Since ash applications did not result in increased leaf Pb contents, translocation of Pb into the food chain did not appear to be a hazard.

Leaf Cd and Pb contents were not correlated with Cd and Pb extracted from the soil by DTPA. Also, the concentration of these two trace

metals was not significantly affected by the banded P fertilizer treatment (Table 26).

Nickel and Cr. Nickel concentrations in the corn leaf tissues (<5 μg/g) were less than could be detected by flame atomic absorption. Since phytotoxic Ni concentrations probably exceed 50 μg/g (Allaway, 1968), the quantity of Ni applied with the sewage sludge ashes (up to 18 kg/ha) was neither sufficiently high nor available to be toxic to corn.

No significant change in corn leaf Cr content with ash application or banded P treatment was observed (Tables 26 and 27). The Cr concentration in the leaves (0.73 to 3.3 μg/g) was below probable phytotoxic levels (5-10 μg/g; Pratt, 1966).

Kernel Elemental Content

Phosphorus, Ca, Mg, K, and Na. The concentration of P, Ca, Mg, and K in the corn kernels was generally unaffected by sewage sludge ash application. Significant increases in the Ca and P content of the kernels from corn grown in 1977 (Table 28) were attributed to the banded P treatment, while variations in Ca and K content in 1978, though significant, were not correlated with the rate of ash material applied (Table 29).

The kernel Na content decreased with lime-ash application in 1977 (Table 28), but did not vary significantly with ash application in 1978 (Table 29).

Trace Elements. The concentration of Zn, Cu, Pb, Cd, Mn, Cr, Mo, and B in the corn kernels (Tables 28 and 29) were generally less than

Table 28. Elemental concentration of corn kernels, 1977.[1]

Treatment														
Ash	P	Zn	Cd	Cu	Ni	Pb	Mn	Cr	Mo	Na	Ca	Mg	K	P
mt/ha	kg/ha	μg/g									%			
0	0	37	0.045	6.2	<5	1.5	16	<0.5	<0.5	49	0.027	0.21	1.8	0.49
0	90	37	0.045	5.8	<5	1.5	16	<0.5	<0.5	53	0.020	0.19	1.6	0.45
11	0	33	0.055	6.0	<5	1.1	15	<0.5	<0.5	59	0.022	0.21	1.6	0.48
11	90	34	0.056	5.2	<5	1.6	14	<0.5	<0.5	48	0.018	0.18	1.6	0.43
22	0	36	0.068	5.6	<5	1.3	16	<0.5	<0.5	28	0.023	0.19	1.6	0.45
22	90	31	0.034	4.9	<5	1.4	18	<0.5	<0.5	41	0.017	0.18	1.5	0.40
43	0	45	0.042	5.7	<5	1.7	15	<0.5	<0.5	32	0.018	0.20	1.7	0.47
43	90	38	0.041	5.1	<5	1.5	15	<0.5	<0.5	32	0.020	0.20	1.6	0.47
LSD(0.10)[2]		NS[3]	NS	NS		NS	NS			19	0.0046	NS	NS	0.047

[1]Average of four replications.

[2]Analysis of variance F values, Appendix VII.

[3]Not significant.

Table 29. Elemental concentration of corn kernels, 1978.[1]

Treatment																		
Ash																		
1977	1978	Total		Zn	Cd	Cu	Ni	Pb	Mn	Cr	Mo	B	Na	Ca	Mg	K	P
— mt/ha —			kg/ha						$\mu g/g$						%		
0	0	0	0	33	0.046	5.8	<5	9.6	20	<0.5	<0.5	0.72	100	0.017	0.19	1.4	0.54
0	0	0	90	40	0.062	6.3	<5	13	21	<0.5	<0.5	1.7	80	0.014	0.19	1.2	0.53
11	0	11	0	59	0.042	5.5	<5	7.9	19	<0.5	<0.5	1.1	110	0.025	0.19	1.2	0.50
11	0	11	90	38	0.071	5.5	<5	8.8	18	<0.5	<0.5	2.5	100	0.015	0.18	1.4	0.51
11	16	27	90	45	0.041	5.0	<5	6.5	15	0.73	<0.5	2.8	70	0.014	0.18	1.3	0.47
22	0	22	0	43	0.061	5.5	<5	4.6	16	1.4	<0.5	0.79	50	0.016	0.17	1.2	0.49
22	0	22	90	51	0.042	6.1	<5	12	15	<0.5	<0.5	1.8	130	0.015	0.19	1.3	0.52
22	31	53	90	51	0.051	5.4	<5	12	16	0.5	<0.5	1.8	100	0.013	0.19	1.4	0.54
43	0	43	0	49	0.045	5.5	<5	8.3	16	0.85	<0.5	1.6	150	0.017	0.20	1.4	0.57
43	0	43	90	49	0.104	6.4	<5	13	14	0.63	<0.5	1.8	50	0.011	0.19	1.2	0.57
43	63	106	90	52	0.038	5.3	<5	5	14	1.4	<0.5	1.2	70	0.013	0.19	1.4	0.55
LSD(0.10)[2]				NS[3]	NS	NS			3.1	NS		0.95	NS	0.006	NS	0.13	NS

[1]Average of four replications.

[2]Analysis of variance F values, Appendix VII.

[3]Not significant.

the concentration of these trace elements in the leaf tissues (Tables
26 and 27). The Ni concentration (<5 µg/g) in the kernels, similar to
the leaves, was less than could be detected by flame atomic absorption.
With the exception of Mn and B in 1978, the trace element content in
the kernels did not vary significantly with ash applications. The Mn
content decreased while the B content increased slightly with ash
applications in 1978 (Table 29).

The Cd concentration in the corn kernels was low, generally less
than 0.07 µg/g (Tables 28 and 29). The highest Cd concentration
detected (0.106 µg/g) was still within the Cd levels (0.035 to 1.2 µg/g)
found in corn kernels from different areas of the United States (Garcia
et al., 1974). Also, the kernel Cd contents were less than the 1.0
µg/g of Cd in feed that has been suggested as a level at which signifi-
cant accumulation of Cd in animal tissues could occur (Williams et al.,
1978).

While both Zn and Cd concentration in the kernels were less than
leaf contents, the ratio of Cd:Zn in the kernels was lower than the
Cd:Zn ratio in the leaves (Table 30), suggesting a greater exclusion
of Cd than Zn during grain filling. With respect to Cd toxicity in
animals, this relative increase in kernel Zn content could be benefi-
cial, since the toxic effects of Cd are reduced by increasing the
dietary concentration of Zn (Underwood, 1977). The Cd:Zn ratio in the
kernels was not affected by ash applications.

The Pb contents of kernels from corn grown in 1977 were less
than 2 µg/g and were unaffected by the ash treatments (Table 28).
Relatively high kernel Pb contents were detected in 1978, but showed no

Table 30. Cd:Zn ratio in corn leaves and kernels.[1]

1977				1978				
		Cd:Zn		Ash			Cd:Zn	
Ash	P	Leaf	Kernel	1977	1978	P	Leaf	Kernel
mt/ha	kg/ha	——— % ———		— mt/ha —		kg/ha	——— % ———	
0	0	0.44	0.12	0	0	0	0.57	0.14
0	90	0.54	0.12	0	0	90	0.49	0.16
11	0	0.54	0.17	11	0	0	0.44	0.071
11	90	0.59	0.16	11	0	90	0.43	0.19
				11	16	90	0.39	0.091
22	0	0.45	0.19	22	0	0	0.40	0.14
22	90	0.48	0.11	22	0	90	0.43	0.082
				22	27	90	0.35	0.10
43	0	0.45	0.093	43	0	0	0.42	0.092
43	90	0.58	0.11	43	0	90	0.47	0.21
				43	63	90	0.39	0.073

[1]Calculated from Tables 26, 27, 28 and 29.

relationship to the ash treatments (Table 29), while the variable occurrence of the high Pb values (Appendix IV, Table 5) suggested the kernels were contaminated by Pb during sample collection, preparation, or analysis. Based on the 1977 kernel Pb contents, the ash applications did not contribute to elevated levels of this potentially toxic trace metal in the edible grain tissue.

The B concentration in the corn kernels increased slightly with sewage sludge ash application in 1978 (Table 29). The B levels of the kernels were low (<3.0 µg/g) compared to B levels reported for plant tissues (5-10 µg/g; Allaway, 1968). The increase in both leaf and kernel B content with ash application suggest the waste materials contained available B.

Silage Elemental Content

The elemental content of the corn silage was not measurably affected by application of sewage sludge ash in 1977 (Table 31). The elemental concentrations in the whole corn plants were comparable to levels of plant tissues and generally less than levels detected in the corn leaves. Hence ash applications did not adversely affect the nutritional feed quality of the silage with respect to the elements assayed (Zn, Cd, Cu, Pb, Ni, Cr, Mn, Mo, Na, Ca, Mg, K, and P).

Summary

Addition of sewage sludge ash increased the pH, exchangeable Ca, available P, and total P, Zn, Cd, Cu, Pb, Ni, and Cr of the Willamette silt loam soil. Zinc, Cd, Cu, and Pb extracted from the soil by DTPA

Table 31. Elemental concentration of corn silage, 1977.[1]

Treatment														
Ash	P	Zn	Cd	Cu	Ni	Pb	Mn	Cr	Mo	Na	Ca	Mg	K	P
mt/ha	kg/ha					µg/g						%		
0	0	44	0.14	5.8	<5	2.0	52	<0.5	0.25	48	0.19	0.17	1.8	0.32
0	90	38	0.15	4.8	<5	2.3	46	<0.5	0.38	42	0.19	0.15	1.8	0.29
11	0	48	0.17	5.6	<5	2.0	50	<0.5	0.45	47	0.22	0.17	2.1	0.32
11	90	36	0.14	4.4	<5	1.7	42	<0.5	0.38	47	0.18	0.16	1.6	0.30
22	0	49	0.14	5.2	<5	2.1	45	<0.5	0.67	46	0.16	0.17	1.5	0.37
22	90	45	0.13	4.8	<5	2.7	43	<0.5	0.53	46	0.18	0.16	1.6	0.32
45	0	44	0.16	4.6	<5	2.1	42	<0.5	0.41	39	0.21	0.16	1.8	0.30
45	90	50	0.14	4.8	<5	2.0	38	<0.5	0.50	39	0.16	0.17	1.9	0.36
LSD(0.10)[2]		NS[3]	NS	NS		NS	NS		NS	NS	NS	NS	NS	NS

[1]Average of four replications.

[2]Analysis of variance F values, Appendix VII.

[3]Not significant.

increased, while extractable Mn decreased, with application of the waste material. Exchangeable Mg, K, and Na, and DTPA-extractable Ni and Cr were not measurably affected by waste applications.

Water extracted a small fraction of the total Zn, Cd, Cu, Pb, Ni, and Cr in the surface soil and little movement of these trace metals (and P) below the 15 cm soil depth was detected. These results suggested the ash applied elements were immobile in the Willamette soil and probably had negligible effect on groundwater quality.

Most elements assayed in the corn kernels and silage were unaffected by application of the waste material to the Willamette soil. Trace metal concentrations in the kernel and silage tissue were less than leaf metal contents, and occurred in concentrations normally found in plant tissues.

Corn ear and silage yield was not depressed at any rate of sewage sludge ash applied (up to 106 mt/ha). Silage, total ear yield, and mature ear yield increased with ash application the second field season. The increase in mature ear yield, in conjunction with the increase in corn leaf P content with ash application, suggested a response to P in the waste product. Lime, micronutrient, and Ca and Mg additions by the ash material may also have contribured to the increase in corn yield.

Deficiency or toxicity symptoms were not observed in the corn tissues and the corn leaves contained adequate levels of the essential nutrients assayed, although B and Mo concentrations were somewhat low. The P, Ca, Mg, Zn, B, and possibly Mo contents of the corn leaves increased with ash applications, while the K and Mn contents decreased.

Normal Cd, Pb, Ni, and Cr levels were detected in the corn tissues and were unaffected by ash applications, except for Cd, which increased slightly with addition of the waste material in 1977. The corn leaf Zn and Mn contents correlated with Zn and Mn extracted from the soil by DTPA, while Cu, Pb, and Cd contents in the corn leaves were not correlated with the soil DTPA-extractable Cu, Pb, and Cd contents, respectively.

At the highest application rate of sewage sludge ash (106 mt/ha); Zn, Cd, Cu, Pb, and Ni additions to the Willamette soil did not exceed the U.S. Environmental Protection Agency's recommended maximum allowable additions. Copper and Zn additions were 79 and 65%, respectively, of the recommended limits, while Pb, Cd, and Ni additions were less than 30% of the maximum allowable additions. Since corn yield increased with ash application without excessive trace element uptake, application of the sewage sludge ashes at rates not exceeding the recommended trace metal additions appeared acceptable. Application of the ash materials containing lime would also be limited by the lime requirement of the soil.

RESULTS AND DISCUSSION: GREENHOUSE STUDY

Corn Growth

Corn seed germination occurred at all rates of ash application, even in the pure ashes. Since poor germination is often associated with high soluble salt concentrations (Tisdale and Nelson, 1975), the soluble salt content of the ashes was not sufficiently high, as was predicted by extract conductivities (Table 10), to inhibit germination.

Corn growth differed markedly in the pots which only contained the two pure ash materials (Table 32). Remarkably, corn grown on the pure ash low in water extractable Cr, with a $CaCO_3$ equivalence of 15%, and an initial pH of 8.1 (ash 3) yielded 10.8 g/pot, comparable to the four week old corn plant yield on the control soils. In contrast, corn grown on the ash high in water extractable Cr, with a $CaCO_3$ equivalence of 25%, and an initial pH of 8.4 (ash 2), yielded only 1.1 g/pot and was severely stunted, chlorotic, and had poorly developed root systems.

The poor growth of corn on pure ash 2 may be attributed to the concentration (12.5 µg/g) of water extractable Cr which, if Cr(VI), exceeded the 10 µg/g of Cr found toxic to corn in sand culture (Soane and Saunders, 1959). The concentration of water extractable Zn, Cd, Cu, Ni, Pb, Mn, and B were low in both ashes (Table 11) and therefore less probable causes of the observed poor growth. However, since the ashes differed in lime content, pH, and in the total concentration of most elements (Tables 8, 10, 11), it is difficult to conclude with certainty that the water soluble Cr in ash 2 was toxic to corn in the pure ash. Of practical importance is that when corn was grown in soil

Table 32. Yield and elemental concentration of whole corn plants grown in the greenhouse on Willamette silt loam treated with sewage sludge ash.[1]

	Ash									Elemental Content						
Appli-cation	Type[4]	Zn Applied	Yield	Zn	Cd	Cu	Ni	Pb	Mn	Cr	Na	Ca	Mg	K	P
mt/ha		kg/ha	g/pot							µg/g					
0	–	0	9.6	48	0.17	4.7	<5	2.6	53	1.1	23	0.23	0.13	2.8	0.13
0+P[5]	–	0	11.1	47	0.20	8.3	<5	2.8	65	2.1	36	0.23	0.14	2.7	0.19
94	3	280	18.0	85	0.23	9.3	<5	2.8	45	1.4	38	0.21	0.20	2.3	0.31
58	2	280	15.8	49	0.22	8.5	<5	4.2	34	1.0	18	0.26	0.16	2.6	0.18
185	3	560	19.5	82	0.18	13.0	<5	4.1	40	2.9	46	0.24	0.25	2.1	0.34
120	2	560	15.7	51	0.21	8.0	<5	3.3	32	1.2	14	0.26	0.20	2.5	0.19
370	3	1120	15.4	86	0.18	9.0	<5	3.5	39	1.3	35	0.29	0.30	2.0	0.38
240	2	1120	15.6	47	0.19	4.5	<5	3.7	28	0.7	32	0.33	0.20	2.5	0.21
740	3	2240	14.9	82	0.20	13.0	<5	3.9	47	1.7	5	0.25	0.29	1.7	0.34
475	2	2240	14.5	36	0.20	7.3	<5	2.6	38	1.1	33	0.37	0.25	2.5	0.18
%															
100	3	–	10.3	106	0.20	15.0	<5	4.2	37	1.1	36	0.41	0.39	0.79	0.18
100	2	–	1.1	37	0.08	6.0	<5	5.9	28	1.5	49	0.57	0.25	1.5	0.10
LSD(0.10)[2]			3.4	10	NS[3]	NS		NS	6.2	NS	22	0.15	0.05	0.04	0.048

[1]Average of four replications.

[2]Analysis of variance F values, Appendix VII.

[3]Not significant.

[4]Ash sample 2 had a greater content of water extractable Cr and lime.

[5]500 kg/ha P(0-45-0).

treated with ash 2 at rates up to 475 mt/ha, no toxicity was observed.
Thus, if the water soluble Cr in ash 2 was toxic to corn in the pure
ash, when mixed with soil this form of Cr was sorbed, or simply diluted,
to tolerable levels.

Both ashes applied at rates up to four times the maximum allowable
addition of 560 kg/ha of Zn enhanced the growth of corn compared to the
P fertilized control soil (Table 32). The greatest yield (19.5 g/pot)
occurred at 185 mt/ha of the ash low in water extractable Cr (ash 3),
which exceeded the yield on the P fertilized control soil (11.1 g/pot)
by 76%. This application rate corresponded to the recommended maximum
allowable Zn addition. At higher application rates of ash 3 the yield
increase over the P fertilized control soil decreased to 39% and 34% at
370 mt/ha and 740 mt/ha, respectively. A similar trend, though less
pronounced, occurred with ash 2 applications. These results suggest
that for optimum corn growth, application of these ashes could be
regulated by the recommended Zn addition.

The effects of ash applications on the pH and bulk density of the
Willamette soil may have been important in relation to the growth of
corn. The soil pH increased and bulk density decreased with the addi-
tion of both ashes (Table 33). Water infiltrated more quickly into the
ash amended soils than in the control soil, as would be predicted from
a decrease in bulk density. The decreased bulk density could have
increased root penetration, improved the rate of oxygen diffusion into
the ash-soil mixtures, and improved the response to the applied N
fertilizer. The negative effects of soil compaction (increased bulk
density) on both the growth of corn and its response to fertilizer has

Table 33. Soil pH and bulk density of ash-soil
mixtures after corn harvest.[1]

Ash			
Application	Type	pH	Bulk Density
mt/ha			g/cm^3
0		4.5	1.14
0+P[2]		4.7	1.10
94	3	5.0	1.00
58	2	5.1	1.04
185	3	5.2	0.96
120	2	5.5	0.98
370	3	5.5	0.92
240	2	6.1	0.98
740	3	5.7	0.90
475	2	6.6	0.93
%			
100	3	7.1	0.57
100	2	7.9	0.54

[1]Average of four replications.

[2]500 kg/ha P(0-45-0).

has been observed (Bertrand and Kahnke, 1957).

The initial pH of the control soils was 5.2-5.3 but decreased, probably from nitrification of applied ammonium ions, to 4.5-4.7 after the growing season (Table 33). In this acid pH range, low levels of available P and Mo and excessive solubility of Al and Mn may reduce crop yields. The low P content of corn grown on the control soils which received P fertilizer compared to corn grown on soil amended with ash 3, may be due in part to the relatively low pH of the control soils. Ash applications increased the soil pH to a more favorable range for corn growth, between 5.0 and 6.6

Elemental Content of Corn Plants

Though a relatively high level of water soluble Cr was present in ash 2, the concentration of Cr in corn plants grown on the pure ash or on ash 2 amended soil was not significantly increased over that measured in corn grown on the unamended soil (Table 32). However, this does not exclude Cr toxicity in the pure ash because this element may exert its toxic effect without being excessively translocated to plant tops (Soane and Saunders, 1959).

With application of 475 mt/ha of ash 2 and 740 mt/ha of ash 3, the recommended allowable additions of Zn, Cd, Cu, Ni, and Pb (Table 3; USEPA, 1977) were exceeded by ash elemental additions (Table 34). Despite these additions, the Cd, Cu, Pb, and Ni concentration in corn plants grown on both ash amended soils, and Zn on ash 2 amended soil, was not measurably affected (Table 32). These results, in conjunction with the low concentration of Zn, Cd, Cu, Pb, and Ni in water extracts

Table 34. Elemental additions to soil treated with sewage sludge ash.

Ash Application mt/ha	Type	Zn	Cd	Cu	Ni	Pb	Cr	B	Mo	Na	Ca	Mg	K	P
						kg/ha						mt/ha		
0		0	0	0	0	0	0	0	0	0	0	0	0	0
0		0	0	0	0	0	0	0	0	0	0	0	0	0.5[1]
94	3	280	0.86	109	13	179	45	3.1	0.52	85	5.7	0.36	0.15	5.5
58	2	280	1.1	87	7.6	151	111	3.6	0.18	67	7.9	0.20	0.16	3.0
185	3	560	1.7	217	27	358	89	6.3	1.0	170	11	0.70	0.30	11
120	2	560	2.1	175	15	302	222	7.1	0.36	134	16	0.42	0.32	6.0
370	3	1120	3.4	435	54	717	179	12	2.1	511	22	1.4	0.59	22
240	2	1120	4.1	350	30	605	444	14	0.72	269	33	0.84	0.65	12
740	3	2240	6.8	869	108	1430	357	25	4.1	1021	45	2.8	1.2	44
475	2	2240	8.6	700	61	1210	883	28	1.4	538	65	1.7	1.3	24

[1]P fertilizer application (0-45-0).

of the ashes (Table 11), suggest that these ash metals are not readily available to corn. Also, the availability of these ash applied trace metals was probably reduced with the concurrent increase in soil pH (Table 33).

The concentration of Zn in corn plants grown on soil treated with ash 3 (lower in lime and water extractable Cr) was greater than that in corn grown on the control soils; however, the Zn content of the plants did not increase in proportion to the amount of ash 3 applied (Table 32). For example, corn grown in soils treated with 94, 185, 370, and 740 mt/ha of ash 3, applications which added 280, 560, 1120, and 2240 kg/ha of Zn, respectively, all had plant Zn contents between 82 and 86 μg/g. The increase in soil pH with ash application (Table 33), which would reduce Zn availability, probably explained why the Zn content did not further increase with the higher application rate of ash 3.

The Mn concentration in the corn plants decreased with ash application (Table 32) as a result of the increase in soil pH (Table 33). The lowest Mn content was 28 μg/g and the highest 65 μg/g, both within the normal concentration range for plant tissues of 5 to 100 μg/g of Mn (Allaway, 1968).

The K content of the corn plants decreased with ash application while the Ca and Mg contents increased (Table 32). This would be expected since the ashes applied greater quantities of Ca and Mg than K (Table 34), which would depress K uptake. The K content decreased from 2.8% in control plants to 1.7% in corn grown on soil amended with 740 mt/ha of ash 3. Conceivably, at higher ash application rates, a Ca/Mg induced K deficiency could develop.

The P content of corn on ash 3 amended soil exceeded that of corn grown on the P fertilized control soil. Since corn yield tends to increase with the P content of young tissues (Adriano and Murphy, 1970), a response to P may account for the yield increase of the four week old corn plants on the ash amended soil. However, this may be an oversimplification since corn grown on soil treated with ash 2 (higher in lime and water extractable Cr) did not have a greater P content than corn grown on the control soil with P fertilizer (Table 32), yet corn yield was still greater on the ash amended soil.

Summary

Corn grown in pure ash containing a relatively greater concentration of water extractable Cr and lime (ash 2) was severely stunted and chlorotic. In contrast, corn yield on the pure ash with only a trace of water extractable Cr and lower in lime equaled plant yield on control soils. Corn yield was greater on all ash amended soils than on control soils. Thus, if the water soluble Cr in ash 2 was toxic to corn in the pure ash, this problem was alleviated when the ash was mixed with soil at rates up to 475 mt/ha.

The greater corn plant yield on the ash amended soils could have been related to the increase in soil pH, the decrease in soil bulk density, and the increase in P uptake with ash applications. The greatest corn yield occurred at the maximum allowable Zn addition, which suggests that for optimum corn growth, ash application rates could be regulated by the recommended Zn addition.

The concentration of Cd, Cu, Ni, Pb, and Cr in the corn plants was not measurably affected by ash applications. This suggests that these trace metals may not be in forms readily available (or easily translocated to plant tops) in the ashes.

Though both ashes applied equivalent amounts of Zn (up to 2240 kg/ha), the concentration of Zn in the corn plants only increased with application of ash 3. Also, at 280 and 560 kg/ha of ash applied Zn, the yield and P content of corn grown on ash 3 amended soil exceeded that of corn grown on ash 2 amended soil. Ashes which differ in water extractable Cr, lime, P, and other constituents, when applied to agricultural land at rates limited by Zn addition, may not have the same effect on crop growth and elemental composition.

SUMMARY AND CONCLUSIONS

Incinerated sewage sludge ash applied at rates up to 106 mt/ha to Willamette silt loam served as a useful soil amendment for sweet corn production. Constituents of the waste material of potential fertilizer value included P, lime, Ca, Mg, and micronutrients Zn, Cu, B, and Mo.

Corn Production

Sweet corn yields were not depressed by application of sewage sludge ash during two crop seasons. Corn ear and silage yield increased the second field season with ash applied at rates up to 106 mt/ha (the highest application rate). The ash treatments primarily enhanced corn ear maturity. Mature corn ear yield and leaf P content increased both with ash application and with P fertilizer treatments, suggesting a P response from the waste product.

The leaf tissues of corn grown on unamended and waste-treated soil contained generally adequate levels of the nutrient elements assayed, although B and Mo concentrations were relatively low. The P, Ca, Mg, Zn, B, and possibly Mo concentration of the corn leaves increased with ash application, while K and Mn contents decreased. The Cu levels of the corn leaves were affected very little by waste application. The concentration in the leaves of trace metals considered nonessential to plants; Cd, Pb, Ni, and Cr, were comparable to levels which normally occur in plant tissue. Lead, Ni, and Cr contents in the corn leaves were not measurably affected by ash application, while a slight increase in leaf Cd content occurred with ash application the first season.

Cadmium availability apparently decreased during the year, since the Cd content of the corn leaves from plants grown the following season on the waste-treated soil decreased to levels below leaves from corn grown on control plots.

Most elements assayed in the corn kernels and silage were unaffected by application of sewage sludge ash to the Willamette soil. Trace metal concentrations in the kernel and silage tissues were less than metal contents of the leaf tissue, and were similar to concentrations commonly detected in crops. Trace metal entry into the food chain, a major concern associated with land application of sewage sludge wastes, did not appear to be a problem on the ash-treated soil.

Addition of sewage sludge ash increased the surface soil pH and exchangeable Ca content, while the DTPA-extractable Mn content decreased; effects particularly beneficial on acid soils. The waste material contained relatively small amounts of Mg, K, and Na compared to Ca, and ash application did not significantly affect the exchangeable Mg, K, and Na content of the soil. Ash produced when lime was used to precipitate P from the sewage effluent was a more effective liming material than ash containing alum.

A significant effect on the fertility status of the soil, with respect to corn growth, was the increase in available P content with ash application. However, a considerably greater broadcast application of P from the ash course was necessary to enhance ear maturity compared to banding P fertilizer.

Although micronutrient additions did not adversely affect corn growth, the contribution of the ash applied Zn, Cu, B, and Mo to the increase in corn yield was not clearly demonstrated.

The highest sewage sludge ash application in the field study was about 80% of the maximum rate that would be allowed according to the U.S. Environmental Protection Agency guidelines (USEPA, 1977) for trace metal additions. Corn was grown in the greenhouse on Willamette soil treated with ash at rates which added up to four times the Zn application recommended in the USEPA guidelines. Excessive trace metal uptake or phytotoxicity was not a problem, and corn plant yield on the ash-amended soil was greater than the plant yield on the P fertilized control soil. Enhanced corn growth may have been attributed, in part, to the decrease in soil bulk density with ash application. Plant yields were greatest when ash was applied at rates which approximated the maximum allowable Zn addition, suggesting that for optimum corn growth, ash application could be regulated by the USEPA guidelines for Zn addition. Depressed K uptake at higher application rates (740 mt/ha) could have been a factor limiting further yield increases.

One of the sewage sludge ashes used in the greenhouse study contained a relatively high content of water extractable Cr. Since Cr toxicity was not observed in corn grown on the ash-amended soil, this level of water soluble Cr in the ash materials would not be a factor limiting application rates of ash when applied according to the Zn limitation.

Trace metal uptake on waste-treated soil in the field and greenhouse study was probably minimized by (1) the increase in soil pH with ash application and (2) the sparingly soluble trace metal species in the ash product. Also, the large amounts of P applied as a constituent of the ashes may have reduced the availability of some trace metals, e.g., Pb.

Soil Enrichment of Trace Metals

A long term hazard in the use of sewage waste material on agricultural lands is accumulation of potentially toxic trace metals in the soil. Trace metal enrichment in the Willamette surface soil, measured by the increase in total metal content with the highest application of sewage sludge ash, was over five-fold for Pb and Cu, between two- and four-fold for Zn, Cr, and Cd, and less than two-fold for Ni. Zinc, Cd, Cu, and Pb extracted from the soil by DTPA increased with application of the waste material, while DTPA-extractable Ni and Cr levels were not measurably affected by ash applications. Since corn grew satisfactorily on the waste-treated soil, the trace metal accumulation thus far did not appear to be a problem for crop production.

The Zn and Mn concentration in the corn leaves correlated with DTPA-extractable Zn and Mn in the soil, indicating the DTPA soil test was a useful indicator of plant-available Zn and Mn on the ash-amended soil. Increases in Cd, Pb, and Cu contents extracted from the soil by DTPA were not reflected by increases in corn leaf contents. The elevated DTPA-extractable Pb, Cd, and Cu contents in the ash-amended soil represented levels insufficient to be phytotoxic to corn or to result in a measurable increase in plant uptake.

Little movement of sewage sludge ash-applied trace metals below tillage depth occurred. Thus, the sparingly soluble trace metals in the waste-treated soil did not represent a source of groundwater contamination.

One ash sample contained a relatively high content of water soluble Cr, probably anionic Cr(VI). The water soluble Cr was only partially

sorbed when the ash was incubated with an equal weight of surface soil and therefore a portion could be leached in soil amended with the ash. However, the water soluble Cr comprised only a small fraction of the total Cr content of the ash; a concentration not sufficient to suggest that ash applications of 106 mt/ha would significantly affect ground-water quality.

Recommendations

The USEPA (1977) has recommended that sewage sludge addition to soil be limited by cumulative added amounts of Zn, Cd, Cu, Ni, and Pb. Applied according to these guidelines, sewage sludge ash may serve as a useful soil amendment for sweet corn production on Willamette silt loam soil. Added amounts of Zn would limit the application rate of a typical ash to about 120 mt/ha. Higher ash application rates may be undesirable for reasons other than trace metal additions, e.g., depressed K uptake and possible overliming. Utilization of the ash material as a source of P, lime, or micronutrients would probably not be as efficient as the use of commercial fertilizer and liming materials, but land application is a feasible waste management option.

Future Research Needs

The USEPA (1977) trace metal application limits may be conservative for sewage sludge ash in that higher loading rates could be tolerated, as suggested by the greenhouse study, without a reduction in corn yield or contribution to trace metal entry into the food chain. Conceivably, depressed K uptake could limit crop growth at very high application

rates of ash, but further field experiments would be required for veri-
fication.

Analysis of additional ash samples would be desirable to determine
if Cr(VI) concentrations occur which could limit utilization of the
waste on agricultural soil. If present, this relatively toxic and
mobile form of Cr may be reduced by soil organic matter to insoluble
Cr(III); but if not, it could restrict crop growth or be leached into
groundwater.

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APPENDICES

APPENDIX I: SOIL DESCRIPTION

Willamette Silt Loam

Described:	May 1977, by M. E. Mellbye.
Location:	North Willamette Experiment Station, Aurora, Oregon.
Landform:	Low, broad valley terraces.
Slope:	0 to 3%.
Parent material:	Silty alluvium.
Drainage:	Well-drained.
Climate:	Modified marine climate, 79 to 130 cm annual precipitation.
Organic matter:	3.7% (OSU Soil Testing Laboratory, March 1979).
Profile:	Located 2 m east of the SE corner of the experimental plots.

Horizon	Depth	Description (moist colors given).
Ap	0-20 cm	Very dark brown (10YR 2/2) silt loam; moderate, medium, granular structure; friable, slightly sticky and slightly plastic; common roots; many fine tubular pores; few to common red sandstone rock fragments; strongly acid (pH 5.2); gradual smooth boundary.
A1	20-46 cm	Dark brown (10YR 3/3) silt loam, moderate, medium, granular structure; friable, slightly sticky and slightly plastic; common roots; many fine, tubular pores; few to common red sandstone rock fragments; strongly acid (pH 5.2); clear, smooth boundary.
A3	46-56 cm	Dark brown (10YR 3/3) silt loam; moderate, medium, granular structure breaking to moderate, fine, subangular blocky structure; firable, slightly sticky and slightly plastic; common roots; common, fine tubular pores; few to common red sandstone rock fragments; strongly acid (pH 5.3); clear, smooth boundary.

B1t	59-69 cm	Dark brown (10YR 4/3) silty clay loam; moderate, medium, subangular blocky structure; friable, sticky and slightly plastic; few roots; common, fine tubular pores; few to common red sandstone rock fragments; few thin clay films; medium acid (pH 5.7); gradual, smooth boundary.
B21t	69-89 cm	Dark yellowish-brown (10YR 3/4) silty clay loam; moderate medium blocky structure; friable, hard, sticky and plastic; few roots; common, fine tubular pores; few to common red sandstone rock fragments; medium clay films; medium acid (pH 5.8); gradual, smooth boundary.
B22t	89-120 cm	Dark yellowish-brown (10YR 3/4) silty clay loam; moderate, medium blocky breaking to weak, medium prizmatic structure; friable, hard, sticky and plastic; few roots; common, very fine tubular pores; few to common red sandstone rock fragments; few clay films; medium acid (pH 5.8); gradual, smooth boundary.
C	120 cm-	Dark yellowish-brown (10YR 4/4) silt loam; massive breaking to coarse, medium, subangular blocky structure; friable, hard, slightly sticky and slightly plastic; few to common red sandstone rock fragments; medium acid (pH 6.0).

Classification: Pachic Ultic Argixeroll: fine-silty, mixed, mesic.

Table II-1. Elemental content of sewage sludge ash.

Ash Sample	Repli-cation	Zn	Cd	Cu	Ni	Pb	Mn	Cr	Mo	B	Na	Fe	Al	Ca	Mg	K	P
		µg/g										%					
1	1	3300	14.9	1400	130	2000	1200	1650	3.3	44	1150	2.6	2.3	16.8	0.31	0.23	4.2
	2	3700	14.9	1300	140	1850	1150	1450	2.5	54	1000	3.0	2.1	16.2	0.31	0.21	4.2
	3	3700	14.9	1200	130	2000	1250	1650	2.7	40	1000	2.8	2.2	16.0	0.29	0.24	4.1
	4	3700	15.3	1400	130	2000	1200	1650	3.3	64	1150	2.8	2.4	16.7	0.32	0.23	4.1
	5	3700	15.0	1300	135	2100	1250	1650	4.7	50	1100	2.8	2.4	16.5	0.30	0.22	4.0
2	1	4900	15.0	1500	135	2650	1400	1950	3.2	44	1150	3.0	2.5	13.4	0.35	0.28	5.2
	2	4600	15.0	1500	125	2600	1350	1850	4.0	82	1150	3.2	2.9	14.8	0.35	0.26	5.7
	3	4600	14.9	1500	135	2750	1400	1900	1.8	54	1200	3.5	2.5	13.7	0.36	0.27	5.1
	4	4800	15.2	1500	125	2600	1400	1900	3.2	61	1100	3.0	2.5	13.9	0.35	0.27	5.0
	5	4400	15.3	1550	125	2600	1450	1900	3.0	64	1200	3.0	2.5	12.4	0.34	0.28	4.8
3	1	3000	15.0	1150	140	1850	1900	605	7.2	33	950	3.0	1.2	6.6	0.39	0.17	4.3
	2	2900	14.6	1150	125	1900	1700	475	5.5	30	900	2.3	1.0	6.2	0.38	0.17	5.3
	3	3100	14.5	1100	145	1950	1750	465	3.4	26	850	2.4	1.1	5.6	0.37	0.15	6.5
	4	3000	15.0	1200	135	1950	1750	450	6.0	34	900	2.7	1.1	6.0	0.38	0.16	5.9
	5	2900	15.0	1150	140	1950	1850	500	3.4	40	900	2.6	1.1	6.0	0.39	0.16	6.9
4	1	4500	15.3	1550	170	3500	1050	900	NA	40	1200	2.2	3.7	10.0	0.25	0.27	7.5
	2	4900	15.1	1700	190	3900	1150	950	NA	72	1150	2.2	3.9	11.7	0.29	0.24	8.2
	3	5000	14.8	1750	200	3700	1100	1150	NA	48	1300	2.3	4.0	11.4	0.26	0.30	8.5
	4	4800	15.1	1750	180	3800	1100	1050	NA	64	1200	2.0	4.2	11.0	0.27	0.26	8.1
	5	5500	15.5	1850	205	3900	1150	1200	NA	56	1200	2.4	4.5	10.9	0.25	0.27	8.1
6	1	2700	10.7	2400	420	3050	1950	600	4.2	20	1000	3.5	NA	6.7	1.0	0.41	6.1
	2	2900	10.3	2150	250	2900	1800	540	4.6	20	1050	2.4	NA	6.3	0.98	0.36	5.6
	3	1700	10.5	2250	260	3100	1800	600	3.4	22	900	3.6	NA	7.1	1.0	0.38	5.8
	4	2700	10.7	2200	290	3000	1800	500	5.8	20	1100	2.9	NA	6.6	1.1	0.40	5.3
	5	3300	10.6	2250	250	3000	1850	560	4.4	26	1000	3.2	NA	6.3	1.0	0.39	6.1

Table II-2. Physical and chemical properties of sewage sludge ash.

Ash Sample	Repli- cation	Extract Conduc- tivity	pH	Lime Value CaCO$_3$ Equivalence	Fineness Factor	Moisture Content	Content Not Acid Digestible
		mmhos/cm		%		%	%
1	1	3.6	10.6	34.9	73.5	2.8	63
	2	3.4	11.0	33.7	69.9	3.0	44
2	1	3.5	8.4	22.8	75.4	1.0	48
	2	3.2	8.3	23.3	81.6	1.4	70
3	1	2.3	8.1	14.9	75.2	0.4	71
	2	2.1	8.0	15.0	72.9	0.6	77
4	1	NA	8.1	4.5	NA	NA	34
	2	NA	8.1	4.3	NA	NA	48
5	1	NA	7.8	1.8	NA	NA	NA
	2	NA	7.6	2.1	NA	NA	NA
6	1	2.8	8.3	13.0	61.8	30.0	56
	2	2.9	7.4	13.5	52.0	31.0	60

Table II-3. Water extractable trace elements in sewage sludge ashes.

Ash Sample	Repli- cation	Zn	Cd	Cu	Ni	Pb	Mn	Cr	B
					---------µg/g---------				
1	1	0.47	0.0067	4.1	<0.5	0.022	0.18	1.0	1.6
	2	0.02	0.0024	2.4	<0.5	0.013	0.04	1.8	1.6
2	1	0.14	0.0012	1.0	<0.5	0.041	0.07	12.9	1.4
	2	0.06	0.0013	1.1	<0.5	0.036	0.08	12.0	1.4
3	1	0.10	0.0031	0.32	<0.5	0.058	0.24	0.05	1.6
	2	0.18	0.0014	0.30	<0.5	0.16	0.34	0.06	1.2
6	1	1.05	0.0049	0.89	<0.5	0.012	1.03	0.18	1.7
	2	0.04	0.0043	0.25	<0.5	0.12	0.16	0.04	1.5

Table II-4. Water extractable metals in ash-soil mixtures after two days incubation.

Ash Sample	Soil Depth (cm)	Soil Condition	Replication	Zn	Cd	Cu	Ni	Pb	Mn	Cr
							µg/ml			
2	0-15	Dried, ground,	1	0.0085	0.12	0.22	<0.5	0.043	0.56	1.95
			2	0.0039	0.14	0.31	<0.5	0.020	0.58	0.89
			3	0.0058	0.31	0.43	<0.5	0.022	0.38	1.05
2	0-15	Fresh, moist, unsieved	1	0.0011	0.02	0.18	<0.5	0.020	0.17	2.29
			2	0.0048	0.03	0.14	<0.5	0.020	0.12	1.80
			3	0.0044	0.04	0.17	<0.5	0.013	0.21	3.03
2	79-90	Dried, ground, sieved	1	0.0066	0.10	0.25	<0.5	0.017	0.13	4.13
			2	0.0018	0.04	0.19	<0.5	0.020	0.11	4.09
			3	0.0040	0.13	0.14	<0.5	0.033	0.28	4.05
2	–	–	1	0.00	0.10	0.96	<0.5	0.020	0.08	7.26
			2	0.00	0.16	0.81	<0.5	0.026	0.09	6.71
			3	0.020	0.14	0.78	<0.5	0.029	0.12	6.92
–	0-15	Dried, ground, sieved	1	0.0024	0.08	0.05	<0.5	0.030	0.25	<0.1
			2	0.0020	0.21	0.17	<0.5	0.031	0.18	<0.1
			3	0.0030	0.64	0.23	<0.5	0.034	0.19	<0.1

APPENDIX III: CORN EAR AND SILAGE YIELD

Table III-1.   Yield of corn grown in 1977.

Treatment		Repli-	Ear			Silage	Moisture	
Ash	P	cation	Mature	Immature	Total		Ear	Silage
mt/ha	kg/ha		------- mt/ha -------			mt/ha	----- % -----	
0	0	1	19.8	26.0	31.5	180	81.1	70.2
		2	8.3	19.5	27.8	78	84.8	72.6
		3	14.1	13.7	27.8	66	82.4	67.7
		4	21.5	8.3	29.8	40	78.9	72.2
0	90	1	22.0	8.5	30.5	94	80.5	69.3
		2	21.5	8.5	34.2	81	80.9	71.8
		3	15.6	14.0	29.7	87	81.5	66.9
		4	25.6	6.8	32.4	72	76.1	68.5
11	0	1	16.3	10.6	26.9	56	81.4	63.2
		2	13.3	13.2	26.4	74	82.9	72.3
		3	20.0	11.7	31.65	85	78.5	73.0
		4	17.0	13.7	30.6	74	82.5	72.4
11	90	1	23.4	7.3	30.7	69	79.4	65.0
		2	16.3	10.7	27.0	74	81.2	66.9
		3	20.0	9.8	29.8	85	78.4	68.6
		4	23.6	10.7	34.5	88	78.9	67.1
22	0	1	9.3	16.6	25.8	65	83.3	71.7
		2	13.7	16.5	30.2	103	82.8	71.8
		3	20.7	12.2	32.9	90	78.1	74.8
		4	19.8	16.2	36.0	101	79.5	72.8
22	90	1	18.8	12.3	31.1	74	81.6	68.7
		2	23.0	10.3	33.4	78	78.4	71.0
		3	23.2	9.8	32.9	85	79.4	67.7
		4	22.9	6.5	29.4	85	76.8	66.7
43	0	1	18.6	10.3	29.0	72	80.5	72.0
		2	17.5	13.9	31.5	85	80.0	68.5
		3	21.3	15.1	36.8	94	80.0	70.8
		4	22.1	8.1	30.2	81	81.4	67.7
43	90	1	19.8	7.6	27.3	81	81.2	67.8
		2	20.2	8.6	28.8	56	80.2	73.6
		3	22.4	11.5	33.9	78	80.2	74.2
		4	23.4	14.0	37.4	101	78.9	28.3

Table III-2. Yield of corn grown in 1978.

Treatment			Repli-	Ear			Silage	Moisture	
Ash		P	cation	Mature	Immature	Total		Ear	Silage
1977	1978								
mt/ha		kg/ha		------ mt/ha ------			mt/ha	-----%-----	
0	0	0	1	11.6	9.9	21.4	63	82.5	74.8
			2	4.8	19.5	21.0	54	82.9	75.3
			3	8.8	9.7	18.5	67	81.8	75.0
			4	12.1	8.2	20.3	60	79.1	72.2
0	0	90	1	12.8	7.0	19.8	72	82.2	73.8
			2	14.1	7.4	21.5	70	80.6	70.3
			3	7.8	10.1	17.9	55	82.8	76.0
			4	16.0	3.4	19.5	62	81.3	73.1
11	0	0	1	10.4	9.7	20.1	75	81.8	72.3
			2	11.3	9.5	20.7	54	83.3	70.7
			3	9.8	9.8	19.6	67	80.4	73.0
			4	7.1	11.7	18.8	60	82.3	74.4
11	0	90	1	14.7	6.6	20.2	32	80.4	75.3
			2	16.2	4.8	21.1	49	81.7	70.2
			3	12.5	8.4	20.9	94	80.5	74.6
			4	15.9	4.8	20.7	72	78.8	77.4
11	16	90	1	11.9	6.6	18.5	75	79.2	78.3
			2	16.2	7.3	23.5	62	79.7	73.3
			3	15.7	7.7	23.5	107	79.8	74.7
			4	17.4	4.9	22.4	49	79.3	69.1
22	0	0	1	10.1	9.0	19.1	59	82.9	72.2
			2	12.6	7.2	19.8	81	81.0	75.5
			3	14.2	6.9	21.1	76	79.2	73.3
			4	14.6	3.9	21.2	83	80.8	75.0
22	0	90	1	13.1	7.3	20.4	78	83.5	75.6
			2	11.9	9.6	21.4	75	80.8	72.2
			3	14.8	5.1	19.9	72	80.7	73.6
			4	15.6	6.0	21.6	72	79.6	72.5
22	32	90	1	14.3	4.0	18.7	75	80.5	70.7
			2	14.5	6.6	21.1	59	80.8	69.8
			3	13.2	5.6	18.8	59	81.9	70.7
			4	18.2	6.0	24.2	59	80.5	74.1
43	0	0	1	13.4	5.2	18.5	72	81.2	69.8
			2	9.4	8.6	18.0	75	82.3	72.3
			3	11.4	9.7	21.1	73	80.1	72.0
			4	15.5	6.7	22.1	83	82.3	69.2

Table III-2. Continued

Treatment			Repli-	Ear			Silage	Moisture	
Ash 1977	1978	P	cation	Mature	Immature	Total		Ear	Silage
mt/ha		kg/ha		------ mt/ha ------			mt/ha	-----%-----	
43	0	0	1	13.4	5.2	18.5	72	81.2	69.8
			2	9.4	8.6	18.0	75	82.3	72.3
			3	11.4	9.7	21.1	73	80.1	72.0
			4	15.5	6.7	22.1	83	82.3	69.2
43	0	90	1	20.4	5.4	25.8	72	79.9	72.0
			2	15.9	6.9	22.8	62	80.9	73.8
			3	16.9	6.2	23.1	72	80.6	75.6
			4	18.5	2.7	21.2	68	79.1	72.1
43	63	90	1	16.7	6.2	22.9	65	79.0	76.9
			2	15.7	7.1	22.8	85	80.1	74.0
			3	15.5	7.7	23.3	85	79.2	72.3
			4	18.4	4.2	22.6	78	77.6	72.7

Table IV-1.   Elemental concentration of corn leaves, 1977.

Treatment Ash	Treatment P	Repli- cation	Zn	Cd	Cu	Ni	Pb	Mn	Cr	Mo	Na	Ca	Mg	K	P
mt/ha	kg/ha		µg/g →									← % →			
0	0	1	58	0.238	10.0	<5	2.4	78	0.6	0.09	72	0.31	0.18	2.6	0.37
		2	52	0.319	9.6	<5	5.2	86	1.4	0.28	152	0.32	0.17	3.0	0.31
		3	64	0.225	10.6	<5	2.6	80	1.6	0.05	82	0.31	0.17	2.8	0.34
		4	60	0.271	11.0	<5	3.9	81	1.6	0.04	24	0.35	0.17	2.8	0.34
0	90	1	54	0.352	8.4	<5	3.5	87	1.2	3.2	50	0.34	0.18	2.6	0.39
		2	56	0.316	5.6	<5	2.2	88	1.2	0.45	88	0.34	0.17	2.7	0.32
		3	50	0.370	8.6	<5	5.2	101	3.0	0.08	44	0.32	0.18	2.6	0.33
		4	66	0.224	8.0	<5	3.9	88	1.2	0.13	120	0.32	0.17	2.6	0.40
11	0	1	60	0.319	9.2	<5	2.5	65	1.1	1.8	124	0.33	0.18	2.6	0.32
		2	62	0.406	9.2	<5	6.4	85	1.0	1.0	20	0.33	0.17	2.8	0.34
		3	72	0.352	10.8	<5	4.8	68	2.4	1.4	20	0.33	0.17	2.8	0.37
		4	64	0.340	9.4	<5	4.0	82	1.0	0.20	104	0.35	0.17	2.8	0.34
11	90	1	56	0.295	7.8	<5	2.4	82	2.4	0.71	44	0.35	0.18	2.5	0.36
		2	66	0.340	9.0	<5	3.8	90	5.2	0.30	18	0.36	0.18	2.6	0.36
		3	58	0.316	7.6	<5	2.6	87	1.4	0.32	26	0.34	0.19	2.4	0.38
		4	56	0.421	6.6	<5	3.0	92	0.8	1.3	52	0.37	0.17	2.5	0.31
22	0	1	62	0.293	9.8	<5	3.0	68	1.2	1.7	32	0.31	0.18	2.6	0.33
		2	70	0.338	10.2	<5	8.8	67	1.8	0.43	90	0.33	0.18	2.8	0.39
		3	70	0.307	10.2	<5	4.0	67	2.0	0.56	276	0.33	0.17	2.7	0.38
		4	74	0.316	10.4	<5	3.0	82	3.0	0.33	48	0.37	0.18	2.8	0.36

Table IV-1. Continued

Treatment		Repli-												
Ash	P	cation	Zn	Cd	Cu	Ni	Pb	Mn	Cr	Mo	Na	Ca	Mg	K	P
mt/ha	kg/ha						--μg/g--						---%---		
22	90	1	60	0.323	9.4	<5	3.1	85	2.2	0.35	20	0.35	0.18	2.3	0.37
		2	54	0.298	8.8	<5	1.6	86	0.8	0.44	22	0.34	0.18	2.1	0.38
		3	58	0.301	8.2	<5	2.2	76	2.2	2.0	26	0.42	0.20	2.5	0.40
		4	66	0.248	9.8	<5	2.0	80	1.8	5.2	122	0.41	0.19	2.6	0.37
43	0	1	68	0.343	10.6	<5	3.8	65	1.4	2.0	48	0.30	0.17	2.6	0.39
		2	62	0.310	10.2	<5	4.0	72	1.4	4.2	36	0.33	0.18	2.7	0.37
		3	64	0.258	10.0	<5	3.8	66	1.8	1.4	102	0.32	0.17	2.4	0.38
		4	80	0.323	11.0	<5	3.6	90	1.4	0.04	74	0.44	0.18	2.6	0.38
43	90	1	58	0.338	9.0	<5	3.9	65	1.0	0.92	28	0.33	0.18	2.6	0.39
		2	54	0.323	8.6	<5	1.2	76	3.4	0.25	46	0.38	0.18	2.6	0.35
		3	64	0.378	8.8	<5	3.4	86	1.8	0.43	54	0.37	0.19	2.5	0.41
		4	62	0.349	8.4	<5	2.4	80	1.0	1.3	68	0.39	0.19	2.7	0.40

Table IV-2. Elemental concentration of corn kernels, 1977.

Treatment Ash mt/ha	P kg/ha	Repli-cation	Zn	Cd	Cu	Ni	Pb	Mn	Cr	Mo	Na	Ca	Mg	K	P
			←──────────────────── µg/g ────────────────────→									←────── % ──────→			
0	0	1	37	0.045	5.6	<5	2.1	17	<1	0.04	49	0.028	0.21	1.7	0.51
		2	35	0.040	8.0	<5	1.9	17	<1	0.12	53	0.036	0.23	2.0	0.55
		3	34	0.056	6.4	<5	1.1	14	<1	0.12	50	0.028	0.21	1.8	0.51
		4	40	0.040	4.8	<5	0.8	15	<1	0.01	43	0.017	0.18	1.5	0.40
0	90	1	30	0.040	5.8	<5	1.6	17	<1	0.19	64	0.020	0.20	1.7	0.48
		2	38	0.050	5.8	<5	1.6	19	<1	0.02	51	0.023	0.19	1.6	0.45
		3	38	0.052	6.6	<5	1.3	17	<1	0.03	25	0.024	0.21	1.7	0.48
		4	50	0.040	4.8	<5	1.4	12	<1	0.04	70	0.012	0.16	1.3	0.39
11	0	1	31	0.040	5.4	<5	1.6	16	<1	0.03	94	0.018	0.19	1.6	0.42
		2	36	0.080	6.8	<5	1.3	12	<1	0.04	31	0.028	0.20	1.6	0.51
		3	32	0.060	5.2	<5	0.4	16	<1	0.01	54	0.021	0.21	1.6	0.47
		4	33	0.040	6.6	<5	1.6	17	<1	0.01	53	0.022	0.23	1.7	0.52
11	90	1	35	0.085	5.6	<5	1.5	17	<1	0.16	63	0.017	0.19	1.0	0.47
		2	40	0.060	4.4	<5	2.1	14	<1	0.08	52	0.016	0.17	1.7	0.42
		3	30	0.040	5.0	<5	1.3	14	<1	0.04	40	0.018	0.18	1.4	0.42
		4	32	0.040	5.6	<5	1.4	12	<1	0.04	34	0.019	1.19	1.6	0.43
22	0	1	34	0.040	4.5	<5	1.3	18	<1	0.25	28	0.019	0.19	1.5	0.43
		2	33	0.050	6.4	<5	1.7	17	<1	0.01	20	0.013	0.20	1.7	0.48
		3	36	0.050	5.4	<5	0.7	13	<1	0.04	24	0.019	0.18	1.6	0.45
		4	39	0.130	5.8	<5	1.3	16	<1	0.02	38	0.023	0.20	1.6	0.46
22	90	1	26	0.035	5.0	<5	1.2	22	<1	0.01	28	0.020	0.18	1.4	0.41
		2	29	0.030	4.8	<5	1.1	18	<1	0.01	20	0.017	0.17	1.4	0.38
		3	26	0.035	4.4	<5	1.6	18	<1	0.11	65	0.017	0.17	1.6	0.42
		4	42	0.035	5.2	<5	1.6	18	<1	0.01	48	0.012	0.18	1.4	0.40

Table IV-2. Elemental concentration of corn kernels, 1977.

Treatment Ash	P	Repli-cation	Zn	Cd	Cu	Ni	Pb	Mn	Cr	Mo	Na	Ca	Mg	K	P
mt/ha	kg/ha		—————————————————————————μg/g—————————————————————									————————————%————————			
43	0	1	36	0.040	6.0	<5	1.3	15	<1	0.18	21	0.019	0.20	1.7	0.48
		2	26	0.042	6.2	<5	1.0	17	<1	0.04	47	0.022	0.21	1.7	0.50
		3	80	0.035	5.0	<5	2.7	13	<1	0.03	33	0.016	0.18	1.6	0.43
		4	38	0.050	5.4	<5	1.7	16	<1	0.04	29	0.016	0.19	1.6	0.46
43	90	1	38	0.050	5.4	<5	0.3	16	<1	0.70	21	0.019	0.21	1.6	0.48
		2	40	0.042	4.8	<5	2.3	13	<1	0.35	32	0.021	0.19	1.5	0.43
		3	34	0.035	5.8	<5	2.1	19	<1	0.04	33	0.023	0.21	1.6	0.50
		4	39	0.035	4.2	<5	1.1	12	<1	0.04	41	0.016	0.18	1.5	0.42

Table IV-3. Elemental concentration of corn silage, 1977.

Treatment Ash	P	Repli-cation	Zn	Cd	Cu	Ni	Pb	Mn	Cr	Mo	Na	Ca	Mg	K	P
mt/ha	kg/ha		────────────────────────μg/g────────────────────────									────────── % ───────────			
0	0	1	48	0.13	6.2	<5	1.4	48	<1	0.28	63	0.19	0.17	1.9	0.33
		2	36	0.09	6.2	<5	1.8	36	<1	0.47	33	0.12	0.16	1.6	0.32
		3	49	0.16	5.8	<5	2.7	49	<1	0.05	38	0.18	0.19	1.5	0.42
		4	41	0.19	4.8	<5	2.2	76	<1	0.19	56	0.27	0.16	2.1	0.23
0	90	1	36	0.10	4.2	<5	1.8	27	<1	0.08	36	0.12	0.15	1.7	0.33
		2	46	0.16	5.4	<5	2.7	56	<1	0.40	20	0.16	0.16	1.6	0.29
		3	32	0.19	4.8	<5	2.4	56	<1	0.56	72	0.28	0.15	2.1	0.24
		4	38	0.15	4.8	<5	2.3	46	<1	0.46	42	0.19	0.15	1.8	0.29
11	0	1	39	0.10	6.6	<5	2.0	30	<1	0.49	37	0.10	0.17	1.6	0.36
		2	50	0.16	5.4	<5	1.3	44	<1	0.35	47	0.17	0.17	1.6	0.40
		3	46	0.18	4.4	<5	2.6	58	<1	0.50	58	0.31	0.14	2.4	0.27
		4	55	0.23	6.0	<5	2.1	66	<1	0.45	43	0.31	0.19	2.7	0.27
11	90	1	32	0.17	3.8	<5	1.7	58	<1	0.59	67	0.27	0.15	1.9	0.24
		2	39	0.16	4.6	<5	2.0	43	<1	0.26	43	0.18	0.16	1.7	0.31
		3	34	0.08	4.6	<5	1.4	32	<1	0.22	33	0.09	0.16	1.0	0.37
		4	42	0.15	4.8	<5	1.7	36	<1	0.46	41	0.17	0.16	1.9	0.29
22	0	1	48	0.16	5.0	<5	2.5	54	<1	0.10	70	0.23	0.18	1.7	0.31
		2	47	0.11	6.0	<5	2.2	48	<1	0.33	48	0.16	0.18	1.4	0.42
		3	54	0.14	4.8	<5	1.8	32	<1	1.2	24	0.13	0.16	1.4	0.39
		4	47	0.14	5.2	<5	1.9	47	<1	0.19	38	0.13	0.16	1.6	0.36
22	90	1	49	0.14	5.8	<5	5.3	49	<1	1.0	46	0.15	0.17	1.3	0.33
		2	36	0.16	4.2	<5	1.9	51	<1	0.66	60	0.23	0.15	1.9	0.26
		3	41	0.13	4.6	<5	1.8	28	<1	0.30	37	0.15	0.16	1.5	0.34
		4	49	0.09	4.8	<5	1.9	44	<1	0.12	40	0.17	0.17	1.6	0.35

Table IV-3. Continued

Treatment		Repli-														
Ash	P	cation	Zn	Cd	Cu	Ni	Pb	Mn	Cr	Mo	Na	Ca	Mg	K	P
mt/ha	kg/ha		----------------------μg/g----------------------									----------%----------			
43	0	1	48	0.15	4.4	<5	1.8	28	<1	0.26	32	0.14	0.17	2.0	0.37
		2	28	0.17	4.0	<5	2.1	41	<1	0.80	44	0.25	0.15	1.9	0.22
		3	44	0.18	5.6	<5	2.3	50	<1	0.23	43	0.27	0.15	1.8	0.29
		4	55	0.14	4.6	<5	2.0	48	<1	0.34	37	0.19	0.16	1.4	0.34
43	90	1	44	0.11	4.0	<5	2.0	25	<1	0.58	31	0.11	0.16	1.8	0.35
		2	39	0.14	5.4	<5	1.7	53	<1	0.26	41	0.19	0.18	1.7	0.37
		3	45	0.14	5.0	<5	2.1	25	<1	0.46	41	0.13	0.18	2.0	0.40
		4	63	0.18	5.0	<5	2.2	49	<1	0.69	40	0.20	0.16	2.1	0.33

Table IV-4. Elemental concentration of corn leaves, 1978.

Treatment				Zn	Cd	Cu	Ni	Pb	Mn	Cr	Mo	B	Na	Ca	Mg	K	P
Ash		P	Repli-														
1977	1978		cation														
mt/ha		kg/ha		----------------------μg/g----------------------										----------%----------			
0	0	0	1	41	0.20	9.0	<1	3.2	74	3.1	0.04	6.2	8.9	0.48	0.15	2.8	0.32
			2	40	0.24	5.0	<1	3.8	70	0.8	0.01	5.3	14.0	0.50	0.16	2.9	0.36
			3	46	0.17	5.5	<1	3.0	68	1.6	0.04	4.8	6.7	0.40	0.15	2.7	0.38
			4	50	0.25	12.0	<1	4.0	77	2.1	0.04	5.0	12.2	0.42	0.15	2.8	0.35
0	0	90	1	50	0.25	6.5	<1	2.8	90	2.0	0.10	4.1	5.6	0.53	0.16	2.8	0.36
			2	31	0.23	9.0	<1	4.0	79	0.9	0.09	6.4	12.2	0.56	0.15	2.7	0.34
			3	52	0.28	11.0	<1	2.7	77	5.6	0.09	4.6	3.3	0.40	0.15	2.7	0.36
			4	55	0.16	8.5	<1	2.8	86	1.2	0.01	4.9	10.0	0.46	0.14	2.9	0.36
11	0	0	1	54	0.22	12.0	<1	2.8	64	3.0	0.18	5.5	14.4	0.41	0.16	2.7	0.36
			2	38	0.28	5.5	<1	2.6	68	2.0	0.14	5.1	5.6	0.53	0.14	2.7	0.34
			3	56	0.18	13.0	<1	3.2	67	2.5	0.17	5.2	7.8	0.43	0.15	2.8	0.39
			4	58	0.25	8.0	<1	30	76	4.5	0.19	5.5	23.0	0.54	0.16	2.4	0.39
11	0	90	1	98	0.21	6.0	<1	4.0	78	3.2	0.22	8.0	8.7	0.52	0.16	2.6	0.37
			2	37	0.23	6.5	<1	3.4	81	1.3	0.04	9.5	8.9	0.52	0.15	2.5	0.37
			3	51	0.22	6.0	<1	2.9	69	4.4	0.10	8.0	8.9	0.43	0.17	2.6	0.37
			4	58	0.20	6.0	<1	5.4	85	4.0	0.10	9.1	7.8	0.60	0.16	2.7	0.38
11	16	90	1	54	0.17	7.0	<1	0.5	68	0.8	0.24	4.6	14.4	0.47	0.15	2.9	0.40
			2	52	0.35	7.5	<1	3.4	90	1.2	0.29	6.7	8.9	0.54	0.17	2.6	0.38
			3	71	0.27	13.5	<1	3.3	71	1.2	0.80	7.1	11.0	0.47	0.18	2.5	0.42
			4	67	0.17	5.0	<1	3.8	90	1.6	0.22	4.8	6.7	0.54	0.17	2.9	0.39
22	0	0	1	49	0.32	8.5	<1	2.6	62	2.9	0.08	4.0	13.0	0.52	0.16	2.7	0.36
			2	36	0.15	6.5	<1	2.8	52	2.8	0.07	7.2	2.2	0.49	0.14	2.7	0.37
			3	56	0.15	5.0	<1	3.4	77	3.9	0.01	4.2	4.4	0.44	0.14	2.8	0.39
			4	58	0.16	6.0	<1	3.2	74	1.6	0.17	6.3	11.0	0.63	0.17	2.8	0.39

Table IV-4. Continued

Treatment																	
Ash		P	Repli-														
1977	1978		cation	Zn	Cd	Cu	Ni	Pb	Mn	Cr	Mo	B	Na	Ca	Mg	K	P
mt/ha		kg/ha		μg/g										%			
22	0	90	1	35	0.22	10.5	<1	2.5	68	5.2	0.14	5.7	8.9	0.46	0.16	2.6	0.39
			2	40	0.23	5.0	<1	3.3	70	4.4	0.04	5.7	11.0	0.54	0.15	2.5	0.45
			3	47	0.22	9.5	<1	2.8	57	1.2	0.12	5.3	1.1	0.44	0.17	3.0	0.36
			4	64	0.15	6.0	<1	2.6	73	1.3	0.34	6.2	11.0	0.55	0.14	2.7	0.39
22	32	90	1	59	0.28	8.5	<1	1.7	66	0.3	0.59	4.0	13.0	0.46	0.17	2.6	0.44
			2	66	0.24	11.0	<1	3.0	66	1.2	0.14	6.7	20.0	0.51	0.18	2.5	0.43
			3	75	0.23	9.0	<1	2.5	72	0.7	0.81	4.6	17.0	0.53	0.21	2.9	0.42
			4	74	0.21	11.0	<1	3.1	70	0.7	0.64	4.6	12.0	0.58	0.16	2.5	0.41
43	0	0	1	53	0.26	8.0	<5	7.4	69	1.6	0.21	6.1	20.0	0.46	0.16	2.6	0.38
			2	36	0.24	11.0	<5	2.9	60	3.5	0.17	6.8	5.6	0.49	0.15	2.7	0.35
			3	58	0.17	13.5	<5	3.1	48	5.4	0.47	7.8	10.0	0.44	0.16	2.6	0.37
			4	45	0.13	8.5	<5	3.0	49	0.6	0.24	3.5	3.3	0.41	0.11	2.0	0.37
43	0	90	1	53	0.22	7.0	<5	0.8	62	3.6	0.41	7.1	11.0	0.47	0.16	2.7	0.41
			2	55	0.25	10.0	<5	3.3	63	2.8	0.31	6.1	16.0	0.52	0.18	2.5	0.41
			3	52	0.22	5.0	<5	2.8	57	3.2	0.83	6.2	5.6	0.49	0.17	3.3	0.42
			4	70	0.38	9.0	<5	3.2	68	3.6	0.28	5.8	6.7	0.57	0.15	2.3	0.41
43	63	90	1	74	0.18	8.5	<5	2.6	57	2.2	0.77	6.7	12.0	0.99	0.17	2.4	0.41
			2	67	0.36	6.0	<5	2.9	65	1.5	0.49	4.1	8.9	0.56	0.18	2.4	0.42
			3	62	0.22	5.5	<5	2.5	57	0.8	1.2	8.7	8.9	0.52	0.18	2.3	0.46
			4	79	0.36	7.0	<5	3.2	64	0.6	1.5	5.3	11.0	0.61	0.19	2.4	0.47

Table IV-5. Elemental concentration of corn kernels, 1978.

Ash 1977	Ash 1978	P	Repli-cation	Zn	Cd	Cu	Ni	Pb	Mn	Cr	Mo	B	Ca	Mg	K	P
mt/ha		kg/ha		μg/g									%			
0	0	0	1	31	0.02	4.5	<5	20.7	18	<0.5	<0.5	0.10	0.026	0.17	1.0	0.52
			2	32	0.09	6.0	<5	2.3	26	<0.5	<0.5	0.56	0.014	0.21	1.4	0.61
			3	34	0.04	8.5	<5	6.8	18	<0.5	<0.5	1.1	0.019	0.20	1.3	0.50
			4	35	0.04	4.0	<5	8.5	18	<0.5	<0.5	1.1	0.010	0.19	1.2	0.51
0	0	90	1	35	0.07	5.0	<5	16.0	28	<0.5	<0.5	0.96	0.015	0.18	1.0	0.51
			2	30	0.02	6.0	<5	2.5	17	<0.5	<0.5	2.9	0.022	0.18	1.3	0.47
			3	67	0.08	6.5	<5	14.8	23	<0.5	<0.5	2.8	0.009	0.21	1.2	0.59
			4	39	0.08	7.5	<5	18.0	16	<0.5	<0.5	0.22	0.011	0.20	1.0	0.53
11	0	0	1	39	0.05	5.5	<5	2.8	19	<0.5	<0.5	2.0	0.041	0.20	1.2	0.58
			2	53	0.04	5.0	<5	5.8	19	<0.5	<0.5	0.48	0.017	0.17	1.1	0.41
			3	42	0.05	6.0	<5	13.2	18	<0.5	<0.5	0.65	0.018	0.20	1.1	0.55
			4	34	0.03	5.0	<5	9.7	20	<0.5	<0.5	1.1	0.023	0.18	1.0	0.47
11	0	90	1	29	0.04	5.0	<5	1.7	16	<0.5	<0.5	3.0	0.015	0.18	1.2	0.47
			2	33	0.16	5.5	<5	5.0	19	<0.5	<0.5	3.4	0.015	0.20	1.3	0.54
			3	33	0.03	6.0	<5	24.0	18	<0.5	<0.5	2.0	0.016	0.20	1.3	0.51
			4	55	0.06	5.5	<5	4.5	20	<0.5	<0.5	1.7	0.015	0.16	1.3	0.52
11	16	90	1	46	0.02	3.5	<5	5.0	28	<0.5	<0.5	32	0.010	0.16	1.0	0.44
			2	45	0.04	4.9	<5	6.5	17	<0.5	<0.5	2.8	0.008	0.18	1.1	0.43
			3	36	0.06	5.5	<5	8.0	23	<0.5	<0.5	2.2	0.017	0.20	1.3	0.55
			4	54	0.04	6.0	<5	–	16	<0.5	<0.5	2.9	0.019	0.18	1.2	0.47
22	0	0	1	30	0.03	5.0	<5	4.3	17	<0.5	<0.5	1.1	0.022	0.17	1.1	0.52
			2	39	0.04	5.5	<5	1.4	18	<0.5	<0.5	1.4	0.011	0.17	1.0	0.46
			3	52	0.10	5.0	<5	4.2	16	<0.5	<0.5	0.10	0.016	0.16	1.2	0.47
			4	50	0.09	6.5	<5	8.6	14	<0.5	<0.5	0.55	0.013	0.18	1.0	0.52

Table IV-5. Continued

Treatment																	
Ash		P	Repli-														
1977	1978		cation	Zn	Cd	Cu	Ni	Pb	Mn	Cr	Mo	B	Ca	Mg	K	P
mt/ha		kg/ha		------------------------------μg/g-------------------------									-------------%------------			
22	0	90	1	80	0.04	6.5	<5	22.0	15	<0.5	<0.5	1.8	0.013	0.18	1.1	0.51
			2	55	0.04	5.0	<5	6.3	16	<0.5	<0.5	1.4	0.016	0.20	1.1	0.53
			3	30	0.04	8.5	<5	14.8	16	<0.5	<0.5	1.7	0.018	0.20	1.1	0.55
			4	38	0.05	4.5	<5	4.9	14	<0.5	<0.5	2.3	0.012	0.17	1.3	0.48
22	32	90	1	47	0.04	6.5	<5	11.8	17	<0.5	<0.5	1.8	0.010	0.18	1.3	0.47
			2	46	0.05	5.0	<5	20.0	18	<0.5	<0.5	1.1	0.017	0.20	1.3	0.53
			3	57	0.06	5.5	<5	13.0	15	<0.5	<0.5	2.4	0.013	0.19	1.1	0.58
			4	55	0.06	4.5	<5	2.4	14	<0.5	<0.5	1.8	0.010	0.18	1.3	0.57
43	0	0	1	39	0.02	5.0	<5	8.3	15	<0.5	<0.5	0.77	0.017	0.19	1.4	0.56
			2	38	0.04	7.0	<5	9.2	20	<0.5	<0.5	0.80	0.016	0.21	1.1	0.53
			3	79	0.10	6.0	<5	6.1	14	<0.5	<0.5	3.2	0.015	0.18	1.1	0.53
			4	41	0.02	4.0	<5	9.5	14	<0.5	<0.5	1.5	0.020	0.19	1.2	0.54
43	0	90	1	60	0.09	9.5	<5	10.3	13	<0.5	<0.5	2.4	0.012	0.20	1.1	0.55
			2	46	0.10	6.0	<5	23.0	15	<0.5	<0.5	1.7	0.010	0.19	1.1	0.67
			3	38	0.07	5.0	<5	4.4	12	<0.5	<0.5	1.8	0.012	0.20	1.1	0.55
			4	51	0.16	5.0	<5	13.2	16	<0.5	<0.5	1.3	0.010	0.17	1.3	0.50
43	63	90	1	66	0.04	6.5	<5	5.7	13	<0.5	<0.5	0.91	0.018	0.19	1.1	0.53
			2	54	0.05	4.5	<5	3.3	15	<0.5	<0.5	2.8	0.009	0.18	1.4	0.63
			3	50	0.04	5.5	<5	6.1	15	<0.5	<0.5	0.40	0.016	0.20	1.3	0.55
			4	38	0.03	4.5	<5	5.8	14	<0.5	<0.5	0.70	0.010	0.17	1.3	0.49

APPENDIX V: SOIL ANALYSIS

Table V-1. Cation exchange capacity (CEC), exchangeable bases, P, and pH of Willamette silt loam collected in September, 1977.

Treatment		Repli-		Exchangeable Bases				P		
Ash	P	cation	CEC	Ca	Mg	K	Na	Total	Avail.	pH
mt/ha	kg/ha		--------- meq/100 g ---------					---μg/g---		
0	0	1	15.1	4.75	1.11	0.43	0.25	1260	62	5.24
		2	14.1	3.94	0.86	0.36	0.21	1450	76	5.25
		3	14.7	5.51	0.91	0.44	0.14	1560	115	5.40
		4	15.6	5.00	0.10	0.44	0.23	1800	76	5.27
0	90	1	14.8	4.47	0.95	0.38	0.35	1960	85	5.35
		2	16.0	4.29	0.87	0.41	0.26	1600	93	5.04
		3	14.7	3.89	0.87	0.36	0.23	1620	97	5.19
		4	16.3	6.21	1.24	0.48	0.30	1500	95	5.16
11	0	1	13.8	5.10	1.07	0.41	0.26	1500	90	5.28
		2	18.3	4.22	0.78	0.35	0.19	1800	99	5.14
		3	16.1	4.90	0.91	0.35	0.40	1450	105	5.13
		4	15.0	3.80	0.66	0.31	0.35	1880	102	5.32
11	90	1	13.8	5.10	0.99	0.37	0.33	1740	101	5.24
		2	13.8	4.32	0.86	0.40	0.18	1800	85	5.29
		3	14.6	3.01	0.41	0.20	0.26	1620	122	5.46
		4	24.7	4.80	0.95	0.42	0.33	1750	91	5.35
22	0	1	15.4	5.38	0.86	0.36	0.28	2050	155	5.40
		2	15.0	4.62	0.91	0.36	0.19	2020	83	5.41
		3	15.6	5.62	0.95	0.43	0.33	1700	113	5.30
		4	16.3	5.63	0.95	0.42	0.25	1820	128	5.36
22	90	1	13.8	4.55	0.70	0.36	0.35	1960	83	5.26
		2	14.5	4.80	0.70	0.31	0.25	1830	83	5.46
		3	14.7	4.81	0.87	0.37	0.23	2240	118	5.48
		4	16.3	6.69	1.40	0.50	0.32	1960	105	5.32
43	0	1	14.9	7.07	1.19	0.45	0.28	1600	95	5.51
		2	14.1	6.21	0.82	0.33	0.25	1960	106	5.68
		3	14.8	6.57	0.86	0.39	0.32	1750	89	5.52
		4	18.2	5.99	1.03	0.43	0.30	1900	85	5.49
43	90	1	14.4	5.96	0.99	0.46	0.25	1600	78	5.28
		2	14.6	5.41	0.66	0.32	0.26	1810	119	5.47
		3	15.4	6.82	0.74	0.38	0.30	1820	76	5.66
		4	16.0	5.63	0.99	0.45	0.32	1830	78	5.35

Table V-2. Trace metal concentration of Willamette silt loam collected in September, 1977.

Treatment Ash mt/ha	P kg/ha	Replication	Total Zn	Cd	Cu	Ni	Pb	Mn	Cr	DTPA Extractable Zn	Cd	Cu	Ni	Pb	Mn	Cr
										————————μg/g————————						
0	0	1	23	0.10	18	24	17	1200	26	0.80	0.062	0.36	0.28	0.34	34	<0.2
		2	12	0.09	17	25	17	1000	22	0.64	0.080	0.50	0.32	0.36	23	<0.2
		3	11	0.11	17	23	16	1050	21	0.98	0.088	0.58	0.52	0.76	24	<0.2
		4	9	0.13	17	22	18	1050	26	1.28	0.092	0.60	0.58	0.46	32	<0.2
0	90	1	14	0.08	18	18	19	1200	26	0.74	0.068	0.48	0.28	0.38	27	<0.2
		2	18	0.13	15	14	16	1100	20	0.58	0.068	0.32	0.48	0.28	21	<0.2
		3	15	0.11	16	22	22	1150	19	1.12	0.076	0.50	0.34	0.36	35	<0.2
		4	11	0.11	20	27	23	1000	23	0.80	0.088	0.44	0.36	0.38	26	<0.2
11	0	1	28	0.12	19	19	21	1200	27	0.84	0.064	0.70	0.36	0.78	25	<0.2
		2	45	0.14	17	23	23	1100	30	0.96	0.110	0.64	0.40	0.72	29	<0.2
		3	23	0.13	17	21	21	1200	27	1.10	0.080	0.60	0.52	0.62	26	<0.2
		4	9	0.25	18	23	22	1200	27	1.30	0.040	0.34	0.50	0.34	17	<0.2
11	90	1	16	0.18	20	23	22	1000	22	1.10	0.070	0.86	0.40	0.80	32	<0.2
		2	11	0.15	19	18	22	1150	25	1.20	0.062	0.80	0.44	0.82	27	<0.2
		3	16	0.12	17	21	23	1150	26	1.28	0.56	0.58	0.60	0.48	25	<0.2
		4	18	0.15	19	23	22	1150	20	0.54	0.04	0.28	0.42	0.44	18	<0.2
22	0	1	20	0.11	26	23	34	1400	33	1.28	0.074	1.06	0.42	1.84	24	<0.2
		2	39	0.14	18	22	22	900	18	1.64	0.084	0.82	0.28	0.98	20	<0.2
		3	15	0.15	20	24	22	1050	28	1.64	0.076	0.84	0.60	1.02	25	<0.2
		4	17	0.15	25	24	32	1100	31	1.50	0.030	0.46	0.32	0.46	21	<0.2
22	90	1	40	0.19	21	18	26	1150	31	0.90	0.094	0.86	0.40	1.00	19	<0.2
		2	39	0.15	23	26	22	1050	31	1.42	0.042	1.16	0.58	1.41	19	<0.2
		3	52	0.13	27	22	28	1180	31	1.16	0.110	0.86	0.52	0.96	21	<0.2
		4	20	0.16	31	28	40	1150	34	2.14	0.086	1.24	0.44	1.60	28	<0.2

Table V-2. Continued

Treatment		Repli-														
Ash	P	cation	Zn	Cd	Cu	Ni	Pb	Mn	Cr	Zn	Cd	Cu	Ni	Pb	Mn	Cr
mt/ha	kg/ha		--μg/g--													
43	0	1	25	0.12	30	25	40	1000	29	1.74	0.080	1.40	0.28	1.74	22	<0.2
		2	40	0.20	30	25	39	1150	26	1.50	0.056	1.32	0.36	1.72	18	<0.2
		3	36	0.15	24	22	32	1120	40	1.28	0.110	1.16	0.40	1.36	19	<0.2
		4	20	0.16	31	28	40	1150	34	2.14	0.086	1.24	0.44	1.60	28	<0.2
43	90	1	22	0.30	22	23	31	1000	23	1.28	0.029	1.06	0.52	1.04	24	<0.2
		2	24	0.22	34	21	30	1150	22	1.60	0.076	1.08	0.28	1.32	21	<0.2
		3	50	0.38	50	28	43	1150	33	1.88	0.120	1.41	0.36	2.08	17	<0.2
		4	45	0.17	45	22	39	1100	37	2.14	0.120	1.16	0.70	1.82	28	<0.2

Table V-3. Exchangeable bases, P, and pH of Willamette silt loam
collected in September, 1978.

Treatment				Exchangeable				P		
Ash		P	Repli-							
1977	1978		cation	Ca	Mg	K	Na	Total	Avail.	pH
mt/ha		kg/ha		--------meq/100 g--------				---µg/g---		
0	0	0	1	5.3	1.32	0.37	0.035	1260	52	5.23
			2	3.7	0.80	0.31	0.024	1450	91	5.10
			3	4.8	1.00	0.41	0.025	1600	70	5.25
			4	3.7	0.88	0.33	0.022	1500	89	5.28
0	0	90	1	4.5	0.92	0.37	0.030	1600	103	5.27
			2	4.2	0.88	0.36	0.025	1600	97	5.35
			3	4.3	0.88	0.34	0.024	1600	107	5.19
			4	5.3	1.16	0.39	0.019	1880	99	5.24
11	0	0	1	4.8	1.04	0.36	0.017	1380	54	5.34
			2	5.	0.92	0.33	0.022	1680	88	5.36
			3	5.2	0.76	0.34	0.025	1600	136	5.34
			4	4.3	0.84	0.31	0.022	1600	95	5.32
11	0	90	1	5.2	1.12	0.36	0.030	2020	91	5.36
			2	4.5	0.88	0.32	0.022	1650	89	5.28
			3	5.3	1.08	0.32	0.024	1590	112	5.45
			4	4.9	1.00	0.37	0.024	1700	125	5.30
11	16	90	1	4.3	0.96	0.34	0.031	1850	116	5.68
			2	4.5	0.96	0.31	0.034	2300	130	5.31
			3	5.1	1.00	0.33	0.025	2050	149	5.40
			4	4.6	0.88	0.36	0.032	2150	95	5.29
22	0	0	1	5.7	0.96	0.35	0.024	1520	95	5.43
			2	5.8	0.92	0.38	0.047	2000	100	5.46
			3	5.8	1.00	0.35	0.025	1700	98	5.50
			4	4.7	0.88	0.32	0.022	1700	136	4.49
22	0	90	1	4.9	0.80	0.32	0.015	1730	105	5.49
			2	4.8	0.80	0.25	0.027	1780	115	5.40
			3	5.6	0.84	0.35	0.029	1830	112	5.43
			4	7.3	1.52	0.47	0.027	2300	116	5.51
22	32	90	1	5.7	1.04	0.32	0.027	2450	93	5.45
			2	4.3	0.96	0.33	0.024	2350	148	5.37
			3	5.6	1.08	0.28	0.034	2400	160	5.57
			4	6.8	5.6	0.41	0.020	2150	116	5.50

Table V-3. Continued

Treatment				Exchangeable				P		
Ash		P	Repli-							pH
1977	1978		cation	Ca	Mg	K	Na	Total	Avail.	
mt/ha		kg/ha		--------meq/100 g--------				---µg/g---		
43	0	0	1	7.0	1.12	0.37	0.024	1960	68	5.81
			2	5.5	0.84	0.30	0.044	1960	120	5.84
			3	5.1	0.88	0.34	0.019	1960	113	5.78
			4	5.4	1.04	0.37	0.025	2100	111	5.60
43	0	90	1	6.0	1.08	0.33	0.022	2100	113	5.66
			2	6.0	1.0	0.30	0.029	2050	144	5.64
			3.	6.0	0.88	0.36	0.029	2000	115	5.80
			4	6.2	0.88	0.37	0.044	2000	128	5.56
43	63	90	1	6.5	1.32	0.37	0.027	2300	126	5.84
			2	6.0	1.0	0.29	0.035	3720	148	5.85
			3	7.0	0.88	0.30	0.032	2680	214	5.94
			4	6.2	1.24	0.39	0.034	3200	174	5.79

Table V-4. Trace metal concentration of Willamette silt loam collected in September, 1978.

Treatment Ash 1977	Ash 1978	P	Repli-cation	Total Zn	Cd	Cu	Ni	Pb	Mn	Cr	DTPA-extractable Zn	Cd	Cu	Ni	Pb	Mn	Cr
mt/ha		kg/ha		---						---	---						μg/g ---
0	0	0	1	65	0.09	19	23	17	950	23	1.12	0.070	0.76	0.30	0.94	28	<0.2
			2	90	0.13	17	21	26	1050	30	0.80	0.054	0.38	0.40	0.46	13	<0.2
			3	125	0.08	16	18	16	1050	31	0.95	0.062	0.48	0.24	0.50	20	<0.2
			4	95	0.11	19	22	15	1050	20	1.20	0.082	0.68	0.58	0.76	24	<0.2
0	0	90	1	40	0.12	16	18	16	1100	22	1.00	0.070	0.50	0.56	0.64	24	<0.2
			2	85	0.24	17	22	13	1050	19	1.00	0.082	0.60	0.44	0.66	22	<0.2
			3	80	0.10	16	15	21	1000	23	0.96	0.080	0.48	0.42	0.40	19	<0.2
			4	80	0.13	18	23	27	1000	23	1.00	0.120	0.72	0.52	0.68	28	<0.2
11	0	0	1	50	0.12	22	21	24	1000	23	1.36	0.050	0.84	0.42	0.78	11	<0.2
			2	115	0.12	20	25	28	1050	26	1.16	0.088	0.72	0.40	0.88	24	<0.2
			3	70	0.14	20	21	28	1000	25	1.84	0.094	0.94	0.46	1.02	26	<0.2
			4	125	0.13	18	24	29	1100	23	1.30	0.082	0.76	0.36	1.04	16	<0.2
11	0	90	1	375	0.10	20	27	25	1000	23	1.46	0.062	0.84	0.30	0.96	25	<0.2
			2	95	0.14	24	31	29	1100	26	2.20	0.128	1.22	0.36	1.48	27	<0.2
			3	60	0.18	18	24	20	1050	27	1.28	0.110	0.76	0.28	0.78	20	<0.2
			4	150	0.12	20	26	22	1050	29	2.50	0.058	0.92	0.56	1.02	12	<0.2
11	16	90	1	65	0.18	27	20	39	1050	21	2.26	0.042	1.28	0.36	1.48	19	<0.2
			2	205	0.18	33	28	44	1150	31	2.76	0.108	1.94	0.62	1.98	22	<0.2
			3	250	0.18	35	22	52	1100	26	3.96	0.076	2.18	0.52	2.28	12	<0.2
			4	165	0.15	31	27	44	1050	33	3.88	0.068	1.68	0.48	2.04	16	<0.2
22	0	0	1	90	0.13	25	25	36	1000	35	1.22	0.094	1.44	0.48	1.74	14	<0.2
			2	55	0.12	23	20	28	1000	30	1.02	0.086	1.12	0.54	1.36	13	<0.2
			3	135	0.18	23	21	33	1150	35	2.20	0.232	1.08	0.50	1.10	24	<0.2
			4	115	0.11	39	23	63	1150	44	3.40	0.116	2.04	0.28	1.78	27	<0.2

Table V-4.   Continued

Treatment Ash 1977	Ash 1978	P	Repli-cation	Total Zn	Cd	Cu	Ni	Pb	Mn	Cr	DTPA-extractable Zn	Cd	Cu	Ni	Pb	Mn	Cr
mt/ha		kg/ha		--------------------------------μg/g--------------------------------													
22	0	90	1	195	0.23	23	25	26	1000	28	1.54	0.062	1.20	0.42	1.24	11	<0.2
			2	100	0.18	26	22	34	1050	33	1.86	0.042	1.32	0.44	1.62	11	<0.2
			3	80	0.11	23	25	31	1050	28	1.66	0.070	1.04	0.64	1.38	13	<0.2
			4	120	0.20	51	26	86	1100	38	6.60	0.144	2.88	0.28	3.34	13	<0.2
22	32	90	1	170	0.23	60	26	89	1100	53	4.98	0.108	1.28	0.60	3.50	11	<0.2
			2	165	0.23	53	27	85	1050	36	4.42	0.094	1.94	0.58	2.78	16	<0.2
			3	190	0.28	51	21	77	1200	41	5.34	0.156	2.18	0.70	3.46	14	<0.2
			4	165	0.23	32	43	45	1100	41	6.44	0.110	1.68	0.66	2.26	21	<0.2
43	0	0	1	100	0.14	36	25	51	950	43	2.58	0.098	1.80	0.50	2.70	15	<0.2
			2	115	0.16	26	26	37	1000	37	1.18	0.030	0.94	0.20	1.34	6.4	<0.2
			3	105	0.13	26	21	47	1150	28	1.62	0.082	1.16	0.50	1.70	16	<0.2
			4	135	0.14	28	23	38	1100	29	2.58	0.064	1.40	0.84	2.16	17	<0.2
43	0	90	1	155	0.27	52	21	81	1000	43	5.42	0.064	3.26	0.38	3.30	12	<0.2
			2	205	0.13	53	28	78	950	33	5.48	0.140	3.48	0.84	3.78	15	<0.2
			3	110	0.20	38	30	54	1000	35	3.68	0.162	2.52	0.86	2.70	12	<0.2
			4	100	0.23	30	25	47	1050	45	3.08	0.086	1.58	0.42	2.42	17	<0.2
43	63	90	1	295	0.28	62	32	90	900	41	4.22	0.100	3.10	0.34	3.50	15	<0.2
			2	360	0.44	157	34	216	1100	75	9.02	0.164	8.10	0.52	6.56	14	<0.2
			3	180	0.32	78	28	120	1100	50	7.52	0.118	4.24	0.76	5.70	11	<0.2
			4	280	0.31	95	34	165	1150	66	5.44	0.132	5.00	0.72	4.30	13	<0.2

Table V-5. Total trace metals, total P, and exchangeable Ca, Mg, and K distribution in the soil profile.[1]

Depth	Repli-cation	Total								Exchangeable		
		Zn	Cd	Cu	Ni	Pb	Mn	Cr	P	Ca	Mg	K
cm		------------------------- μg/g -------------------------								----- meg/100 g -----		

0 mt/ha Ash

15-30	1	147	0.074	16	·9	15	900	29	1100	6.6	2.3	0.91
	2	128	0.120	19	13	23	950	24	1300	5.0	1.4	0.76
	3	80	0.013	19	10	20	1000	25	1500	5.2	1.3	0.95
	4	90	0.016	18	10	17	1150	26	1500	5.3	1.2	0.83
30-45	1	90	0.038	23	18	18	850	24	1800	5.6	2.3	0.85
	2	66	0.038	19	16	18	700	29	1000	5.7	2.3	0.72
	3	80	0.018	19	17	17	850	31	1100	5.7	1.8	0.99
	4	75	0.11	15	13	19	1000	23	1500	4.9	1.6	0.98
45-60	1	78	0.018	22	18	21	900	32	1100	7.3	2.8	0.97
	2	75	0.026	20	11	21·	700	29	950	7.1	2.7	0.81
	3	109	0.080	23	13	21	700	24	1000	7.5	2.6	1.18
	4	136	0.038	18	16	20	850	31	1100	5.3	2.0	0.95
60-75	1	100	0.017	24	15	18	800	33	700	8.6	3.4	1.02
	2	65	0.038	26	15	14	700	31	1050	9.8	3.3	0.56
	3	65	0.018	24	11	18	800	30	1100	8.1	3.1	1.22
	4	108	0.025	23	13	19	700	28	900	6.3	2.5	0.98
75-90	1	107	0.018	29	17	20	750	32	700	9.1	3.6	0.87
	2	96	0.017	26	18	24	750	30	900	9.8	3.3	0.61
	3	63	0.028	22	14	15	700	25	1000	9.9	3.5	1.14
	4	73	0.014	24	13	18	700	32	900	8.2	3.0	0.91

Table V-5. Continued

Depth	Repli-cation	Total								Exchangeable		
		Zn	Cd	Cu	Ni	Pb	Mn	Cr	P	Ca	Mg	K
cm		------------------------------ μg/g ------------------------------								----- meg/100 g -----		

106 mt/ha Ash

Depth	Repli-cation	Zn	Cd	Cu	Ni	Pb	Mn	Cr	P	Ca	Mg	K
15-30	1	156	0.17	33	13	41	900	34	1500	6.9	1.8	0.80
	2	198	0.084	20	14	32	900	31	1400	4.9	1.4	0.68
	3	124	0.090	29	11	31	1050	36	1900	7.5	1.1	0.72
	4	121	0.11	23	14	26	1050	31	1800	5.2	1.4	0.82
30-45	1	124	0.028	24	11	24	750	35	1100	5.7	2.4	0.84
	2	98	0.038	22	11	21	700	26	1000	4.6	1.8	0.67
	3	90	0.050	28	10	25	700	26	1000	6.1	1.8	1.06
	4	71	0.080	17	13	20	900	24	1500	4.1	1.4	0.87
45-60	1	92	0.044	28	13	23	700	32	1000	6.4	2.4	0.66
	2	65	0.035	24	16	18	750	30	900	6.9	2.6	0.78
	3	144	0.026	22	14	22	750	33	900	6.7	2.7	0.79
	4	71	0.076	17	12	15	800	28	1400	6.6	2.8	1.29
60-75	1	103	0.025	28	18	20	800	30	900	6.7	3.5	0.62
	2	66	0.018	24	11	19	700	26	1000	7.3	2.6	1.11
	3	79	0.028	26	14	22	750	26	1050	7.9	3.2	1.27
	4	84	0.018	21	31	20	750	28	1000	5.7	2.3	0.87
75-90	1	82	0.017	28	13	16	800	28	900	9.0	3.5	0.60
	2	101	0.018	25	16	28	750	32	700	9.0	3.5	0.60
	3	90	0.018	28	18	19	750	32	800	8.9	3.7	1.42
	4	88	0.029	26	13	20	800	33	950	6.0	2.8	0.78

[1]0-15 cm soil depth trace metals and exchangeable bases listed in Tables V-4 and V-3, respectively.

Table V-6. Water extractable trace elements of Willamette silt loam
collected in September, 1978.

Ash 1977	1978	Repli-cation	Cd	Zn	Cu	Ni	Pb	Mn	Cr	B
			ng/ml				µg/ml			
0	0	1	1.1	2.25	0.02	<0.5	0.017	0.18	<0.05	<0.2
		2	0.3	0.05	0.05	<0.5	0.004	0.03	<0.05	<0.2
		3	0.3	0.10	0.05	<0.5	0.017	0.22	<0.05	<0.2
		4	1.7	0.30	0.10	<0.5	0.06	0.36	<0.05	<0.2
43	0	1	0.9	0.30	0.08	<0.5	0.02	0.03	<0.05	<0.2
		2	2.6	0.40	0.05	<0.5	0.007	0.09	<0.05	<0.2
		3	7.0	2.1	0.10	<0.5	0.036	0.19	<0.05	<0.2
		4	0.7	0.15	0.60	<0.5	0.014	0.25	<0.05	<0.2
43	63	1	6.0	1.0	0.10	<0.5	0.14	0.22	<0.05	<0.2
		2	0.8	0.40	0.05	<0.5	0.019	0.19	<0.05	<0.2
		3	0.3	0.20	0.05	<0.5	0.016	0.03	<0.05	<0.2
		4	0.9	0.75	0.50	<0.5	0.019	0.22	<0.05	<0.2

Table VI-1. Yield and elemental concentration of whole corn plants grown in the greenhouse on Willamette silt loam treated with sewage sludge ash.

Application mt/ha	Ash Type	Zn kg/ha	Replication	Zn	Cd	Cu	Ni	Pb	Mn	Cr	Na	Ca	Mg	K	P	Corn yield g/pot
				μg/g								%				
0		0	1	43	0.19	6	<5	2.0	50	0.98	33	0.23	0.13	2.5	0.13	10.0
			2	33	0.14	12	<5	0.5	41	2.6	29	0.24	0.14	2.7	0.13	10.1
			3	69	0.24	1	<5	5.1	62	1.4	28	0.24	0.13	3.5	0.17	6.0
			4	45	0.12	1	<5	2.8	58	0.75	29	0.25	0.14	2.6	0.11	12.4
0+P[1]		0	1	56	0.24	10	<5	1.7	67	2.4	29	0.28	0.17	2.9	0.18	7.2
			2	44	0.19	11	< 5	3.2	71	1.3	27	0.24	0.14	3.0	0.21	9.3
			3	32	0.20	9	<5	2.5	63	1.4	51	0.21	0.13	2.5	0.20	11.1
			4	56	0.21	3	<5	3.7	60	3.5	37	0.21	0.13	2.5	0.17	16.9
94	3	280	1	98	0.30	12	<5	2.9	45	2.6	43	0.22	0.22	1.9	0.27	17.6
			2	71	0.24	11	<5	4.3	39	1.2	42	0.17	0.19	2.3	0.34	13.9
			3	80	0.20	4	<5	1.3	48	0.53	44	0.24	0.21	2.6	0.36	20.6
			4	92	0.17	10	<5	2.6	48	1.4	29	0.21	0.20	2.2	0.27	20.1
58	2	280	1	42	0.19	2	<5	4.6	30	0.75	26	0.23	0.16	2.3	0.18	18.8
			2	40	0.20	11	<5	3.8	34	1.2	19	0.33	0.18	2.8	0.20	12.4
			3	64	0.33	4	<5	3.5	39	1.3	6.7	0.19	0.12	2.9	0.20	18.1
			4	50	0.16	17	<5	4.9	34	0.90	21	0.30	0.19	2.4	0.15	13.9
18.5	3	560	1	83	0.22	13	<5	2.8	43	0.60	80	0.21	0.24	1.8	0.30	21.2
			2	78	0.14	14	<5	6.5	35	0.90	47	0.21	0.21	2.2	0.32	17.7
			3	82	0.16	4	<5	2.8	40	5.7	33	0.20	0.23	2.2	0.36	16.8
			4	83	0.19	19	<5	4.3	40	4.1	24	0.34	0.33	2.0	0.38	22.2

[1] 500 kg/ha P (0-45-0)

Table VI-1. Continued

Appli-cation	Ash Type	Ash Zn	Repli-cation	Zn	Cd	Cu	Ni	Pb	Mn	Cr	Na	Ca	Mg	K	P	Corn yield
mt/ha		kg/ha		---------------------μg/g--------------------								----------%----------				g/pot
120	2	560	1	45	0.17	12	<5	4.5	26	0.90	13	0.27	0.17	2.4	0.21	14.1
			2	42	0.24	3	<5	2.8	25	0.75	31	0.27	0.16	2.4	0.19	12.9
			3	51	0.26	9	<5	2.2	44	0.90	14	0.28	0.18	2.7	0.13	30.5
			4	67	0.17	8	<5	3.6	31	4.7	–	0.28	0.28	2.7	0.23	15.1
370	3	1120	1	71	0.17	6	<5	3.0	37	1.4	76	0.25	0.29	1.7	0.36	17.3
			2	74	0.16	4	<5	3.5	35	0.75	23	0.28	0.26	2.1	0.35	14.9
			3	102	0.22	7	<5	3.8	42	2.3	8.9	0.19	0.25	2.1	0.41	14.5
			4	98	0.19	19	<5	3.6	41	0.98	36	0.45	0.42	2.0	0.38	14.9
240	2	1120	1	39	0.16	3	<5	3.2	36	0.98	28	0.34	0.18	2.3	0.21	14.1
			2	45	0.17	4	<5	3.8	27	0.23	36	0.31	0.19	2.5	0.19	14.9
			3	52	0.25	5	14	3.6	28	0.60	43	0.31	0.20	2.8	0.21	15.0
			4	50	0.19	6	<5	4.0	31	0.83	22	0.41	0.22	2.8	0.22	18.3
740	3	2240	1	90	0.17	14	<5	1.8	43	1.8	51	0.25	0.30	1.7	0.33	18.2
			2	81	0.15	12	<5	4.7	42	1.3	22	0.28	0.36	1.7	0.30	11.8
			3	77	0.26	9	<5	6.2	57	1.7	86	0.22	0.25	1.8	0.38	15.1
			4	81	0.23	16	<5	3.0	44	1.7	39	0.25	0.27	1.7	0.33	14.4
480	2	2240	1	30	0.18	3	<5	1.4	31	1.8	39	0.34	0.17	2.2	0.17	14.8
			2	36	0.18	11	<5	4.6	33	1.1	3	0.46	0.24	2.4	0.18	21.8
			3	46	0.29	8	<5	3.7	50	0.30	57	0.41	0.23	2.9	0.22	8.8
			4	33	0.13	7	<5	0.5	38	1.1	36	0.31	0.17	2.2	0.16	12.4
%																
100	3		1	109	0.19	10	<5	0.8	33	0.98	28	0.40	0.38	0.64	0.18	9.9
			2	99	0.24	10	<5	4.8	48	1.7	46	0.38	0.39	0.91	0.18	9.4
			3	106	0.21	28	<5	3.5	38	0.75	51	0.47	0.43	0.83	0.17	9.9
			4	109	0.17	.12	<5	7.8	30	1.1	19	0.42	0.40	0.79	0.19	12.0

Table VI-1. Continued

Appli-cation	Ash Type	Zn	Repli-cation	Zn	Cd	Cu	Ni	Pb	Mn	Cr	Na	Ca	Mg	K	P	Corn yield
%		kg/ha		<------------------------<g/g--------------------								---------%----------				g/pot
100	2		1	30	0.068	1	<5	6.3	21	0.75	22	0.40	0.23	1.0	0.13	1.0
			2	33	0.090	1	<5	10.2	27	1.2	57	0.47	0.23	1.2	0.11	1.0
			3	45	0.06	13	11	5.7	30	2.9	57	1.0	0.39	1.3	0.08	0.5
			4	41	0.068	9	<5	1.3	33	1.2	58	0.29	0.18	2.6	0.10	1.9

Table VI-2. Soil pH and bulk density of ash-soil mixtures after corn harvest.

Application	Ash Type	Zn	Replication	pH	Bulk Density
mt/ha		kg/ha			g/cm^3
0		0	1	4.6	1.12
			2	4.6	1.20
			3	4.5	1.18
			4	4.4	1.06
0+P[1]		0	1	4.6	1.21
			2	4.6	1.23
			3	4.7	1.03
			4	4.7	0.93
94	3	280	1	5.0	0.98
			2	4.9	1.01
			3	4.9	1.02
			4	5.0	1.00
58	2	280	1	5.1	1.00
			2	5.2	1.06
			3	5.2	1.04
			4	5.0	1.06
185	3	560	1	5.1	0.97
			2	5.2	0.95
			3	5.2	1.00
			4	5.2	0.92
120	2	560	1	5.5	0.89
			2	5.6	1.03
			3	5.4	1.01
			4	5.5	0.98
370	3	1120	1	5.6	0.95
			2	5.5	0.98
			3	5.5	0.87
			4	5.3	0.88
240	2	1120	1	6.0	0.92
			2	6.0	0.98
			3	6.4	0.98
			4	6.0	1.05
740	3	2240	1	5.8	0.89
			2	5.7	0.85
			3	5.5	1.07
			4	5.8	0.91

Table VI-2. Continued

Application mt/ha	Ash Type	Zn kg/ha	Replication	pH	Bulk Density g/cm^3
475	2	2240	1	6.7	0.89
			2	6.7	0.85
			3	6.6	1.07
			4	6.5	0.91
%					
100	3		1	7.2	0.57
			2	7.0	0.50
			3	6.9	0.63
			4	7.1	0.56
100	2		1	7.9	0.54
			2	7.9	0.54
			3	7.9	0.51
			4	7.8	0.57

[1]500 kg/ha P (0-45-0)

APPENDIX VII: ANALYSIS OF VARIANCE F VALUES

Table VII-1. Sweet corn yield: analysis of variance F values.[1]

Source of Variation	Degrees of Freedom	Ear			Silage
		Mature	Immature	Total	
<u>1977</u>					
Replications	3	6.74[a]	1.69	2.18	2.20
Treatments	7	2.92[b]	2.04[c]	0.617	1.42
Ash	3	0.860	0.569		
P	1	15.5[a]	10.1[a]		
Ash x P	3	0.778	0.808		
<u>1978</u>					
Replications	3	3.57[b]	4.11[b]	0.837	0.490
Treatments	10	6.37[a]	4.32[a]	2.74[b]	2.00[c]

[1] a = significant at $p < 0.01$
b = significant at $p < 0.05$
c = significant at $p < 0.10$

Table VII-2. Soil chemical properties: analysis of variance F values.[1]

Source of Variation	Degrees of Freedom	CEC	Exchangeable				P		pH
			Ca	Mg	K	Na	Total	Available	
1977									
Replications	3	0.42	1.42	0.39	3.25	4.37^b	0.42	0.66	0.61
Treatments	7	1.09	3.87^a	0.50	0.82	1.73	4.12^a	1.39	5.77^a
Ash	3		8.56^a				8.3^a		34.1^a
P	1		1.06				1.67		0.23
Ash x P	3		0.11				0.77		2.01
1978									
Replications	3		1.29	0.35	0.34	1.03	2.15	5.67^a	2.76^b
Treatments	10		4.35^b	0.21	0.26	0.86	7.65^b	4.91^a	24.36^a

[1] a = significant at $p < 0.01$
b = significant at $p < 0.05$

Table VII-3. Soil trace metal content: analysis of variance F values.[1]

Source of Variation	D.F.[2]	Total							DTPA-extractable					
		Zn	Cd	Cu	Ni	Pb	Mn	Cr	Zn	Cd	Cu	Ni	Pb	Mn
_1977_														
Replications	3	0.02	0.94	1.65	2.09	1.38	0.64	2.40[c]	1.35	1.20	3.09[b]	1.33	0.96	0.81
Treatments	7	4.06[a]	0.94	14.0[a]	1.41	16.7	1.56	3.40[b]	6.56[a]	1.44	12.2[a]	0.34	2.84[a]	9.84
Ash	3	5.89[a]		31.0[a]		38.7[a]		5.40[a]	13.7[a]		27.9[a]		19.3[a]	
P	1	0.07		0.21		0.003		0.66	1.52		0.13		0.33	
Ash x P	3	3.57		1.21		0.69		0.07	1.09		0.35		0.09	
_1978_														
Replications	3	0.25	0.51	1.00	3.05[b]	0.80	0.03	0.07	1.17	2.46[c]	1.18	1.31	1.74	0.29
Treatments	10	3.54[a]	10.0	11.0[a]	3.15[a]	11.6[a]	1.18	9.84[a]	9.58[a]	2.05[c]	11.3[a]	1.21	16.3[a]	2.19[c]

[1] a = significant at $p < 0.01$
b = significant at $p < 0.05$
c = significant at $p < 0.10$

[2] Degrees of freedom

Table VII-4. Water extractable trace elements of Willamette silt loam
collected in September, 1977: analysis of variance F
value.[1]

Source of Variation	Degrees of Freedom	Zn	Cd	Cu	Pb	Mn
Replications	3	5.82^b	0.29	5.57^b	0.70	1.76
Treatments	2	0.052	0.55	1.68	0.13	0.34

[1]b = significant at p < 0.05

Table VII-5. Elemental concentration of corn tissues: analysis of variance F values.[1]

Source of Variation	D.F.[2]	Zn	Cd	Cu	Pb	Mn	Cr	B	Mo	Na	Ca	Mg	K	P
1977 corn leaves														
Replications	3	2.98^c	0.53	0.40	0.48	4.21^b	1.75		0.78	0.39	5.33^a	0.31	1.56	0.67
Treatments	7	3.59^b	2.17^c	7.79^a	1.54	5.80^a	1.15		0.82	0.89	2.72^b	2.90^a	6.12^a	11.6^a
Ash	3	3.05^c	3.39^b	2.52^b		7.06^a					2.33^c	3.02^c	1.89	3.17^b
P	1	13.2^a	1.13	43.1^a		13.5^a					8.33^a	9.65^a	26.6^a	1.78
Ash x P	3	0.94	1.24	1.28		1.47					0.68	0.81	3.51^b	0.11
1978 corn leaves														
Replications	3	14.8^a	1.02	0.52	0.75	3.40^b	0.49	0.81	1.05	1.33	10.3^a	1.45	1.38	3.60^b
Treatments	10	9.25^a	0.78	1.37	1.06	6.22^a	1.66	3.37^a	0.11	0.82	1.68	3.84^a	1.54	15.7^a
1977 corn silage														
Replications	3	2.16	0.74	0.33	0.34	1.42	2.81^c		0.12	0.40	0.43	0.13	0.76	0.60
Treatments	7	1.72	0.46	1.55	0.66	0.52	1.47		0.35	0.21	0.90	1.22	1.12	0.79
1977 corn kernels														
Replications	3	0.28	0.14	0.88	0.36	2.46^c				0.23	4.70^b	0.27	1.54	0.98^b
Treatments	7	0.88	1.19	1.45	0.27	0.65				2.11^b	3.44^b	1.35	2.00	2.44^b
Ash	3									3.84^b	2.35^c			1.42
P	1									0.19	10.3^a			10.7^a
Ash x P	3									1.02	2.27			0.71
1978 corn kernels														
Replications	3	1.13	0.95	1.78		1.13	1.11	0.29			1.61	3.27^b	0.68	0.81
Treatments	10	1.63	0.96	0.48		3.52	0.82	2.96^b			2.03	1.04	2.02^c	1.41

Table VII-6. Yield and elemental concentration of whole corn plants grown in the greenhouse: analysis of variance F values.[1]

Source of Variation	D.F.[2]	Yield	Zn	Cd	Cu	Pb	Mn	Cr	Na	Ca	Mg	K	P
Replications	3	1.01	3.10^b	3.99^b	0.74	1.22	5.4^a	0.90	0.05	0.47	1.11	7.01^a	0.69
Treatments	10	12.0^a	24.0^a	0.19	1.24	1.02	17.5^a	1.04	16.6^a	2.81^b	14.8^a	14.0^a	25.3^a

[1] a = significant at $p < 0.01$
b = significant at $p < 0.05$

[2] Degrees of freedom